Dimensiones sociales y espaciales del transporte público masivo evaluadas mediante técnicas de análisis espacial y métodos multicriterio. El caso de Área Metropolitana de Guadalajara, México

Tesis doctoral

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Transportes, Energía y Medioambiente

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Prefacio

Esta tesis es un trabajo original de investigación que se presenta como una agrupación de publicaciones, de acuerdo con el artículo 18.4 de las Normas Reguladoras de las Enseñanzas Oficiales de Doctorado y del Título de Doctor por la Universidad de Granada. Esta normativa indica que la tesis debe de incluir al menos tres artículos publicados o aceptados en los que la doctoranda tenga una contribución científica relevante.

Las contribuciones científicas originales resultan de una investigación independiente que aporta al conocimiento de la planeación del territorio y el transporte, desde una perspectiva interdisciplinar. Las publicaciones atienden la tendencia nacional e internacional de ciencia abierta, de manera particular, en lo que se refiere al acceso abierto.

Los tres casos de estudio (CE) propuestos para ser aprobados por el Consejo Académico del Doctorado en Ingeniería Civil en la sesión de abril 2022 y ser considerados como parte sustancial de esta tesis por compendio de artículos fueron:

1. Ochoa-Covarrubias, G., Grindlay, A. L., & Lizarraga, C. (2021). Does the Mass Public Transport System Cover the Social Transport Needs? Targeting SDG 11.2 in Guadalajara, Mexico. *Applied Sciences*, *11*(16), 7709. https://doi.org/10.3390/app11167709

   JCR (2021): Factor de impacto 2,679, Clasificación: Q2 (Engineering, Multidisciplinary-SCIE, 91 revistas en la categoría)

2. Ochoa-Covarrubias, G., Gonzalez-Figueredo, C., DeAlba-Martínez, H. & Grindlay, A. L. (2021) Air Quality and Active Transportation modes: A Spatiotemporal Concurrence Analysis in Guadalajara, Mexico. *Sustainability*, *13*(24), 13904. https://doi.org/10.3390/su132413904

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3. DeAlba-Martínez, H., Grindlay, A. L., & Ochoa-Covarrubias, G. (2021). (In)Equitable Accessibility to Sustainable Transport from Universities in the Guadalajara Metropolitan Area, Mexico. *Sustainability*, *13*(1), 55. https://hdl.handle.net/11117/7402. https://doi.org/10.3390/su13010055

   JCR (2020): Factor de impacto 3,251, Clasificación: Q2 (Environmental Studies-SSCI, 125 revistas en la categoría)

Esta disertación se estructura como se muestra en la **Figura 1.**

La sección I es una introducción que incluye la presentación general de la investigación, así como los marcos teórico y metodológico de las publicaciones.

La sección II corresponde al contenido sustancial de la tesis, es decir, los CE. Esta sección incluye los tres CE publicados en revistas científicas, por lo cual vienen inglés (DeAlba-Martínez et al., 2021; Ochoa-Covarrubias, González-Figueredo, et al., 2021; Ochoa-Covarrubias, Grindlay, et al., 2021).

La sección III muestra la discusión y las conclusiones generales, así como las reflexiones finales. Se redacta en inglés en cumplimiento con el doctorado internacional solicitado.

La sección IV incluye los anexos que constan del resumen de los CE, el listado de la producción académica y de los cursos de formación, además de las referencias, tanto de esta tesis como de los CE.

Esta tesis doctoral fue financiada por el Consejo Nacional de Ciencia y Tecnología y el Fideicomiso de Desarrollo de México, bajo el convenio 2018-000013-01EXTF-00038. Además, recibió apoyo del Instituto Tecnológico y de Estudios Superiores de Occidente (ITESO), México a través del Programa de Superación del Nivel Académico. La estancia de investigación en el Laboratorio de Planeamiento, Economía y Transporte (LAET, por sus siglas en francés) en Lyon, Francia fue sostenida parcialmente por el programa ERASMUS de la Unión Europea y posibilitó experimentar la multimodalidad del completo sistema de transporte público lionés.

Figura 1. Estructura de la tesis

Preface

This dissertation is an original research work presented under a compendium of academic publications. The innovative scientific contributions are the results of independent research that contributes to the knowledge of transportation planning, from an interdisciplinary perspective and follows the worldwide trend of open science, particularly in regard to open-access data.

According to article 18.4 of the Regulations of Official Doctoral Studies and of the Doctoral Title by the University of Granada, an article-based dissertation must have at least three scientific contributions authored by the candidate in a relevant indexation. In consequence, three case studies were proposed to be approved by the Academic Committee of the Civil Engineering Doctoral Program, from the International Postgraduate School of the University of Granada in April 2022.

The publications comply with current regulations regarding the quality of the dissemination of results during the doctoral training process at the University of Granada and were considered a substantial part of this thesis through the compilation of articles.

The three academic articles published in international journals comply with the current regulations of quality of the University of Granada:

1. Ochoa-Covarrubias, G., Grindlay, A. L., & Lizarraga, C. (2021). Does the Mass Public Transport System Cover the Social Transport Needs? Targeting SDG 11.2 in Guadalajara, Mexico. *Applied Sciences*, *11*(16), 7709. https://doi.org/10.3390/app11167709

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Based on this consent, this thesis is structured as shown in **Figure 1**.

Section I presents research context, goals and questions, as well as theoretical, methodological and contextual frameworks.

Section II constitutes the main core of the dissertation. The empirical studies are presented as published.

Section III presents the discussion and conclusions.

Section IV includes references and annexes

The research work was supported by the National Council for Science and Technology (Mexico) and the Mexico Development Trust, through a four year scholarship abroad (2018-000013-01EXTF-00038).

This doctoral thesis was also supported by the Western Institute of Technology and Higher Studies, Mexico (ITESO, from its initials in Spanish). The research residence at the Laboratory of Planning Economy Transport (LAET, from its acronym in French) in Lyon, France was partially supported by the European Union ERASMUS program and made it possible to experience the multimodality of the Lyon's public transport system.

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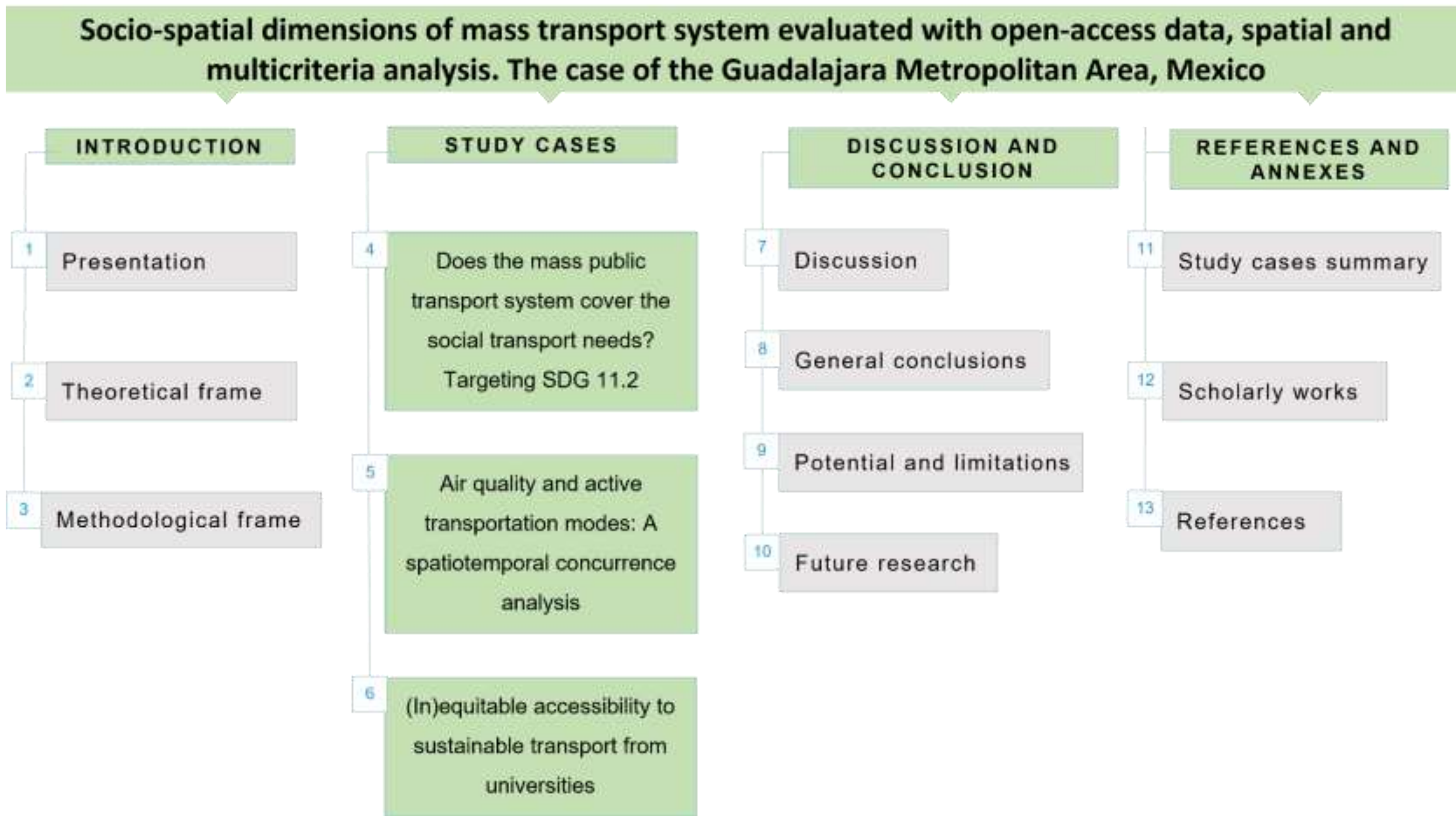

Figure 1. Dissertation structure.

Préface

Cette thèse est un travail de recherche original présenté dans un recueil de publications académiques. Les contributions scientifiques innovantes sont les résultats de recherches indépendantes qui contribuent à la connaissance de la planification des transports, dans une perspective interdisciplinaire et suivant la tendance mondiale de la science ouverte, notamment en ce qui concerne les données en libre accès.

Selon l'article 18.4 du Règlement des enseignements officiels de doctorat et du titre de docteur de l'Université de Grenade, une thèse par articles doit avoir au moins trois contributions scientifiques rédigées par le candidat dans une indexation pertinente. En conséquence, trois cas d'étude ont été proposés pour leur acceptation au Comité Académique du Programme de Doctorat en Génie Civil, de l'École Internationale de Troisième Cycle de l'Université de Grenade en avril 2022.

Les trois articles académiques publiés dans des revues internationales sont conformes aux normes de qualité en vigueur de l'Université de Grenade :

1. Ochoa-Covarrubias, G., Grindlay, A. L., & Lizarraga, C. (2021). Does the Mass Public Transport System Cover the Social Transport Needs? Targeting SDG 11.2 in Guadalajara, Mexico. *Applied Sciences*, *11*(16), 7709. https://doi.org/10.3390/app11167709

   JCR (2021): Impact factor 2,679, Classification: Q2 (Engineering, Multidisciplinary-SCIE, 91 journals in this category)

4. Ochoa-Covarrubias, G., Gonzalez-Figueredo, C., DeAlba-Martínez, H. & Grindlay, A. L. (2021) Air Quality and Active Transportation modes: A Spatiotemporal Concurrence Analysis in Guadalajara, Mexico. *Sustainability*, *13*(24), 13904. https://doi.org/10.3390/su132413904

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JCR (2020): Impact factor 3,251, Classification: Q2 (Environmental Studies-SSCI, 125 journals in this category)

Les publications sont conformes à la réglementation en vigueur concernant la qualité de la diffusion des résultats au cours du processus de formation doctorale à l'Université de Grenade et ont été considérées comme une partie substantielle de cette thèse par la compilation d'articles. Sur la base de ce consentement, cette thèse est structurée comme suit (**Figure 2**)

La section I présente le contexte, les objectifs et les questions de la recherche, ainsi que les cadres théoriques et méthodologiques.

La section II correspond au corps principal de la thèse. Les études empiriques sont présentées telles qu'elles ont été publiées.

La section III présente la discussion et les conclusions.

La section IV comprend des références et des annexes.

Les travaux de recherche ont été soutenus par le Conseil National de Science et Technologie (Mexique) et le Fiducie de développement du Mexique, grâce à une bourse de quatre ans à l'étranger (2018-000013-01EXTF-00038).

Cette thèse de doctorat a également été soutenue par l'Institut Occidental de Technologie et des Études Supérieures, Mexique (ITESO par ses initiales en espagnol). Le séjour de recherche au Laboratoire d'aménagement, d'économie et de transport (LAET, pour son sigle en français) à Lyon, France a été partiellement soutenu par le programme ERASMUS de l'Union européenne et a permis d'essayer la multimodalité de l'ensemble du système de transports en communs lyonnais.

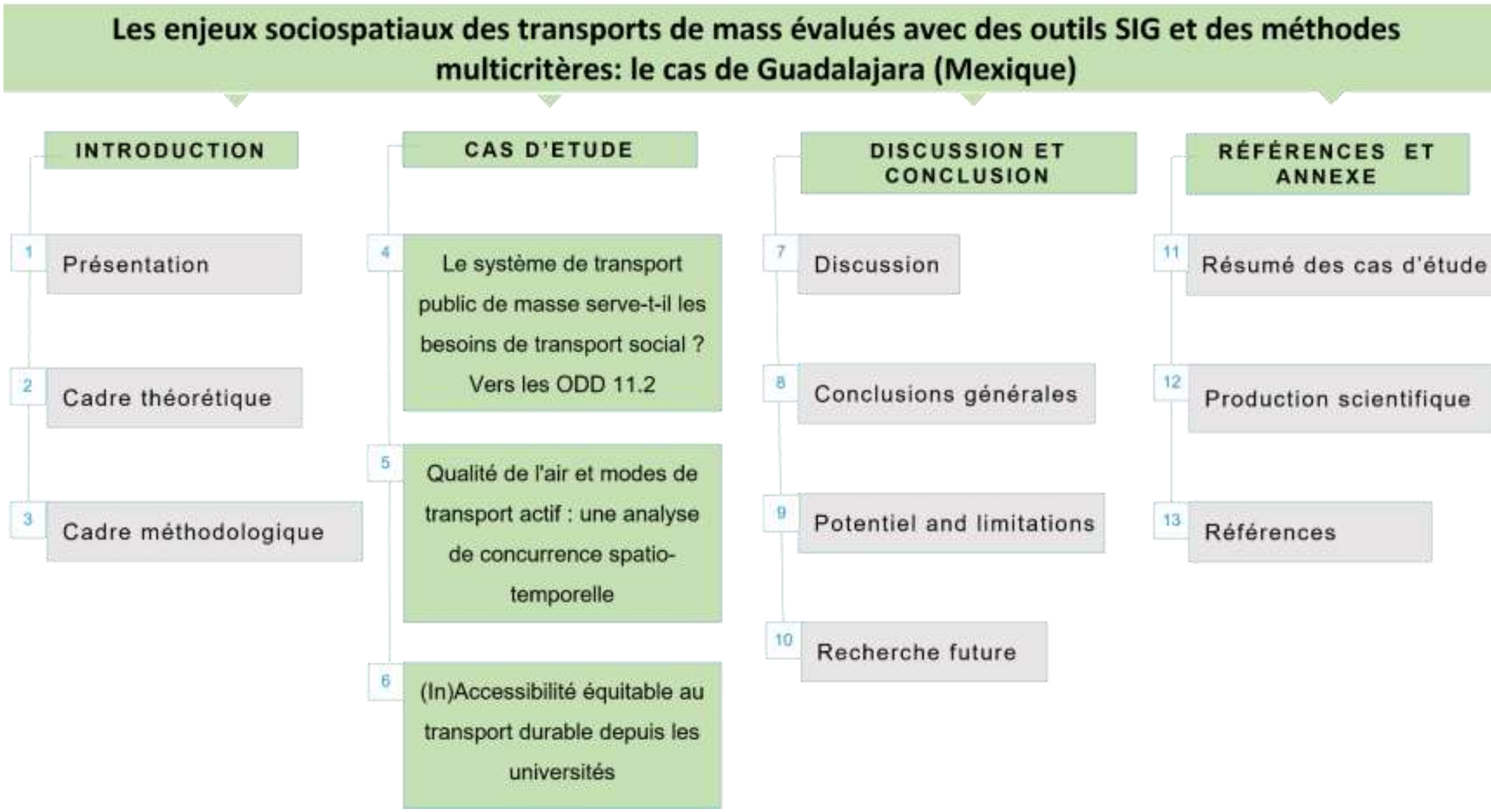

Figure 2. Structure de la dissertation

Resumen

Desplazarse es un derecho fundamental de las sociedades democráticas y permite alcanzar las oportunidades de desarrollo social, económico y cultural que la ciudad ofrece. La movilidad está determinada, en gran medida, por las condiciones socioeconómicas de las personas, así como por la localización y pertinencia de las oportunidades. En contextos metropolitanos con inequidades estructurales, el acceso a los sistemas de transporte masivos es limitado. Esto incrementa la vulnerabilidad y contribuye a la exclusión social relativa al transporte. Esta exclusión, a su vez, deriva en un incremento de la desigualdad y la pobreza. Esta tesis contribuye a la compresión de las dimensiones sociales y espaciales del transporte público urbano que subyacen en metrópolis latinoamericanas.

La hipótesis general fue que las dimensiones sociales y espaciales del transporte público masivo pueden estimarse por medio de la accesibilidad, de forma particular, identificando zonas con diferentes grados de exclusión social por transporte, a partir de datos de libre acceso y análisis espaciales y multicriterio.

A fin de comprobar la hipótesis se propuso una metodología cuantitativa para estimar el acceso al transporte como un indicador de exclusión social diseñada para contextos con limitaciones financieras y técnicas. Ésta se aplicó al Área Metropolitana de Guadalajara (AMG), México, atendiendo a problemas estructurales intrínsecos al transporte, como la desigualdad social, la expansión urbana y la mala calidad del aire, en tanto que dimensiones sociales y espaciales del transporte público.

¿Es suficiente el sistema de transporte masivo para atender a las necesidades sociales del transporte? ¿En qué condiciones ambientales se desplazan los usuarios del transporte público? ¿La distribución espacial de sus estaciones promueve el acceso a colectivos vulnerables? Esta tesis prueba conceptos teóricos y metodológicos en la zona de estudio seleccionada para responder a estas y otras preguntas y ofrece hallazgos empíricos para profundizar en la comprensión del papel del transporte público en el contexto de la complejidad urbana.

El presente documento se estructura a partir de tres CE empíricos publicados en revistas académicas internacionales de alto impacto que confirman altos grados de exclusión social relativa al transporte en el ámbito metropolitano estudiado.

Los hallazgos del primer caso demuestran que la movilidad reducida, el analfabetismo, el desempleo y el ingreso son variables que definen en gran medida las necesidades sociales del transporte en la metrópoli. Además, se observó que el sistema de transporte masivo sirve de manera limitada para subsanar las necesidades sociales del transporte tanto en la periferia como en áreas centrales específicas.

Por su parte, en el segundo caso se pudo identificar que los usuarios de transportes sostenibles son expuestos a episodios de mala calidad del aire en una pequeña proporción. Asimismo, se confirma la generación limitada de datos por parte de autoridades encargadas de gestionar cuestiones medioambientales y de movilidad.

Los resultados del tercer caso mostraron que el colectivo universitario está en desventaja de transporte respecto a otros colectivos de la ciudad y que, en consecuencia, sufren de exclusión social por transporte.

Todos estos CE prueban que las dimensiones sociales y espaciales del transporte pueden ser explicadas con datos de acceso abierto, análisis espaciales y multicriterio. En particular, se confirma la pertinencia de utilizar métodos acumulativos simplificados para estimar el acceso al transporte público para contextos con limitaciones técnicas y financieras.

Los hallazgos aportan evidencia empírica para las políticas públicas de los sectores de la planeación urbana y del transporte, como complemento de políticas sociales y económicas que promuevan la inclusión social y el desarrollo en las ciudades latinoamericanas.

Abstract

Traveling is a fundamental right of democratic societies and provides opportunities for the social, economic and cultural development that the city offers. Mobility is largely determined by transport systems and their relationship with the urban environment, by people's socioeconomic conditions, and by the location and relevance of opportunities. In metropolitan contexts with structural inequities, access to mass transportation systems is limited. This increases vulnerability and contributes to social exclusion related to transport. This exclusion, in turn, leads to an increase in inequality and poverty. This dissertation contributes to the comprehension of the underlying social and spatial dimensions of public transport (PT) in Latin American metropolises.

The general hypothesis was that the social and spatial dimensions of mass public transport can be estimated through accessibility, specifically by identifying areas with different degrees of transport related social exclusion through open-access data and spatial and multi-criteria analyses.

To prove the hypothesis, a quantitative methodology was proposed to estimate access to PT as an indicator of social exclusion, and designed for contexts with financial and technical limitations. This was applied to the Guadalajara Metropolitan Area (GMA), Mexico, addressing structural problems intrinsic to transportation, such as social inequality, urban sprawl and poor air quality, as social and spatial dimensions of PT.

Is the mass transit system adequate to meet the social needs of transportation? Does the spatial distribution of PT stations provide access to vulnerable groups? What are the conditions of the urban environment when active mode users commute? To answer these and other questions, this dissertation proves theoretical and methodological concepts in the study area mentioned above. Thus, it shows empirical findings to contribute to the comprehension of the role of PT in the context of urban complexity.

This document is structured using three empirical case studies (CS) published in high-impact international academic journals. In addition to the specific findings in

each case, this research confirms High degrees of social exclusion related to transport in the metropolitan area studied.

Results of the first CS show that reduced mobility, illiteracy, unemployment and income are variables that largely define the social needs of transportation in the metropolis. In addition, it was observed that the mass transit system scarcely served the social needs of transportation in the periphery and some central areas.

The second CS highlights that users of sustainable transport are exposed to episodes of poor air quality in a small proportion of trips. In addition, the limited generation of open-access data produced by authorities from the transport and environmental sectors is confirmed.

The findings of the third CS show that the university group is in transport disadvantage compared to other groups in the city, thus they suffer from transport related social exclusion.

The three CS prove that the social and spatial dimensions of transport can be estimated with open-access data, spatial analysis and multicriteria. In particular, the relevance of using simplified cumulative methods to estimate access to public transport for contexts with technical and financial limitations is confirmed.

The results provide empirical evidence for public policies in the urban planning and transportation sectors, as a complement to social and economic policies that promote social inclusion and development in Latin American cities.

Résumé

Se déplacer est un droit fondamental des sociétés démocratiques qui conditionne les opportunités de développement social, économique et culturel offertes aux villes. La mobilité est largement déterminée par les conditions socio-économiques des personnes et par le transport, ainsi que par la localisation et la convenance des opportunités. Dans les métropoles qui se caractérisent par des inégalités structurelles, l'accès aux systèmes de transport en commun est limité. Cela accroît la vulnérabilité, contribue à l'exclusion sociale et entraîne une augmentation des inégalités et de la pauvreté. Cette thèse contribue à la compréhension des enjeux sociospaciaux du transport public dans les métropoles latino-américaines.

Le système de transport est-il suffisant pour répondre aux besoins sociaux de transport ? Dans quelles conditions environnementales les usagers des modes actifs se déplacent-ils ? La distribution spatiale des stations favorise-t-elle l'accès aux groupes vulnérables ?

L'hypothèse générale de cette thèse soutient que les enjeux sociospatiaux de transports publics de masse peuvent être estimés à travers le critère de l'accessibilité, notamment, en identifiant des zones d'exclusion sociale à l'aide de données en accès libre et d'analyses spatiales et multicritères.

Pour justifier cette hypothèse, une méthodologie quantitative a été proposée en vue d'évaluer l'accessibilité au transport comme indicateur d'exclusion sociale. La méthodologie a été appliquée à la métropole de Guadalajara, au Mexique, une ville qui connaît de nombreux problèmes structuraux sur la question du transport, parmi lesquels s'imposent d'abord la prégnance des inégalités sociales et la mauvaise qualité de l'air. Les résultats empiriques contribuent à étudier le rôle social des transports publics dans un contexte de grande complexité urbaine.

Ce document est structuré à partir de trois études de cas publiées dans des revues académiques de référence sur le plan international, qui confirment le degré élevé d'exclusion sociale lié au transport dans la ville.

Les résultats du premier cas confirment que la mobilité réduite, l'analphabétisme, le chômage et le niveau de revenu sont les variables les plus pertinentes à retenir pour définir les besoins sociaux de transport dans la ville. L'étude confirme en outre la localisation essentiellement périphérique des besoins sociaux de transport même si ce besoin est également attesté dans certains quartiers centraux où le système de transport de masse est limité.

Le deuxième cas montre que seulement une faible proportion des usagers des transports actifs se trouve exposée aux épisodes de mauvaise qualité de l'air. Les résultats confirment aussi des limitations de production systématique des données des transports de masse et de l'environnement.

Le troisième cas démontre que les communautés universitaires sont désavantagées vis-à-vis du transport et qu'elles souffrent d'exclusion sociale. L'inégalité verticale entre aménités publiques et privées n'a pas été confirmée.

Les résultats contribuent aux politiques publiques tant des secteurs de l'urbanisme et des transports, que sociales et économiques pour favoriser l'inclusion sociale et le développement dans les villes d'Amérique latine.

Tabla de contenidos

Siglas y acrónimos en Español

AM	Análisis multicriterio
APC	Análisis de componentes principales
AGEB	Área geoestadística básica
AMG	Área Metropolitana de Guadalajara
BRT	Tren articulado de gran capacidad[1]
CONAPO	Comisión Nacional de Población (México)
CONEVAL	Comision Nacional para la Evaluación de las Políticas Sociales (México)
DOT	Desarrollo orientado al transporte
ESRT	Exclusión social relativa al transporte
IIEGJal	Instituto de Información Estadística y Geográfica del Estado de Jalisco (México)
INEGI	Instituto Nacional de Estadística y Geografía (México)
IPTM	Índice de provision del transporte masivo
IMEPLAN	Instituto Metropolitano para la Planeación y Desarrollo (México)
INST	Índice de necesidades sociales del transporte
LRT	Tren ligero[1]
NST	Necesidades sociales del transporte
PTM	Provisión de transporte masivo
SIG	Sistema de información geográfica
SITEUR	Sistema de Tren Eléctrico Urbano
SEMADES	Secretaría del Medio Ambiente y Desarrollo Sustentable (México)
STP	Sistema de transporte público
STPM	Sistema de transporte público masivo
TP	Transporte público

[1] Por sus siglas en Inglés.

Acronyms in English

BRT	Bus rapid transit
CONAPO	Population Nacional Committee (México) [1]
CONEVAL	National Committee for the Social Policies Evaluation (México)[1]
CS	Case study/ies
CS_*i*	Case study_*i*
GIS	Geographic information system
GMA	Guadalajara Metropolitan Area
GS	Geographical section
IIEGJal	Instituto of Statistics and Geography Information of the State of Jalisco (México) [1]
INEGI	National Instituto of Statistics and Geography Information (México) [1]
IMEPLAN	Metropolitan Planning and Development Institute (México) [1]
IMTP	Index of mass transport provision
ISTN	Index of social transport needs
LRT	Light rail transit
MA	Multicriteria analysis
MTP	Mass transport provision
MPTS	Mass transport provision system
PCA	Principal Component Analysis
PT	Public transport
PTS	Public transport system
SITEUR	Urban Electric Train System [1]
TOD	Transport Oriented Development
STN	Social transport needs
TRSE	Transport related social exclusion
UF	University facility/ies

[1] From its initials in Spanish

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I. INTRODUCCIÓN

Este capítulo incluye tres secciones. Primero la presentación con los antecedentes y generalidades de la tesis. Después el marco teórico que fundamentó la propuesta. Finalmente, el marco metodológico de investigación.

UNIVERSIDAD DE GRANADA

I. INTRODUCCIÓN

1. Presentación

I. INTRODUCCIÓN

Esta sección describe el contexto general de la tesis, además de las hipótesis y la descripción de la estructura de la tesis.

Contexto general

Más de la mitad de los habitantes del planeta viven en ciudades (ONU-Hábitat, 2021). En Latinoamérica, la población urbana se incrementó un 24.8% en las últimas cuatro décadas y se estima que alcanzará el 87.8% en 2050 (CEPAL, 2020). En México, el Consejo Nacional para la Evaluación de la Política Social (CONEVAL) estima que el 81% de la población mexicana vive en ciudades (CONEVAL, 2019b). En este contexto de urbanización global, regional y local, las decisiones que los habitantes tomen respecto a la manera como habitar las ciudades, definirán en gran medida el futuro de la humanidad.

Las ciudades ofrecen oportunidades sociales, culturales y económicas. Sin embargo, además de ofrecer oportunidades, las urbes también ponen en evidencia desigualdades y pobreza. Uno de cada cuatro hogares que viven en ciudades del mundo no comparten los beneficios de la interacción con sus semejantes para acceder a oportunidades sociales, culturales y económicas (Wilson, 2020). Aunque la pobreza urbana en América Latina ha disminuido del 28.1% al 26.4%, la pobreza extrema ha incrementado del 5.5% al 8.4%, y, además, ambos indicadores son mayores para las mujeres (CEPAL, 2020). En México, las condiciones demandan acciones inmediatas, pues el 35% de los habitantes que viven en ciudades sufren de pobreza o pobreza extrema (CONEVAL, 2019b) y se estima que la situación se ha agravado con la pandemia del COVID19.

Los sistemas de transporte público (STP) posibilitan o dificultan el acceso a las oportunidades que ofrecen las ciudades (Jaramillo et al., 2012). Es reconocido que las características socioeconómicas determinan en gran medida la decisión de utilizar o no un modo de transporte para resolver las necesidades de desplazamientos. (Lucas, 2019; Talavera-Garcia & Valenzuela-Montes, 2018; Vecchio, Tiznado-Aitken, et al., 2020). Esta investigación contribuye a la comprensión de la complejidad de las metrópolis latinoamericanas, en lo general, y los beneficios e impactos de los STP, en particular.

En el contexto mexicano, el análisis teórico y empírico de las dimensiones sociales y espaciales de los STP es reciente y fue abundante (Ballesteros et al., 2018; Bayón, 2008; Capron & Pérez López, 2016; Delfin Ortega & Melo Vázquez, 2017; Guerra et al., 2018b; López, 2013, 2017; C. Medina et al., 2013; Medina Ramírez & ITDP, 2012; S. Medina & Patlán, 2016; Murata et al., 2017; Suarez et al., 2016). Sin embargo, la producción académica es aún limitada en el Área Metropolitana de Guadalajara (AMG). Prevalecen publicaciones con perspectiva sociológica que utiliza prioritariamente métodos cualitativos para analizar la dimensión social del transporte (Aceves-González et al., 2020; Calonge Reillo, 2017a; Calonge-Reillo, 2021; Castañón Reyes, 2019; Guerrero Contreras & Valenzuela Montes, 2020; Meza, 2017; Rodriguez, 2019). No se encontraron publicaciones científicas que refieran análisis cuantitativos de las dimensiones sociales y espaciales en la metrópoli, menos aún que utilicen sistemas de información geográfica y métodos multicriterio para complementar las reflexiones existentes sobre estas dimensiones.

Hipótesis

El objetivo genera de esta investigación fue contribuir a la compresión de las dimensiones sociales y espaciales del TP que subyacen en metrópolis latinoamericanas. Para alcanzarlo se propuso una metodología innovadora que estima el acceso al TP por medio de datos abiertos y análisis espaciales y multidimensionales.

La hipótesis general fue que **las dimensiones socioespaciales del transporte público masivo pueden estimarse a través de la accesibilidad, particularmente, identificando zonas con diferentes grados de exclusión social por transporte a partir de datos de libre acceso y análisis espaciales y multicriterio (HG)**.

Para comprobar la hipótesis se propuso una metodología para estimar el acceso al transporte como un indicador de exclusión social diseñada para contextos con limitaciones financieras y técnicas. El principio que sustentó el método fue que el acceso se define, en gran medida, por las características sociales de los usuarios y por el acceso espacial hacia las estaciones o paradas del sistema. Ésta se aplicó al Área Metropolitana de Guadalajara (AMG), México, atendiendo a problemas estructurales intrínsecos al transporte, como la expansión urbana, la desigualdad social o la mala calidad del aire, en tanto que dimensiones socioespaciales del TP.

La expansión urbana en el AMG ha provocado desigualdades sociales (Cruz Solís et al., 2008; Harner et al., 2018), mala calidad del aire, entre otras problemáticas. De acuerdo con Castañón Reyes (2019), el problema estructural de la desigualdad en esa metrópoli es la definición de la tarifa del TP, pues se fundamenta en criterios técnicos y económicos y sin considerar los sociales. El porcentaje del ingreso destinado al transporte es del 15.63% para los ingresos más altos. En contraste, los hogares con ingresos más bajos destinan el 35.63% (Calonge Reillo & Aceves Arce, 2019), dando lugar a inequidad de acceso al transporte público en razón de la renta (Diaz Olvera et al., 2017). Más aún, el 40% de los desplazamientos en la metrópoli se realizan en modos no motorizados, en su mayoría por dificultades para pagar la tarifa del transporte (Asprilla Lara et al., 2018).

Por otro lado, la fragmentación y expansión del modelo urbano también dificultan el acceso al TP, con lo cual se incentiva el uso del automóvil particular. Entre 1980 y 2010, la tasa de motorización de la metrópoli incrementó un 942% (Jalisco, 2019) con el consecuente deterioro de la calidad del aire. En 2019, ésta excedió los parámetros recomendados por la Organización Mundial de la Salud durante 267 días del año, siendo el ozono y las partículas suspendidas los contaminantes más comunes (Jalisco, 2019).

La desigualdad se intensifica para aquellos que viven en la periferia. Este grupo social puede verse limitado a utilizar modos de transporte de corta distancia, como la caminata o la bicicleta y, por lo tanto, ser sujeto de exclusión social relativa al transporte (ESRT).

Esta monografía da cuenta del análisis empírico de dimensiones socioespaciales del transporte público urbano a partir del potencial de acceso al TP. En este documento se presentan tres ensayos empíricos de la metodología (**Figura 1**) que atienden a las problemáticas antes mencionadas. Los casos de estudio (CE) se incluyen en formato de artículos y se estructuran con base en preguntas de investigación que derivan en hipótesis particulares al área de estudio (**Tabla 1**).

Tabla 1

Preguntas de investigación e hipótesis de los casos de estudio

CE[1]	Título	Hipótesis particular	Preguntas de investigación
1	¿El sistema de transporte masivo cubre las necesidades sociales del transporte? Hacia el objetivo de desarrollo sostenible 11.2 en el AMG	La distribución espacial de las necesidades sociales del transporte y de las estaciones del sistema de transporte público en el AMG es desigual	¿Cuáles son las principales variables que determinan las necesidades sociales del transporte en la ciudad? ¿En qué medida responde el sistema de transporte masivo a ellas?

Tabla 1 (continuación)

CE[1]	Título	Hipótesis particular	Preguntas de investigación
2	Calidad del aire y usuarios de modos activos: un análisis de concurrencia espacio-temporal en el AMG	Los usuarios de modos activos de transporte son altamente expuestos a episodios de mala calidad del aire en el AMG	¿Cuándo y en dónde se exponen usuarios del transporte público a episodios de mala calidad del aire?
3	(In)Accesibilidad a transporte sostenible desde universidades en el AMG	El acceso a los sistemas de transporte sostenible desde diversos equipamientos urbanos en el AMG es limitado, específicamente desde los planteles de educación superior	¿Cuál es el grado de accesibilidad al transporte desde el equipamiento universitario? ¿La red de TP promueve un cambio modal en la generación de estudiantes universitarios? ¿El acceso es mayor desde equipamiento universitario público o privado?

[1] CE: Caso de estudio

Estructura de la tesis

Esta tesis se organiza en torno a tres CE que constituyen la sustancia de la disertación. El documento consta de cuatro capítulos y las secciones se numeran de forma continua a lo largo de toda la tesis (**Figura 1**).

El capítulo I Introducción incluyen tres secciones: la presentación, el marco teórico y el metodológico. La primera sección presenta el contexto, los objetivos del proyecto de investigación doctoral y la estructura de la tesis. La sección 2, refiere el marco teórico relativo a las dimensiones socioespaciales de los sistemas de transporte público masivo (STPM). La sección 3 describe la meta-metodología de investigación y la metodología general para los tres CE, con el objeto de facilitar la replicación con otros modos de transporte, equipamientos o ámbitos metropolitanos.

El capítulo II presenta los tres CE que sustentan esta tesis. El primer caso compara las necesidades sociales del transporte con el servicio que ofrece el STPM en el contexto de la meta 11.2 de los objetivos de desarrollo sostenible. El segundo caso cuantifica la concurrencia espacio-temporal los usuarios de modos activos expuestos con episodios de mala calidad del aire. El tercer caso estima la inequidad de acceso al transporte sostenible desde las universidades, como ejemplo de la posibilidad de aplicación de la metodología a equipamientos urbanos. En el momento de la redacción de esta tesis, otros dos artículos se encuentran bajo revisión por parte de revistas científicas indexadas en JCR. El primero incluye un análisis complementario al caso de estudio 1 al considerar la red de autobuses convencionales en el modelo y datos socioeconómicos más recientes. El segundo artículo compara valores de un índice compuesto del mejoramiento del contexto urbano en el entorno de las estaciones de transporte masivo respecto al resto de la ciudad.

El capítulo III consta de dos secciones. En la sección 7 se discuten los principales hallazgos de la tesis en diálogo con las preguntas de investigación e hipótesis. La sección 8 presenta un resumen de la tesis a manera de conclusión general. La sección 9 plantea las fortalezas y limitaciones de la investigación. Finalmente, la sección 10 plantea líneas futuras de investigación y los retos científicos que conllevan.

El capítulo IV incluye cuatro secciones a manera de anexos. La sección 11 incluye un resumen de los CE con preguntas de investigación, métodos, indicadores, datos utilizados y hallazgos principales. La sección 12 contiene un resumen de la producción académica de esta investigación que se difundieron en formato de publicaciones, comunicaciones y secciones de libros y la lista los cursos y talleres de formación, como evidencia de la formación doctoral. Finalmente, la sección 13 contiene las referencias de esta disertación.

2. Marco teórico

Esta sección describe aportaciones teóricas que fundamentaron los casos de estudio (CE) incluidos en esta disertación. Primero se describe la estrecha relación ciudad-transporte. Después se refieren conceptos generales del transporte público (TP) en general y del transporte público masivo, en lo particular. Finalmente se describe la evolución de conceptos vinculados a la dimensión social del transporte, como la exclusión social y la accesibilidad espacial como instrumento para estimarla.

Ciudad y transporte

Las etapas iniciales de las ciudades industrializadas de los siglos XIX y XX dieron lugar a la expansión de los asentamientos apoyada primero en los ferrocarriles, después en los tranvías y, por último, en los modos motorizados. Esto provocó finalmente una desmesurada dependencia al automóvil privado que se demostró nociva para los habitantes de las urbes. La ciudad extendida agravó las disparidades económicas, sociales y espaciales al marginar a los colectivos más desfavorecidos y a quienes vivían en las áreas periféricas.

Durante la segunda mitad del siglo XX los conceptos teóricos urbanos evolucionaron. Fue entonces que se reconoció que la forma urbana, la actividad económica, la vida en la calle y la cultura configuraban, entre otros, a las ciudades. A principios de los 60´s, la periodista J. Jacobs (1961) publicó un libro periodístico que trascendería su época y revolucionaría la percepción de la ciudad (Delclòs-Alió & Miralles, 2018; Gómez-Varo et al., 2022). La autora propuso generadores de diversidad que facilitaran la interacción, por ejemplo, el uso de suelo mixto promovería la vida en las calles a diferentes horas del día; el diseño urbano con bloques pequeños aumentaría la oportunidad de contacto; la cohabitación de edificios con diferentes grados de envejecimiento promovería la mezcla social, además de la diversidad comercial; la densidad concentraría las actividades y los espacios de interacción. De esta manera, la diversidad promovería la vitalidad urbana que requerían las ciudades.

Durante esos años también se reconoció que el transporte facilitaba o dificultaba el acceso a las oportunidades que ofrecía la ciudad (Hansen, 1959). Lowdon Wingo

(1961) abordó la relación entre el transporte y el uso de suelo desde la perspectiva del sector inmobiliario. El autor sostuvo que la relación espacial entre las viviendas y las oportunidades era atendida en mayor o menor medida por los sistemas de transporte. El Informe Buchanan (Ministry of Transport (UK), 1963) expuso el eminente incremento del uso del vehículo privado y su impacto negativo en la calidad de vida urbana, proponiendo un modelo viario segregado de vehículos y peatones. Sin embargo, la planeación urbana no siempre consideró los planteamientos periodísticos, académicos y gubernamentales antes expuestos. A mediados del siglo XX muchas ciudades latinoamericanas siguieron el modelo norteamericano de desarrollo urbano, optaron por abandonar sus centros y apostaron por la conurbación de la periferia. Posteriormente, Gorz (1973) vislumbró la catástrofe que traería la dependencia del automóvil.

En los 80´s del siglo XX, surgió el paradigma del “nuevo urbanismo” como contrapropuesta a la planeación tradicional basada en el automóvil privado. Newman y Kenworthy confirmaron el crecimiento vertiginoso de la dependencia del automóvil (1999; 1989) prevista decenios antes, y aludieron al Desarrollo Orientado al Transporte (DOT o TOD, por sus siglas en inglés) como solución para revitalizar las ciudades (1996). Tanto ellos como Cervero y Kockelman (1997) refirieron el “nuevo urbanismo” como paradigma para vincular el medio construido con el transporte. Los autores sostuvieron que la densidad, la diversidad y la accesibilidad definían los desplazamientos y, en consecuencia, los sistemas de transporte que los posibilitaban. Otro referente de esa época desde el diseño urbano fue Montgomery (1998), quien propuso criterios de densidad, diversidad y proximidad a través de elementos formales y funcionales que promovían la urbanidad y vitalidad: el flujo peatonal, los atractores de personas, la variedad de usos del suelo, la densidad de población, la actividad en las calles y la economía a pequeña escala.

Al final del siglo XX la Organización de las Naciones Unidas (ONU), impulsando el concepto de desarrollo sostenible, sugiere la consideración simultanea de las dimensiones ambiental, económica y social en los instrumentos de política pública. Los estudiosos de la ciudad de principios del siglo XXI se hicieron eco de este paradigma. Por ejemplo, el arquitecto Rogers (1995) planteó acciones de planeamiento urbano para alcanzar ciudades sostenibles. En 2003, tanto Hall (2003) como Wegener y Fuerst (2004; 2004) analizaron el ciclo de retroalimentación transporte-uso de suelo con base en Hansen (1959) y Lowdon (1961), adaptando de esta manera conceptos de los desplazamientos urbanos a la dimensión económica del paradigma del desarrollo sostenible. En 2002, C. Miralles señaló las dificultades en la relación ciudad-transporte (Miralles-Guasch, 2002). Posteriormente, Banister identificó la importancia de los viajes con motivos diferentes al trabajo (Banister, 2005). El autor puntualizó sobre la pertinencia de considerar un tiempo de viaje “razonable” y no necesariamente el tiempo “mínimo”. Posteriormente, este autor atendió al diseño urbano como promotor de la caminata a la escala barrial (Banister, 2008). En esta misma época, Bertolini et al. (2005) propusieron la accesibilidad como herramienta para integrar la planeación del uso del suelo y del transporte.

En el segundo decenio del siglo XXI la producción académica referente a la ciudad y el transporte proliferó. Córdova España (2010) ratificó en México el impacto del paradigma del automóvil y la dispersión urbana en la marginación social. Por su parte, Hall y Tewdwr-Jones (2011) confirmaron el incremento en el uso del vehículo privado e insistieron en la necesidad de que el transporte público fuera suficientemente atractivo como para que los usuarios del primer modo cambiaran al segundo. Higgings et al. (2014) sostuvieron que los modos de transporte masivo, particularmente, el tren ligero (LRT, por sus siglas en inglés) tenían un gran potencial para remodelar y revitalizar las ciudades. Por su parte, Vuchic (2017) identificó múltiples ciudades que promovían el TP y la intermodalidad y que parecían ser más habitables que las orientadas al vehículo privado. En ese decenio, tanto académicos (Castañeda Huizar et al., 2009; Haghshenas & Vaziri, 2012; Mendo-Gutiérrez, 2008) como entidades gubernamentales (UEA, 2012) y organizaciones profesionales (Murakami et al., 2013; USGBC, 2018) diseñaron indicadores y propuestas de sostenibilidad urbana que involucraban al transporte.

En 2015, Newman y Kenworth (2015) sostuvieron que el paradigma del automóvil particular declinaría frente a modos activos, en coherencia con el paradigma de DOT expuesto desde finales del siglo XX y consolidado, con clarooscuros, en el segundo decenio del siglo XXI (Bentayou et al., 2015; Grindlay et al., 2015; IMEPLAN, 2016a; ITDP, 2018). Por su parte, Kasraian et al. (2016) identificaron la temporalidad del impacto del transporte en el contexto urbano en el corto, medio y largo plazo en el contexto del DOT. Bertolini (2017) afirmó la necesidad de que las ciudades del siglo XXI se plantearan coordinadamente desde la planeación tanto del transporte como de la urbana. En 2018, Pelé et al. (2018) modelaron la interrelación entre la forma urbana y el transporte en Lyon. Al año siguiente, Coppola y Silvestri (2019) propusieron elementos para modificar la elección hacia modos más sostenibles en Roma. En México, Guerra et al. (2018a) analizaron la relación entre la forma de las ciudades y el transporte en 100 áreas urbanas del país y encontraron que las políticas públicas analizadas seguían promoviendo la dispersión y el paradigma del automóvil privado en la planeación urbana. Fandio et al. (2020) también estudiaron la consideración de la equidad en las políticas del transporte.

Estudios teóricos y empíricos recientes confirmaron que la relación entre el sistema urbano y el transporte era bidireccional y sostuvieron que los patrones de viaje y la localización de las actividades era una interacción de doble vía que definía en gran medida la eficiencia de la ciudad y la calidad de vida de sus habitantes (Bertolini, 2017; Guzman & Bocarejo, 2017; Miralles-Guasch, 2002). Algunos inclusive sostuvieron que la forma de las ciudades era definida, en gran medida por los avances del transporte (Guzman & Bocarejo, 2017; Hall & Tewdwr-Jones, 2011). Diversos autores han confirmado que las ciudades compactas, complejas y conectadas disminuyen el uso de recursos como el suelo, los costos de operación, tiempos de recorrido y la energía (Chao et al., 2018; Navarro Vera & Ortuño Padilla, 2011; UEA, 2012; Xiaobin et al., 2017).

Numerosas políticas públicas en Latinoamérica ya incluyen la armonización de los instrumentos de planeación urbana con los del transporte (IMEPLAN, 2016a; UN-Habitat, 2018; Jalisco Cómo Vamos & Rodríguez Rodríguez, 2019; IMCO, 2019; Gobierno del Estado de Jalisco, 2013) en coherencia con la literatura antes mencionada. Sin embargo, se encontraron escasos estudios académicos que estimen con métodos cuantitativos las dimensiones socioespaciales de los STPM en México (Muñoz et al., 2016; Ochoa Arevalo, 2011; Pfannenstein et al., 2019; Toumi et al., 2017; Vicuña et al., 2019). Hasta ahora, el estudio del impacto de estos sistemas en el AMG ha sido limitado (Calonge Reillo, 2016, 2017c; Calonge Reillo & Aceves Arce, 2019; Diaz Olvera et al., 2017). De ahí la pertinencia de contribuir a la comprensión de las dimensiones socioespaciales de los STPM con métodos cuantitativos accesibles a los organismos de planeación municipal y metropolitana.

Los modos de transporte

Los modos de transporte pueden clasificarse con base en diferentes criterios, por ejemplo, según su uso, la capacidad de los vehículos, el derecho de vía por el que transita, la permanencia de la ruta, la propulsión o la promoción a la salud, etc. (**Tabla 2**). Se hace notar que los criterios de la lista no son exhaustivos, ni los límites entre clases categóricos. Para mayor profundidad en la comprensión sistémica y tecnológica de los diferentes modos de transporte, se recomienda consultar a Vuchic (2007).

La gestión del modo de transporte pública o privada impacta en el acceso a las oportunidades. Los modos privados suelen ser priorizados por dotar de independencia al usuario (Freudendal-Pedersen, 2009). Sin embargo, no suelen ser utilizados por la mayoría de la población, pues demandan recursos económicos para la adquisición, el mantenimiento, el seguro y los impuestos correspondientes. Además, en algunos contextos culturales la conducción de los automóviles puede estar condicionada al género o a la edad. En contraste, los usuarios de modos públicos están a disposición de la mayoría. Aunque el acceso tampoco está garantizado, pues los STP han de responder a necesidades individuales o colectivas, como la edad, el género, la condición de incapacidad física o mental, la renta, entre otras variables urbanas y culturales propias de contextos particulares.

Tabla 2

Modos de transporte urbana y su clasificación

Modo	Uso		Derecho de vía		Ruta		Propulsión		Salud		Capacidad		
	Público	Privado	Segregado	Mixto	Flexible		Motorizado		Activo		Individual	Colectivo	Masivo
					Sí	NO	Sí	NO	Sí	NO			
Caminata		✓	✓	✓	✓			✓	✓		✓		
Bicicleta	✓	✓	✓	✓	✓		✓	✓	✓		✓		
Motocicleta		✓		✓	✓		✓			✓	✓		
Patinetes	✓	✓		✓	✓		✓	✓	✓	✓	✓		
Automóvil		✓		✓	✓		✓			✓	✓		
Taxi	✓			✓	✓		✓			✓	✓		
Autobús	✓			✓	✓		✓		✓			✓	
Trolebús	✓		✓	✓		✓	✓		✓			✓	
BRT[1]	✓		✓	✓		✓	✓		✓				✓
LRT[2]	✓		✓	✓		✓	✓		✓				✓
Metro	✓		✓			✓	✓		✓				✓

[1] Autobús articulado de alta capacidad o Bus Rapid Transit. Se utiliza el acrónimo del término anglosajón para una mayor claridad; [2] Tren Ligero o Light Rail Transit. Se utiliza el acrónimo del término anglosajón para una mayor claridad.

El derecho de vía es una estrategia tradicional para mejorar la velocidad del trayecto a pesar de impactar en el aprovechamiento de la capacidad el carril (Rau et al., 2019). Es común encontrar que la bicicleta y el transporte público compartan la misma vía. También hay ocasiones en que la segregación del carril no es física y puede variar en función de las horas punta. Los carriles segregados suelen aplicarse al transporte público, por lo que favorece a sus usuarios.

La ruta de los modos puede ser flexible o fija. La mayoría de los modos individuales permiten rutas flexibles. Las rutas de autobús suelen estar definidas, aunque pueden ser flexibles en ciertos momentos o zonas de la ciudad. En contraste, los STPM dan servicio con rutas definidas e invariables.

Los combustibles que se utilizan para propulsar los modos de transporte impactan de manera definitiva en la calidad del aire. Los modos no motorizados contribuyen notablemente a la mejora de la calidad del aire y suelen ser promovidos con intervenciones urbanas (Bautista-Hernández, 2021). Los STPM suelen utilizar motores eléctricos, por lo que se les considera amigables con el medio ambiente.

Algunos modos de transporte se consideran activos, pues implican un esfuerzo físico al desplazarse. Los modos reconocidos tradicionalmente como promotores de la salud son la caminata y la bicicleta (Chillón et al., 2011; Rodrigues et al., 2020; Rojas-Rueda, 2021). Sin embargo, algunos autores también consideran a los transportes colectivo y masivo como activos, ya que demandan la caminata para llegar a paradas y estaciones por lo que así aportan beneficios a la salud (Brown & Werner, 2008; Huang et al., 2017; Mageau-Béland & Morency, 2021; H. J. Miller et al., 2015; Morency et al., 2011; Xiao et al., 2019).

La capacidad de los vehículos impacta en la eficiencia del espacio. Es reconocido que los transportes colectivo y masivo ocupan el espacio público de una manera mucho más eficiente que los automóviles y los taxis, cuando se compara el número de pasajeros transportados por hora en carril de 3,5 m (Vuchic, 2007). Naturalmente, la capacidad de los sistemas de transporte público masivo (STPM) como metros, trenes ligeros (LRT), autobuses articulados (BRT) facilitan el acceso a oportunidades a un mayor número de personas que los transportes individuales.

Desde la perspectiva de los criterios de la **Tabla 2,** en el área de estudio de esta tesis, los modos de transporte tienen las siguientes características: en relación con el derecho de vía, en el AMG se observa un incremento en el número de kilómetros de ciclovías segregadas (ITDP, Institute for Transportation and Development Policy. Mexico et al., 2020, 2021), además de las destinadas para tren ligero (LRT, por sus siglas en inglés) y autobús articulado (BRT, por sus siglas en inglés). Los autobuses suelen compartir la vía con automóviles particulares y taxis en la metrópoli. Respecto a la flexibilidad de las rutas, el transporte colectivo suele modificar las rutas de la periferia de la metrópoli, mientras que el derrotero es estable en las zonas centrales de la metrópoli. En general, la propulsión motorizada aporta la mayor parte del reparto modal. El vehículo privado es considerado la principal fuente de contaminación del aire en las áreas urbanas y particularmente en el AMG (El Informador, 2019; Instituto Nacional de Ecología y Cambio Climático, 2020). A pesar de que este modo aporta únicamente un cuarto del reparto modal, esta área es la que mayor el índice de motorización presenta entre 25 metrópolis latinoamericanas monitoreadas por el CAF, esto es, 329.7 vehículos por 1,000 habitante (CAF, 2007). A pesar de su probada eficiencia y alto costo de construcción y operación con recursos públicos, la aportación de los modos masivos frente a los modos colectivos es marginal en el AMG, esto es, 3% y 33%, respectivamente. Los modos individuales son los que más aportan al reparto modal, principalmente el no motorizado y, en menor proporción, el vehículo individual, con 40% y 24% respectivamente. Los CE de esta disertación consideraron vehículos individuales, colectivos y masivos.

La inclusión de los modos en cada caso se definió en función de la pregunta de investigación y de la disponibilidad de los datos en acceso abierto. Los tres CE incluidos en esta tesis analizaron modos de transporte público, particularmente, BRT, LRT, autobuses y bicicleta. El análisis no consideró el criterio del derecho de vía, dado que los cálculos se refirieron al potencial de acceso a las redes de transporte público y no a los trayectos dentro de éstas. Los CE 1 y 3 consideraron las paradas/estaciones de modos con rutas flexibles y fijas: bicicleta pública, autobuses convencionales, BRT y LRT. En general, fueron consideraron tanto modos de transporte no motorizados como motorizados: la bicicleta, los autobuses convencionales, el BRT y el LRT. En cuanto al criterio relativo a la aportación a la salud, los tres CE de este documento incluyeron modos activos: sistema de bicicletas públicas, autobuses convencionales, BRT y LRT.

Los STPM se asocian al crecimiento urbano en las etapas iniciales de las ciudades industrializadas de los siglos XIX y XX (Giuntini et al., 2004; P. Newman & Kenworthy, 2006, 2015) y, con algunos cambios, siguen presentes en las ciudades de principios del XXI (Banister, 2005; Bentayou et al., 2015; IMEPLAN, 2015). El metro es un sistema de tren urbano de alta capacidad y frecuencia que funciona en vías segregadas, generalmente subterráneas. Los LRT son sistemas guiados de ferrocarril urbano que pueden operar compartiendo espacio con otros modos (UITP, 2019b) en superficie, aéreos o subterráneos. Los LRT han sido reconocidos como catalizadores de la renovación y vitalidad urbana (Bertolini, 2017; Grindlay et al., 2021; Vuchic, 2017). En 2018, había más de 389 trenes ligeros funcionando en el planeta y la tendencia parecía ir en aumento, principalmente en Europa (UITP, 2019a), mientras que la predisposición para implementar nuevos proyectos no parecía ir a la alza en América Latina (UITP, 2019b) y su uso seguía siendo marginal en este continente.

Los BRT son sistemas basados en autobuses de alta y media capacidad que ofrecen servicio de alta calidad, originalmente desarrollados como alternativa más económica a los metros y metros ligeros. Normalmente utiliza carriles segregados, aunque en algunos ámbitos opera en carriles exclusivos, a contraflujo o, inclusive mezclados con el tráfico (Grindlay Moreno et al., 2012). Este sistema ocupa deliberadamente el espacio que antes utilizaban los automóviles y desde su diseño se ha incluido la planeación urbana en su entorno. A partir de su primer desarrollo en Curitiba en los setenta, de acuerdo con Global BRT Data (2021), 191 ciudades han optado por BRT para resolver su movilidad en 2021. Esa misma fuente indica que, en 2021, Santiago de Chile, Bogotá, Sao Paolo, Ciudad de México, Monterrey, León y Guadalajara son las principales metrópolis latinoamericanas que lo utilizan. Ambos modos incluyen el prepago y suelen estar conectados con líneas alimentadoras de menor capacidad servidas por autobuses y minibuses convencionales. Al inicio de esta investigación operaban en el AMG dos líneas de LRT y una de BRT. Actualmente se ha concretado el esfuerzo gubernamental de promoción del TP y la movilidad sostenible añadiendo una línea más de LRT y otra de BRT.

La opinión sobre la pertinencia para implementar BRT o LRT es diversa. Por un lado, algunos autores han documentado múltiples ventajas del BRT, siendo el menor costo en la construcción del BRT el argumento más recurrente (Munoz & Paget-Seekins, 2016; Muñoz et al., 2016; Venter et al., 2018). De acuerdo con Lindau et al. (2016) y Córdova España (2010), si los BRT son gestionados adecuadamente, pueden ofrecer capacidad y velocidad de crucero semejante al LRT con un menor costo de construcción, operación y renovación tecnológica. En contraste, Hensher et al. (2016) sostienen que la percepción de servicio y diseño del tren ligero es más favorable que la del BRT. Vuchic (2017) y Higgins et al. (2014) sostienen que el LRT reduce el tráfico, mejora la calidad del medio ambiente y reduce los gases de efecto invernadero, además de modificar y revitalizar las ciudades. Asimismo, Ferbrache y Knowles (2017), destacan su elevada capacidad de generación de espacios y de dinamización urbana. Las ventajas de limpieza, silencio y eficiencia espacial han puesto en valor el tren ligero, a pesar de sus altos costos de operación y renovación tecnológica (UITP, 2019b). Aunque Heilmann (2018) cuestionó los beneficios del LRT, frente a evidencias de gentrificación en el caso de Dallas, un contexto de alta dependencia del automóvil. Por otro lado, Córdova España (2010) no se pronunció a favor de uno u otro sistema sino que sostuvo que las diversas tecnologías tenían validez, siempre que se implementaran en el momento correcto y con un paradigma de integración física, operativa y tarifaria.

Aunque el planteamiento original de los CE de esta tesis consideraba únicamente los STPM, los resultados de los modelos no fueron representativos de las dimensiones socioespaciales, dada la baja aportación de estos modos al reparto modal en el AMG. En consecuencia, se integraron otros modos para responder las preguntas de investigación planteadas. Así pues, se consideraron los modos públicos y privados; individuales y colectivos; segregados y mixtos; flexibles y fijos; no motorizados y motorizados; y activos (**Tabla 3**).

Tabla 3

Modos considerados en los casos de estudio de esta investigación

Modo	Caso		
	1	2	3
Caminata			✓
Bicicleta		✓	✓
Autobús			✓
Trolebús	✓		✓
BRT	✓	✓	✓
LRT	✓		✓

Integración de la planificación del transporte y la urbana: Desarrollo orientado al transporte (DOT)

El DOT es una estrategia de planeación promovida a partir de finales del siglo XX para integrar el desarrollo urbano y las estaciones y corredores de los STPM, particularmente, el cambio de uso de suelo. La estrategia parte del principio de que las condiciones físicas y sociales en las estaciones y sus ámbitos de proximidad son determinantes en el cambio de uso de suelo (Knowles et al., 2020). Si las características de actividades, seguridad, equipamiento u otros elementos físicos son atractivas para los desarrolladores y los posibles habitantes, será más fácil que se produzca un cambio. Este paradigma promueve el desarrollo y/o la renovación del entorno de las estaciones y la mejora de calles y aceras a lo largo del STPM, intentando armonizar el desarrollo urbano y el del transporte (Bertolini et al., 2005; Cervero et al., 2002; Filion & McSpurren, 2007; Hall & Tewdwr-Jones, 2011; Williams, 2017).

Desde inicios del siglo XX el DOT se ha implementado en ámbitos de diversas latitudes a través de planes de zonificación, financiamiento, estacionamientos, vialidades restringidas al automóvil, densificación, entre otros. En general, promueve la coordinación entre las autoridades dedicadas a la planeación urbana y las del transporte desde el inicio del proyecto de TPM hasta su puesta en marcha y operación (Ashri Prawesthi & Yola, 2022; Bentayou et al., 2015; Campos-Sánchez et al., 2019, p.; Furlan, 2017; Higgins et al., 2014; Huang et al., 2017; Ibraeva et al., 2020; ITDP, 2013, 2015, 2018; Quintero-González & Quintero-González, 2019; Yu et al., 2022). En general, se han documentado los beneficios del DOT como la mejora de calidad del aire y en la vivienda, así como el decrecimiento de viajes en automóvil y menos viajes/km/vehículo privado (Cervero & Kockelman, 1997; Knowles et al., 2020; Zhou et al., 2019).

En contraste, Heilmann (2018) sostuvo que los efectos de los STPM son heterogéneos desde el punto de vista social y varían en función de las características originales de los barrios en donde se implementa el DOT. Este investigador mencionó que provoca gentrificación en el citado ámbito norteamericano. También Guthrie (2018) puso en evidencia que la equidad social ha sido poco atendida en los proyectos de TOD. En este contexto, la gentrificación a lo largo del corredor es un efecto de conveniencia de los estratos pobres que están dispuestos a afrontar mayores tiempos de traslado en el transporte masivo frente al incremento de alquiler en sus barrios originales. Para evitarlos, es necesario que la implementación de STPM venga acompañada de políticas y planes de desarrollo social que conduzcan los efectos positivos y negativos del TOD producidos por el STPM.

Las dimensiones sociales y espaciales del transporte público

Las dimensiones sociales y espaciales del transporte público se refieren a la consideración de las necesidades y características socioeconómicas y culturales de individuos y colectivos específicos para facilitar el acceso a las oportunidades (Hine & Mitchell, 2003; Kamruzzaman et al., 2016; Kenyon et al., 2002; Lizárraga et al., 2020; Preston & Rajé, 2007). En esta tesis, el análisis de las dimensiones socioespaciales comprende la estimación cuantitativa del potencial de acceso físico a las paradas o estaciones del STPM, considerando las características socioeconómicas de los usuarios del transporte.

La dimensión social del transporte fue estudiada formalmente en las últimas décadas del siglo XX. En los 70's, Wachs y Kimagai (1973) propusieron que se considerara el aspecto social en la medición del impacto del transporte, oponiéndose a los métodos con perspectiva únicamente técnica y económica. En esa época King (1978; 1983) publicó análisis empíricos sobre la dimensión social del transporte. Estas aportaciones trascendieron el ámbito académico, dando lugar a que las políticas de planeación del transporte integraran paulatinamente conceptos de inclusión social en los 90's.

A principios del siglo XXI se incrementó el número de propuestas académicas y gubernamentales que integraban explícitamente la dimensión social en el estudio de la relación ciudad-transporte. Litman (2002) y Kenyon (2002) utilizaron el término de exclusión social por transporte y el de inequidad del transporte, trascendiendo de esta manera a académicos contemporáneos, como Bhatta y Drennan (2003), quienes aún referían los asuntos sociales como un retorno social de la inversión bajo la óptica tradicional de la economía. En 2003 se creó la Unidad de Exclusión Social en Reino Unido, referente como instrumento de política pública para disminuir la exclusión social, en general, y por transporte, en particular (SEU, 2001, 2003). Hine y Mitchell (2003) realizaron análisis empíricos que pretendían comprender la relación entre la desventaja del transporte y la exclusión social en esa región. Preston y Rajé (2007) propusieron un método para detallar el análisis social y espacial del transporte, desde la perspectiva de las políticas públicas en el Reino Unido. En Latinoamérica, Avellaneda (2007) estudió la exclusión social por transporte en Lima, en donde la características socioeconómicas de la mayoría de los habitantes impedían el pleno acceso al sistema de transporte público. En 2009 y años posteriores, Currie et al. (2009, 2010; 2011a, 2011b; 2010; 2015) estudiaron ampliamente la exclusión social y las desventajas del transporte en Australia, aportando metodologías probadas empíricamente.

En 2015, la ONU renovó su política de desarrollo urbano y declaró los objetivos de desarrollo sostenible (ODS) que confirmaban la estrecha relación del binomio ciudad-transporte. El ODS 11 buscará que el diseño e implementación de sistemas de transporte consideraran las necesidades de colectivos en desventaja, como mujeres, jóvenes o personas con discapacidad y en pobreza, garantizando el acceso a las oportunidades sociales, económicas y culturales de sus ciudades (UN-Habitat, 2021). Además, el ODS 13 promoverá la eficiencia de los desplazamientos para mejorar la calidad del aire. A partir de entonces, gran parte de la reflexión académica se ha alineado con el paradigma de los ODS

A partir del segundo decenio del siglo XXI se incrementó la investigación relativa a la dimensión social del transporte. Lucas et al. (2012; 2018; 2015) publicaron varios estudios sobre la exclusión social relativa al transporte (ESRT), así como sus vínculos con la desventaja y la pobreza del transporte, conceptos que se explicarán más adelante. Estudiosos de las dimensiones socioespaciales del transporte en Latinoamérica encontraron evidencia de altos porcentajes de inequidad que éste provoca (Arellana et al., 2020; Bocarejo & Urrego, 2020; Bocarejo S. & Oviedo H., 2012; Guzman, 2018; Guzman et al., 2015, 2017, 2021; Guzman & Bocarejo, 2017; Guzman & Oviedo, 2018; Rosas-Satizábal et al., 2020; Vecchio, Castillo, et al., 2020; Vecchio, Porreca, et al., 2020; Vecchio, Tiznado-Aitken, et al., 2020). Montejano et al. (2018) confirmaron la segregación socioeconómica derivada del paradigma del automóvil que prevaleció en México entre 1990 y 2010. Guerra el al. (2018a) estudiaron la relación entre la forma urbana, la oferta del TP y la elección del modo en 100 ciudades mexicanas y concluyeron que las políticas públicas recientes incrementan, en lugar de reducir, la conducción y la congestión, la contaminación en el país. En el AMG se analizaron las dimensiones socioespaciales del transporte con un énfasis sociológico (Calonge Reillo, 2016, 2017b, 2017c, 2018a; Calonge Reillo & Aceves Arce, 2019; Calonge-Reillo, 2021; Colmenero-Fonseca et al., 2021). Además, Diaz Olvera et al. (2017) encontraron que el acceso a las oportunidades estaba más vinculado al ingreso que a la localización de las viviendas en esa metrópoli.

De acuerdo con Hidayati et al. (2021), en los últimos cincuenta años, la ESRT se analizó desde cuatro enfoques que en ocasiones se combinaron. Primero, las ciencias del transporte midieron la exclusión con métodos técnico-funcionales, utilizando variables como tiempo de viaje, distancia, patrón espacial o modo. Segundo, la investigación sociológica aplicó estilos narrativos. Tercero, los estudios de planificación o geográficos utilizaron técnicas espaciales, generalmente cualitativas. Y cuarto, los estudios interdisciplinarios que incluyeron dos o más disciplinas y son menos abundantes que la perspectiva monodisciplinaria. Los CE de esta tesis se abordaron desde una perspectiva geográfica, con método cuantitativo, planteando y analizando el problema desde la transdisciplina entre geografía, economía e ingeniería.

La literatura refiere cinco conceptos interrelacionados y con límites difusos que permiten comprender las dimensiones socioespaciales del transporte: necesidades sociales del transporte (NST), desventaja del transporte, pobreza en el transporte, inequidad en el transporte y ESRT (**Figura 2**). Las NST son los requerimientos de desplazamientos determinados por características socioeconómicas y culturales. La desventaja del transporte se refiere a situaciones que causan dificultades para acceder al transporte, ya sea por las características de la red o por los "desiertos de transporte". Estos "desiertos de transporte" son zonas en donde no hay servicio de transporte que atienda a las NST (Cai et al., 2020). La pobreza del transporte sugiere dificultades para pagar el transporte público urbano (TP). La inequidad en el transporte estima las diferencias entre el potencial para cumplir con NST entre individuos o grupos (Litman, 2002). La ESRT es el acceso limitado a las oportunidades que ofrece la ciudad debido a la desventaja del transporte, la pobreza del transporte o la inequidad del transporte. Dadas estas definiciones, se deduce que las NST, la inequidad en el transporte, la desventaja en el transporte y la pobreza en el transporte son causas y efectos entrelazados de ESRT (Schwanen et al., 2015) (**Figura 2**).

La equidad en el transporte compara la atención a las NST de una población en su conjunto o de colectivos en particular. El análisis de la inequidad del transporte fue planteado por Litman (2002) quien propuso dos clases: horizontal y vertical. La equidad horizontal parte del principio de que las personas deben ser tratadas por igual y compara un servicio entre todos los grupos de la población. La equidad vertical asume que la sociedad debe brindar un apoyo adicional a los grupos vulnerables o desfavorecidos y que deben tener una mejor calidad o cantidad de TP. La equidad vertical evalúa el servicio para grupos con características socioeconómicas particulares, por ejemplo, renta, edad o género (Delbosc & Currie, 2011b; Litman, 2002).

La inequidad del transporte no está necesariamente vinculada con la inexistencia de infraestructura de TP o la calidad del servicio, ya que puede cambiar en función de las condiciones espaciales, como la distancia a las estaciones/paradas o la calidad de la marcha (Talavera Garcia et al., 2018; Talavera-García & Valenzuela-Montes, 2018); de factores económicos, por ejemplo, el acceso a un automóvil privado; o de contextos culturales, p. ej. la prohibición social o legal para que las mujeres tengan una licencia de conducir.

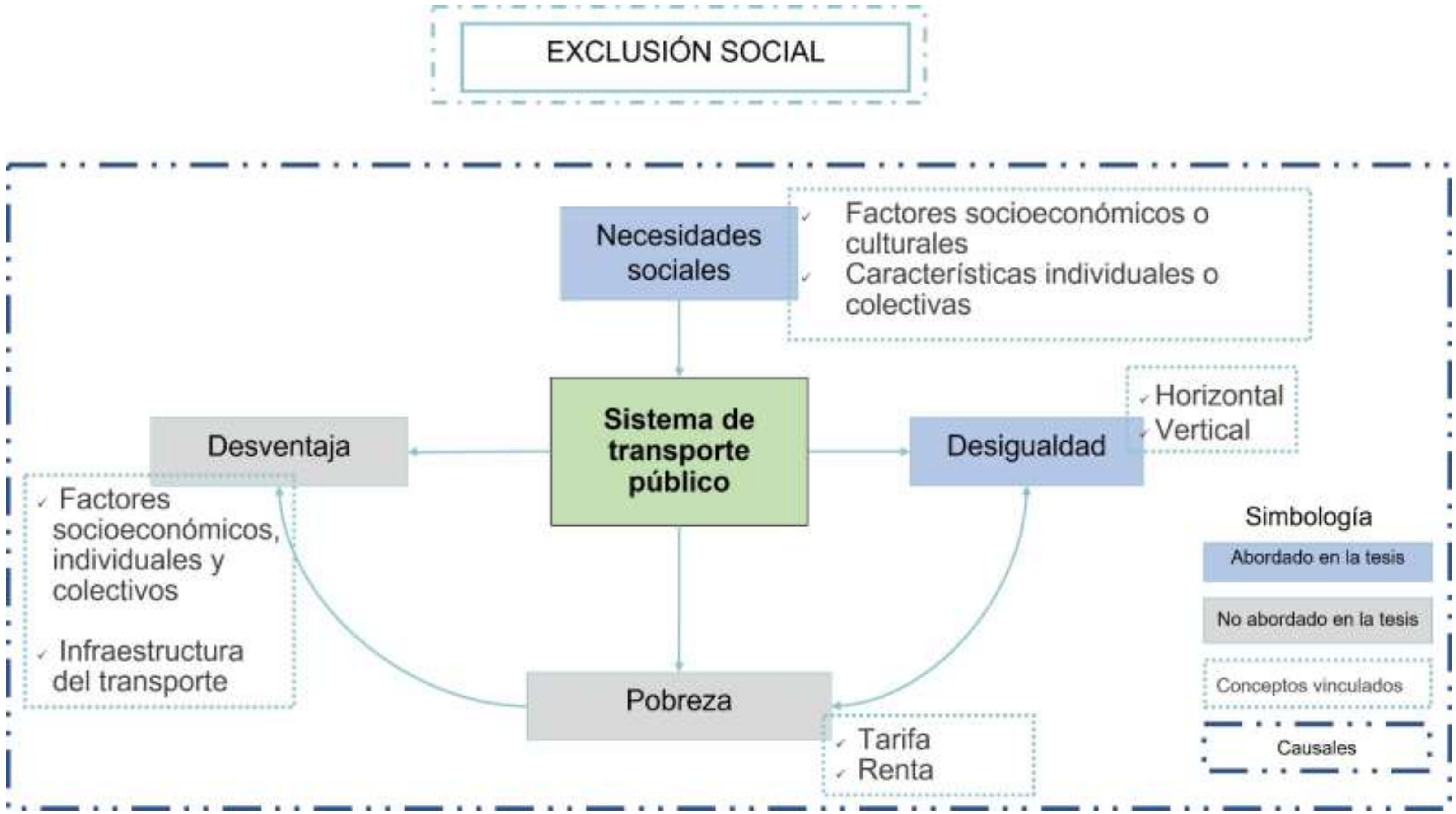

Figura 2. Causas y efectos de exclusión social relativa al transporte.

La inequidad puede presentarse en diversos contextos. Por ejemplo, la inequidad para acceder al automóvil privado se presenta, sobre todo, en función de la edad, la renta u otras características personales o sociales. Aunque el automóvil privado también entraña costos, suele ser considerado más atractivo que el transporte público, especialmente por la sensación de libertad para elegir diferentes destinos o para cambiar de ruta cuantas veces se desee (Freudendal-Pedersen, 2009). Las grandes inversiones en infraestructura para el automóvil también son fuente de inequidad, tanto respecto al uso del espacio público, como de la aplicación de recursos públicos en beneficio de una minoría. El impacto es mayor en países con grandes índices de desigualdad como los latinoamericanos.

Otro elemento de inequidad son los costos que los hogares destinan al transporte en función de su renta. En algunas ciudades latinoamericanas, como Bogotá, el gasto en movilidad alcanza hasta el 17% del ingreso para los estratos económicos más desfavorecidos (Bocarejo & Urrego, 2020). Esto es aún más sensible en el AMG, en donde los hogares con menos ingresos destinan hasta 35% del ingreso (Diaz Olvera et al., 2017).

El transporte también juega un papel importante en la inequidad relativa a la salud. La mala calidad de las vialidades y la informalidad de los modos de transporte que suelen dar servicio a las áreas en donde habitan los estratos socioeconómicos más bajos, incrementan la posibilidad de sufrir accidentes para quienes habitan esas áreas (Boutueil et al., 2020; Goldwyn & Vergel-Tovar, s. f.; Lesteven & Boutueil, 2018). En este sentido, la formalización e integración del transporte público masivo en áreas de bajos recursos podría disminuir la inequidad en relación a la salud (Bocarejo & Urrego, 2020). Privilegiar al automóvil, también afecta el consumo energético y las emisiones de CO_2 por pasajero. En distancias menores a 10 kilómetros, el vehículo privado emite el doble de emisiones y consume el doble que el autobús y cinco veces más, en general, que los vehículos eléctricos como el metro y LRT (Commission of the European Communities, 2001). La contaminación emitida por los automóviles afecta a todos los habitantes de la ciudad en su conjunto y no únicamente a quienes utilizan este modo poco sostenible.

Otra fuente de inequidad se refiere a la distribución espacial del transporte. Las distancias y el congestionamiento dificultan la llegada de quienes viven en la periferia o alejados de los centros de trabajo. En ciudades dispersas, esta inequidad suele afectar tanto a estratos socioeconómicos altos como a bajos (Bocarejo & Urrego, 2020). En este aspecto, la puesta en marcha de STPM que vincule hogares con trabajos es efectiva para disminuir la inequidad relativa tanto a la salud como a la distribución espacial, pues mejora la calidad del aire y los tiempos para acceder a oportunidades.

Los CE de esta tesis analizaron la ESRT y la inequidad del transporte utilizando la accesibilidad espacial como indicador. Los CE 1 y 3 de esta tesis analizaron la inequidad del transporte tanto en el ámbito metropolitano, como en un colectivo en particular, las comunidades universitarias del AMG.

Accesibilidad

La dimensión espacial del transporte puede estudiarse desde la perspectiva de la accesibilidad, entendiéndola como la facilidad con la que se llega a oportunidades sociales, económicas o culturales, tanto desde la perspectiva espacial como desde las NST de quienes requieren acceder a ellas, así como su pertinencia (Lucas et al., 2019).

La accesibilidad ha sido utilizada tanto para medir fenómenos, como para guiar propósitos de instrumentos o políticas públicas, generalmente vinculadas a la regulación del uso de suelo (Levine, 2020). En los 20’s del siglo XX se propuso el concepto como indicador para prescribir zonificación urbana, es decir, con fines normativos. En 1959, Hansen (1959) definió la accesibilidad como el potencial de oportunidades de interacción y sostuvo que ese acceso definía, en gran medida, el uso del suelo en las ciudades. Los avances informáticos de mediados del siglo XX facilitaron la medición de la accesibilidad con fundamentos matemáticos. Los

Sistemas de Información Geográfica (SIG) permitieron aplicar el concepto de accesibilidad a la planeación urbana como una relación topológica que medía la eficiencia de la red (Kansky, 1963).

En los 70's se presentó un punto de inflexión en la concepción de la accesibilidad. Hasta entonces, el impacto del transporte era estimado con indicadores de volumen y tiempos de viaje. Wachs and Kimagai (1973) propusieron un cambio de paradigma para medir el impacto del transporte y diseñaron un indicador social vinculado a la accesibilidad física. En este contexto, definieron la accesibilidad como la facilidad con la que los ciudadanos llegaban a diversas oportunidades de empleo y de servicios. Desde finales del siglo XX, Cervero (1997) refería a la accesibilidad como una estrategia de planeación: gestión de uso de suelo, avances en telecomunicación para gestión de transporte bajo demanda (p. ej. el actual Uber) y transportes públicos y no motorizados a escala "comunitaria".

A principios del siglo XXI, Kenyon et al. (2002) relacionaron las restricciones de movilidad con el acceso a las oportunidades y la consecuente exclusión social. Bertolini et al. (2005) definieron la accesibilidad como el qué y el cómo se puede alcanzar un punto específico en el espacio. Y Molero Melgarejo et al. (2012; 2007) definieron la accesibilidad desde una perspectiva espacial, como "el factor de interacción del territorio donde las relaciones entre dos puntos aumentan en función de la disminución del coste de desplazamiento entre ellos". Estos autores sostuvieron que la proximidad no estaba relacionada únicamente con la distancia, sino también con la conectividad.

En 2012, Litman (2012) propuso la evaluación de la accesibilidad como herramienta para la planeación urbana. Lucas et al. (2016) propusieron un método para evaluar la igualdad en la accesibilidad y Talavera et al. (2018) refirieron el concepto de "calidad de la distancia de caminata" y sostuvieron que las condiciones del espacio por el que se transita determinan fuertemente la elección del modo de transporte. Lo anterior también fue explorado por Calonge-Reillo (2021) quien analizó la influencia de la percepción de seguridad en la elección del modo, particularmente en municipios del área de estudio de esta disertación. Pucci et al. (2019) sostuvieron que la accesibilidad está determinada por las características de tres aspectos: (a) las características intrínsecas de la infraestructura de transporte, como tarifas, tiempo de viaje, horarios, frecuencia, capacidad, distribución espacial de las paradas y estaciones, entre otros; (b) el entorno físico que posibilita el desplazamiento y la distribución espacial de las oportunidades; y (c) los factores individuales, como condiciones físicas, motrices, sociales, culturales y económicas. Los CE de esta disertación consideraron el primero y el tercer aspecto de la accesibilidad referidos.

En las últimas décadas se han planteado modelos urbanos vinculados a la accesibilidad como el Nuevo Urbanismo que plantea que los problemas sociales y urbanos se pueden resolver con intervenciones físicas, el DOT, el desarrollo de espacios vacíos, la conectividad vial o las ciudades inteligentes (Verma et al., 2019), vinculadas con las tecnologías de la información y la comunicación (Cervero et al., 2002; Knowles et al., 2020). Recientemente, el ITDP (2020) sostuvo que la accesibilidad era la oportunidad para medir la conexión y la distancia, pero, sobre todo, la manera como se puede llegar a muchos sitios a través del transporte. Desde esta perspectiva, la accesibilidad está vinculada al concepto de “ciudades compactas”, ya consideradas respecto a la movilidad en el siglo XX y ampliamente difundido en los años recientes, como aquellas cuya configuración espacial reduce la demanda y distancia de los desplazamientos y contribuyen a la movilidad sostenible.

En Latinoamérica, Jaramillo et al. (Jaramillo et al., 2012) vincularon la accesibilidad a los derechos humanos como la vivienda, salud, educación, trabajo y, en general, a la libertad de los individuos para participar en actividades de su entrono; Oviedo y Guzmán (2020) sostuvieron que la accesibilidad es una manera de ejercer el “Derecho a la Ciudad”, expresado por Lefebvre en los 70’s, es decir, un requisito para garantizar la posibilidad individual de participar en actividades socioculturales y, por ende, de acceder a oportunidades en un contexto de igualdad.

Estos autores reconocieron, como elementos de la accesibilidad, el desplazamiento, la existencia de destinos y su pertinencia, y añadieron otros tres: la preservación del medio ambiente, la estructura espacial y la posición social de los usuarios del transporte.

Se han diseñado una gran variedad de métodos para medir la accesibilidad (Manout et al., 2018). La **Figura 3** muestra los más comunes, de acuerdo con Wu y Levinson (2020). Su aplicación depende, fundamentalmente, del objetivo del estudio y de los datos disponibles. Todos los métodos pueden conservar los umbrales de “costos” constantes y medir el número de oportunidades alcanzables en estos rangos, o bien, mantener un número de oportunidades constantes y medir el “costo” para alcanzarlas, definidos estos como método *primal* y *dual*, respectivamente. Los autores propusieron cuatro clases generales:

- **Topología**. Los métodos topológicos se fundamentan en la Teoría de Grafos que permite modelar fenómenos reales mediante nodos y líneas. El modelo simula la relación de vecindad entre los nodos y las líneas, que suelen representar la vinculación entre la red vial y los orígenes/destinos. Algunas variantes son relativamente simples, como la cuantificación de nodos en la red (tamaño de la red), la ponderación de los nodos en función de las líneas que llegan a él (Grado nodal o matriz de accesibilidad total), la relación entre nodos y líneas (adyacencia) o la cuantificación del número de segmentos rectos a cruzar (sintaxis espacial), entre otros.
- **Acumulación**. Diseñado originalmente por Hansen (1959). Utilizan los fundamentos topológicos y añaden elementos más complejos. Los métodos cuantifican el número de oportunidades que se pueden alcanzar en una función de impedancia. Usualmente se considera al tiempo, la distancia o el dinero como resistencia al desplazamiento, aunque en teoría, es posible considerar otras variables físicas como la superficie o ancho de banqueta, alumbrado público, sombra o, inclusive, variables de percepción, como inseguridad o vitalidad urbana, entre otros. Kelobonye

et al. (2019) lo explican como la suma de las oportunidades que pueden alcanzarse en un umbral de tiempo definido. Los mismos autores sostienen que la dificultad del método es encontrar el umbral. Sin embargo, hay diversos estándares y producción académica que permite definirlo, bajo ciertas hipótesis. Stepniak (2019) menciona que se comportan bien con rangos entre 5 y 15 minutos. La aplicación de este método es relativamente sencilla y se utiliza con frecuencia en documentos académicos (Barboza et al., 2021). Estos poseen dos variantes:

- *Gravitacional.* Consiste en ponderar la impedancia del tiempo o distancia de viaje. Esto implica un sistema de ponderación que, dada la complejidad de las variables que componen la impedancia, suele ser difícil de interpretar. Además, es muy sensible a la ponderación. Está de acuerdo con la primera ley de Geografía, conocida como Ley de Tobler, según la cual "todas las cosas están relacionadas entre sí, pero las más cercanas tienen más relación que las lejanas".
- *Ponderación*. Permite ponderar las oportunidades de acuerdo con diversos criterios. Por ejemplo, si se refiere a estaciones o paradas, el peso de la estación del metro sería mayor que la parada de un autobús, valorándose así la capacidad de los vehículos.

- **Utilidad.** También conocida como basado en el usuario (Kelobonye et al., 2019). Se fundamentan en la teoría del comportamiento de viaje que asume que cada individuo, independientemente de su área geográfica, decide a dónde viajar, por lo que no cuantifican el número total de oportunidades, sino que miden una "utilidad neta" por viaje, que es función de la preferencia por cada sitio disminuida por el "costo" del viaje. Utiliza la topología para calcular el costo.

- **Rango del lugar**. Consideran el potencial teórico de atracción de cada lugar. Es decir, la cantidad de viajes que podrían generar de acuerdo con encuestas de origen-destino.

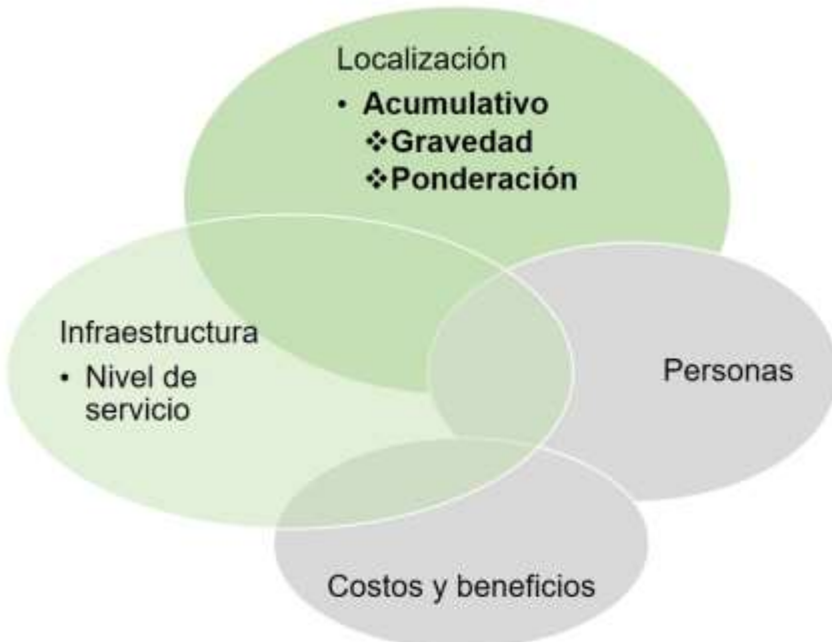

Figura 3. Clases de métodos para estimar la accesibilidad.

Fuente propia, con base en Wu y Levinson (2020).

Para una explicación exhaustiva de los análisis empíricos de accesibilidad, se recomiendan revisiones de literatura reciente. Levinson y Wu (2020), antes mencionados, quienes analizaron críticamente los enfoques de medición del acceso. Hidayati et al. (2021) estimaron 5 décadas de artículos académicos sobre desigualdades de movilidad e identificaron estudios limitados en países de bajos ingresos. Vecchio et al. (2020) revisaron estudios empíricos de América Latina e identificaron indicadores referidos en la literatura, además de identificar las implicaciones presentes y futuras de los hallazgos analizados en las políticas de planeación del transporte.

El primer caso de estudio de esta disertación utilizó el método de acumulación con la simplificación gravitacional al considerar el tiempo de caminata como resistencia al desplazamiento. El análisis de componentes principales permitió ponderar las variables sociales. El tercer caso utilizó la acumulación con ponderación, sumando las paradas/estaciones dentro de los umbrales de tiempo definidos para cada modo. Además, se aplicó el método del grado nodal al contabilizar el número de líneas que llegaban a cada estación/parada y ponderarlas con análisis de componentes principales, tal y como se explicará en el siguiente capítulo.

I. INTRODUCCIÓN

3. Marco metodológico

I. INTRODUCCIÓN

En una tesis por compendio de publicaciones es pertinente presentar una perspectiva general de la metodología utilizada en los análisis particulares. Puesto que los detalles metodológicos se incluyen en cada artículo, esta sección describe las similitudes y diferencias entre ellos a manera de meta-metodología. De este modo se deduce un método replicable a partir de etapas metodológicas comunes a los casos estudiados, de manera que los índices empleados puedan aplicarse a otros modos de transporte, equipamientos y/o ámbitos metropolitanos.

La metodología atendió a la replicabilidad en contextos con habilidades técnicas restringidas y recursos financieros limitados, situación usual en metrópolis latinoamericanas, particularmente las mexicanas. Las etapas metodológicas fueron:

1. Construcción del fundamento teórico
2. Definición de hipótesis y objetivos particulares
3. Diseño de índices
4. Cálculo de índices
5. Análisis de resultados
6. Discusión de resultados y generación de conclusiones

Construcción del fundamento teórico

Las diferentes fuentes y herramientas para construir los marcos teóricos se muestran en la **Figura 4**. La retroalimentación de expertos en **seminarios** y **congresos** orientaron la revisión de la literatura en un proceso iterativo. En ambos espacios de reflexión se identificaron los conceptos relevantes para cada caso de estudio.

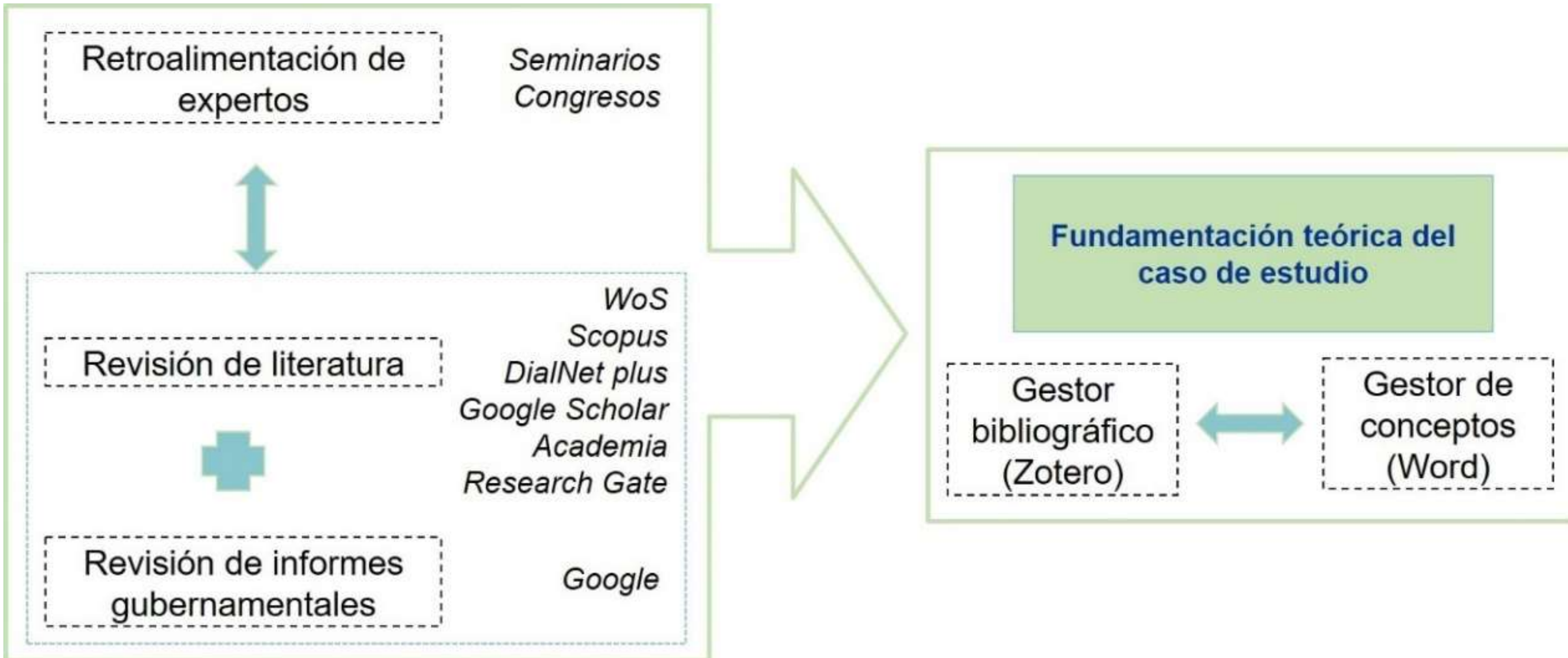

Figura 4. Construcción del marco teórico de casos de estudio

La literatura se revisó con la ayuda de **bases de datos, buscadores y redes sociales** académicas. Las bases de datos *Web of Science y Scopus* fueron consultadas para la producción académica en inglés y la Dialnet Plus para referencias en español. Con lo anterior se identificaron publicaciones relevantes para cada caso.

Posteriormente se utilizó el buscador **Google Scholar** con la técnica de bola de nieve que permitió identificar los autores principales y sus artículos recientes. Además de la producción académica, se consultaron numerosos informes gubernamentales, tanto de orden global (ONU-hábitat, Organización Mundial de la Salud), como internacional (Comisión Económica para América Latina y el Caribe, Agencia del Medio Ambiente de los Estados Unidos de América), nacional (Instituto Nacional de Estadística y Geografía, Secretaría de Desarrollo Social, Consejo Nacional para la Evaluación de la Política Social) y local (Instituto de Planeación y Gestión del Desarrollo del Área Metropolitana de Guadalajara, Secretaría del Medio Ambiente y Desarrollo Sustentable). Los últimos dos facilitaron la contextualización del marco teórico internacional al ámbito del Área Metropolitana de Guadalajara.

La actualización de publicaciones posteriores a la primera búsqueda se realizó con ayuda de **alertas en revistas y redes sociales**. Por un lado, el *Journal Citation Reports* facilitó la identificación de revistas que pertenecieran a los primeros cuartiles en la investigación de dimensiones sociales y espaciales del transporte público masivo. Se programaron alertas de Cities, Journal of Transport Geography y Sustainability. De manera similar, DialNet Plus alertó sobre publicaciones recientes en español sobre Geociencias y Medio ambiente. Por otro lado, la participación en redes como ResearchGate y Academia.edu, permitió identificar las publicaciones recientes de investigadores de la ciudad y el transporte, particularmente en el ámbito iberoamericano.

Con objeto de gestionar la gran cantidad de referencias se utilizó el gestor bibliográfico **Zotero** y un gestor de conceptos personal. Se eligió Zotero por su gratuidad, los plugin en exploradores y procesadores de texto, el soporte técnico de comunidad de usuarios y la librería de estilos bibliográficos propios de las principales revistas científicas. Este gestor de referencias facilitó la clasificación por conceptos, la inserción de notas y la integración de referencias en los artículos. En este momento se cuenta con 1806 títulos catalogados en 31 colecciones que seguirán incrementándose con las alertas y servirán a futuras investigaciones.

La **gestión de conceptos** se diseñó en Word (Office 365®). La organización jerárquica de estilos facilitó la gestión de conceptos. Para cada uno se identificaron autores, palabras clave y el análisis de su producción académica. En cada caso se respondió qué relataba el autor, un comentario personal y en qué sección de la tesis se podría incorporar.

Definición de hipótesis y objetivos particulares

Cada caso de estudio (CE) requirió de la formulación de preguntas de investigación e hipótesis específicas. Con base en ellas, se plantearon objetivos particulares. El CE_1 evaluó la cobertura del Sistema de Tren Eléctrico Urbano (SITEUR) respecto a las necesidades sociales del transporte. El CE_2 cuantificó el número de usuarios de modos de transporte activos expuestos a episodios de mala calidad del aire; el CE_3 estimó la inequidad de acceso a transporte sostenible como indicador de la exclusión social relativa al transporte para el colectivo de las comunidades universitarias.

Diseño de índices

Se buscó que los índices implicaran procedimientos relativamente sencillos para el contexto de la complejidad metropolitana, por lo que se diseñaron con las siguientes características:

- Pertinentes para probar la hipótesis del caso

- Susceptibles de ser calculados a partir de datos abiertos, con herramientas de sistemas de información geográfica y/o métodos multicriterio
- Computables con recursos informáticos convencionales
- Con resultados en clave cartográfica

Todos los índices fueron originales, excepto el del quinto caso en el que se utilizó el Índice de Calidad del Aire diseñado por la Agencia de Protección del Ambiente de los Estados Unidos de Norteamérica (Environmental Protection Agency, 2016b).

Cálculo de índices

Los datos

Los datos compartidos son una de las estrategias para la movilidad sostenible recientemente integradas en la “Guía para las Ciudades Sostenibles del Foro Económico Mundial” (2020). Las ventajas del uso de datos con acceso abierto en la metodología fueron dos: Primera, su uso incrementará el potencial de replicabilidad en otras áreas geográficas, tanto por cuestiones financieras como por ser datos que se producen sistemáticamente en otros ámbitos metropolitanos; segunda, las fuentes garantizan la calidad de los datos de entrada del proceso, pues se generan de acuerdo con metodologías publicadas y generalmente aceptadas por actores usuarios del método, tanto sociales como gubernamentales.

Sin embargo, los datos abiertos también implican retos intrínsecos al uso para casos particulares, pues suelen generarse bajo una perspectiva generalista, es decir, para usos “transversales”. En los casos de estudio (CE) descritos en esta tesis, la explotación de los datos del Open Street Map ® requirió trabajos técnicos para modelar únicamente los elementos de interés y algunos datos de INEGI (nacional), SEMADES (estatal) y MiBici (metropolitano) requirieron cierta adaptación, fundamente de formato o vinculación con objetos geográficos. Por ejemplo, fue necesario editar los registros “sin dato” o “no aplicable” de bases de datos censales; las bases de datos de contaminantes y de modos de transporte activos requirieron un grado de adecuación para hacerlas coincidir concurrentemente en la dimensión temporal. La **Tabla 4** resume los tipos de fuente productoras de los datos utilizados en esta investigación.

Tabla 4

Datos requeridos en los casos de estudios y tipos de fuentes

Datos	Tipo de fuente
Datos operativos del sistema de transporte público urbano: frecuencia, capacidad, número de pasajeros en franja horaria para cada parada/estación	Organismo operador del transporte
Vialidades con topología de red	Organismo integrador de datos viales, ya sea gubernamental o de *crowdsourcing**
Variables socioeconómicas	Organismo a cargo de censos socioeconómicos
Concentración de contaminantes	Organismo encargado del monitoreo del aire
Localización geográfica de equipamientos urbanos	Organismo a cargo de censos económicos o del contexto urbano

*Término utilizado para referir datos generados por inteligencia artificial y verificados por grupos de personas dedicados a esto, por ejemplo, las bases de datos del Google Street Map®.

Las herramientas

El método cuantitativo fue aplicado a todos los CE. Puesto que los STP cuentan con un importante componente espacial y es un fenómeno complejo, se utilizaron Sistemas de Información Geográfica (SIG), como el ArcMap® de ESRI y el QGis®, además del método multicriterio conocido como análisis de componentes principales procesados en StatGraphics® o SPSS Los índices se calcularon con ordenadores comunes, i.e., Intel i5- 4200U, 1.60HGz, 8 GB en RAM.

Las funcionalidades del SIG más utilizadas se muestran en la **Figura 5**. Se utilizaron diversas bases de datos, incluidas en esquemas de grandes bases de datos, particularmente las bases de datos anuales por franja horaria del BRT, del sistema de bicicleta compartida y la red vial de Google Street Data®. Las bases de datos geográficas fueron editadas con base en la ponderación de variables que arrojó el análisis de componentes principales.

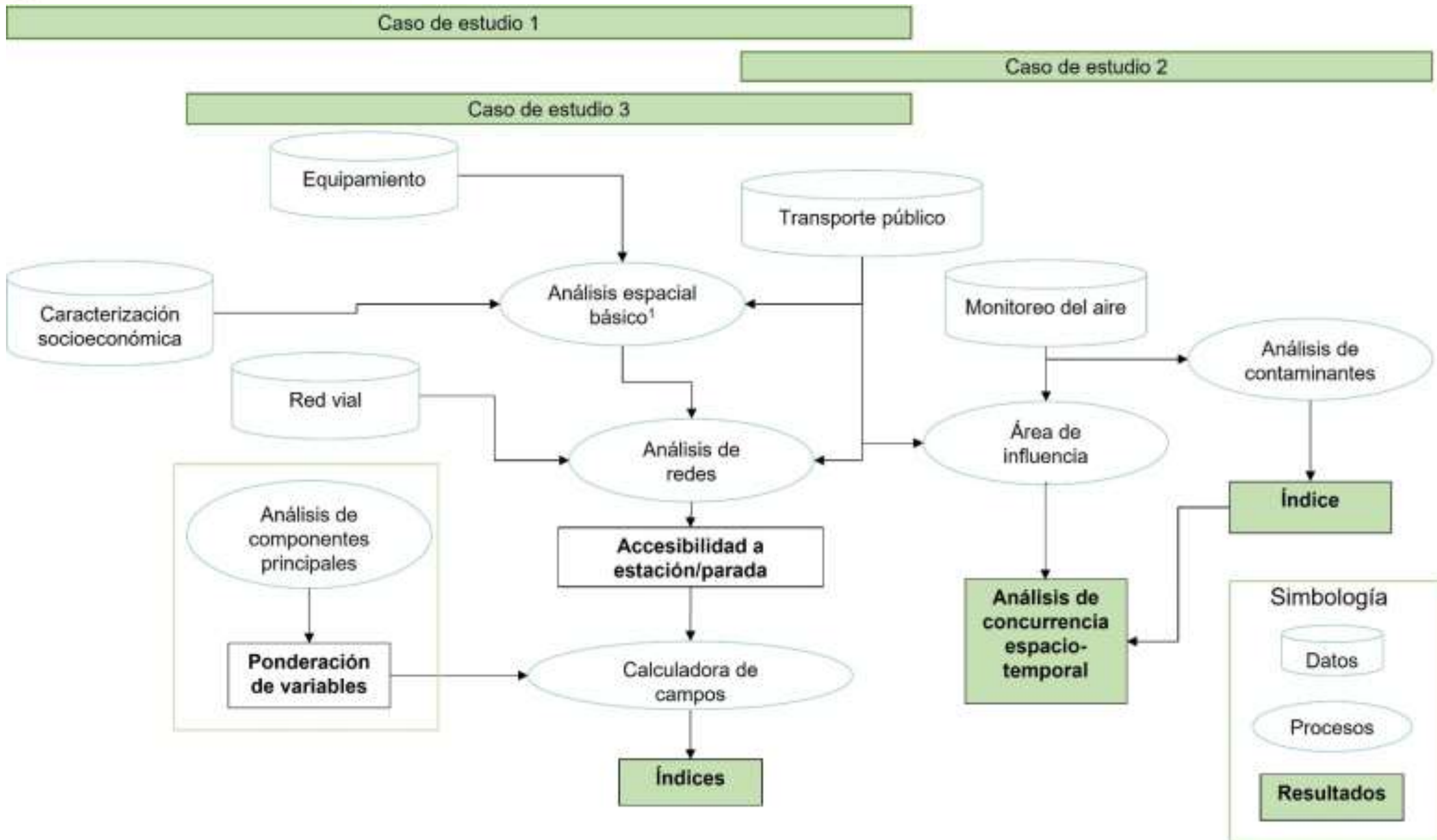

Figura 5. Funcionalidades principales de análisis espacial utilizadas en el método.

[1] Selección por ubicación, el área de influencia, la unión de tablas por atributos, entre otras.

El método multicriterio de análisis de componentes principales (ACP) se utiliza para reducir la correlación entre variables que explican un fenómeno. Fue utilizado en los CE 1 y 3. En el caso del primero, se accedió a una base de datos socioeconómicos y se modeló el fenómeno con el componente principal y los pesos de las variables que le correspondían. En el segundo caso, se consideró el número de estaciones/paradas de transporte sostenible en áreas de servicio de equipamiento universitario, previamente calculado con el SIG y se eligió el vector del componente principal que mejor se adecuó al fenómeno analizado.

Los parámetros de calidad del análisis multicriterio de ACP fueron el porcentaje explicativo de la correlación de variables, el eigenvalor y la varianza medida con Kaiser-Meyer-Olkin (KMO), debiendo ser mayores a 75%, 1,0 y 0,6, respectivamente, de acuerdo con la literatura (Anderson, 1984; Jolliffe, 2002; Peres-Neto et al., 2005) . En seguida, se interpretaron los componentes propuestos y se analizó la relevancia para explicar el fenómeno estudiado con base en la ponderación de las variables del componente elegido.

Las unidades de análisis espacial elegidas fueron los polígonos de secciones geoelectorales, los puntos de equipamiento universitario y el área de influencia de las estaciones de monitoreo de la calidad del aire. Se asumió las limitaciones que implicaron las unidades de análisis en el momento de la interpretación de resultados. Posteriormente se calcularon los índices para todas las unidades de análisis espacial, con ayuda de la calculadora de datos del SIG. El proceso general se muestra en la **Figura 6**.

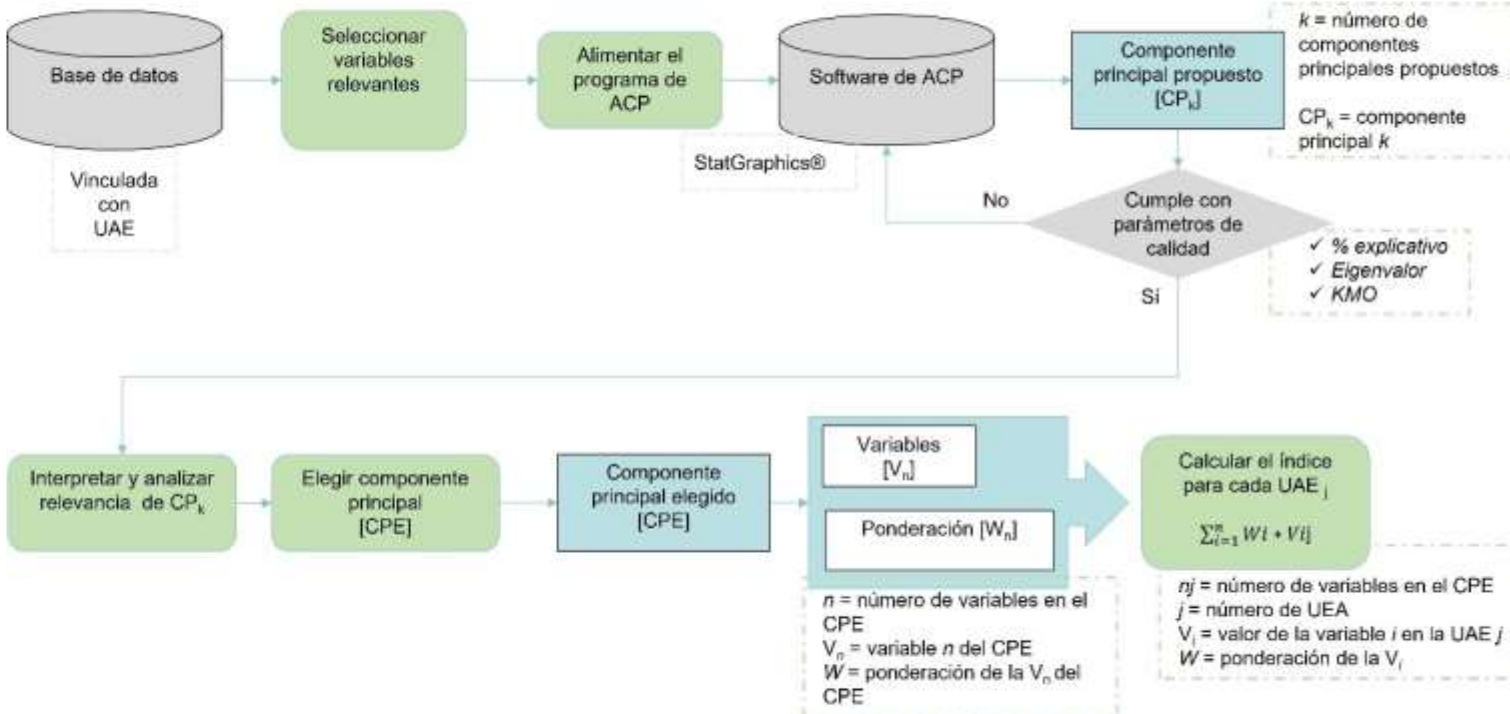

Figura 6. Proceso del análisis de componentes principales.

[1] El número de variables depende del conjunto de datos disponible;[2] El índice fue calculado con la media de tres componentes principales, pues no se identificó uno que representara por sí solo el fenómeno.

UAE = unidad de análisis espacial

ACP = análisis de componente principales

Análisis de resultados

Durante esta etapa se revisaron los resultados de los cálculos y se identificaron patrones espaciales y/o estadísticos. Estos fueron contrastados con el conocimiento del sitio para descubrir fenómenos esperados o diferentes a lo esperado, con el objeto de cotejar las hipótesis de partida.

Discusión de resultados y generación de conclusiones

Estas etapas metodológicas fueron un complemento del marco teórico. Por un lado, se estableció un diálogo entre los hallazgos de los CE y los registrados en la literatura. De esta manera se contrastaron los resultados de otros contextos y se encontraron diferencias y similitudes con experiencias anteriores. Por otro lado, durante estas etapas se probaron conceptos descritos en el marco teórico, con lo cual se materializaron las aportaciones al área de estudio a partir de hallazgos empíricos. Finalmente, a partir de dicho trabajo, se compusieron unas conclusiones generales.

I. INTRODUCCIÓN

II. CASOS DE ESTUDIO

Este capítulo constituye la sustancia de la tesis pues describe los casos de estudio (CE) con los que se evaluaron las hipótesis planteadas en la sección 1. Cada CE refirió a hipótesis particulares (Tabla 1). Con base en ellas, se plantearon objetivos: el primer caso evaluó la cobertura del Sistema de Tren Eléctrico Urbano (conocido como SITEUR) respecto a las necesidades sociales del transporte; el segundo estudio cuantificó el número de usuarios de modos de transporte activos expuestos a episodios de mala calidad del aire y el tercero estimó la inequidad de acceso a transporte sostenible como indicador de la exclusión social relativa al transporte para el colectivo de las comunidades universitarias. Las tres secciones del capítulo corresponden a la publicación de cada CE.

UNIVERSIDAD DE GRANADA

4. Does the mass public transport system cover the social transport needs? Targeting SDG 11.2 in Guadalajara, Mexico

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Article

Does the Mass Public Transport System Cover the Social Transport Needs? Targeting SDG 11.2 in Guadalajara, Mexico

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Abstract: This paper analyses how SITEUR, the Mass Public Transport System (MPTS) in the Guadalajara Metropolitan Area (GMA), covers transport social needs, contributing to achieve Sustainable Development Goals (SDG) 11.2. In order to facilitate this, an Index of Mass Transport Provision (IMTP) was measured through proximity, frequency, and capacity. Then, an Index of Social Transport Needs (ISTN) was calculated by means of transport disadvantage indicators. Finally, the Index of Social Transport Needs Covered (ICSTN) was calculated. The calculations used geographic information systems and principal component analysis in 1834 geographic sections. Findings highlight that 50.3% of the inhabitants have a very high level of social transport needs, while only 6.8% of the population have very low social transport needs. Results show that SITEUR promotes advancement in public transport systems within the GMA relative to quality, security, and reliability and it also contributes to tackling social exclusion in the GMA. A proposal related to transport systems integration is included, to address an important aspect of social exclusion in the city.

Keywords: mass public transport; social transport needs; social exclusion; Guadalajara; Latin America

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1. Introduction

The role of transport in sustainable development has been widely recognized since the 1992 United Nations Earth Summit and Agenda 21 document. Further, at the 2002 World Summit on Sustainable Development and at the 2012 United Nations Conference on Sustainable Development (Rio +20) transportation and mobility were considered central to sustainable development. Sustainable transport achieves better integration in the economy when it respects the environment; it improves social equity, health, the resilience of cities, urban-rural linkages and productivity of rural areas [1]. In the 2030 Agenda for Sustainable Development, sustainable transport is mainstreamed across several Sustainable Development Goals (SDGs) and targets. Specifically, target 11.2 is aimed at providing "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" [2]. In this sense, studying transport social needs served by public transportation is an essential matter to evaluate target 11.2.

In recent decades, the expansive urban development model of the Guadalajara Metropolitan Area (GMA) has increased individual motorized journeys. The kilometres travelled by private vehicle increased by more than 942% between 1980 and 2017 [3]. Despite this growing trend of private vehicle use, 34% of daily trips are made by public transport. In this context, the transport policy focused on the mass public transport system (MPTS), known as SITEUR, to increase multimodal choices, reduce air pollution and

Abstract

This paper analyses how SITEUR, the Mass Public Transport System (MPTS) in the Guadalajara Metropolitan Area (GMA), covers transport social needs, contributing to achieve Sustainable Development Goals (SDG) 11.2. In order to facilitate this, an Index of Mass Transport Provision (IMTP) was measured through proximity, frequency, and capacity. Then, an Index of Social Transport Needs (ISTN) was calculated by means of transport disadvantage indicators. Finally, the Index of Social Transport Needs Covered (ICSTN) was calculated. The calculations used geographic information systems and principal component analysis in 1834 geographic sections. Findings highlight that 50.3% of the inhabitants have a Very High level of social transport needs, while only 6.8% of the population have Very Low social transport needs. Results show that SITEUR promotes advancement in public transport systems within the GMA relative to quality, security, and reliability and it also contributes to tackling social exclusion in the GMA. A proposal related to transport systems integration is included, to address an important aspect of social exclusion in the city.

Keywords

mass public transport; social transport needs; social exclusion; Guadalajara; Latin America

Introduction

The role of transport in sustainable development has been widely recognized since the 1992 United Nations Earth Summit and Agenda 21 document. Further, at the 2002 World Summit on Sustainable Development and at the 2012 United Nations Conference on Sustainable Development (Rio +20) transportation and mobility were considered central to sustainable development. Sustainable transport achieves better integration in the economy when it respects the environment; it improves social equity, health, the resilience of cities, urban-rural linkages and productivity of rural areas (P. Miller et al., 2016). In the 2030 Agenda for Sustainable Development, sustainable transport is mainstreamed across several Sustainable Development

Goals (SDGs) and targets. Specifically, target 11.2 is aimed at providing “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” (United Nations (UN), 2015). In this sense, studying transport social needs served by public transportation is an essential matter to evaluate target 11.2.

In recent decades, the expansive urban development model of the Guadalajara Metropolitan Area (GMA) has increased individual motorized journeys. The kilometres travelled by private vehicle increased by more than 942% between 1980 and 2017 (Jalisco, 2019). Despite this growing trend of private vehicle use, 34% of daily trips are made by public transport. In this context, the transport policy focused on the mass public transport system (MPTS), known as SITEUR, to increase multimodal choices, reduce air pollution and improve the quality of journeys (Vuchic, 2017). SITEUR mainly serves the center of the metropolis. Specifically, it serves four of the nine municipalities with a multimodal system: light rail transit, bus rapid transit, and buses. A considerable proportion of people living in the suburbs travel on conventional buses operated by private carriers. Even though the fare is the same for SITEUR and conventional buses, the latter have poor regulation and make inefficient attempts to improve the quality of travel (Jalisco, 2019).

Besides the private carriers over the last mile to access the mass transport system and reduce transport related exclusion, other features, such as Park and Ride, are designed to support the successful operation of the system. Park and Ride are parking areas located in the vicinity of mass transport peripheral stations. People can leave their private vehicles there and use public transportation to travel to central areas. Unfortunately, the Park and Ride paradigm is not as well-established in the GMA, as it is in many cities. For instance, the Park and Ride system in Warsaw reduces social exclusion as cars, bikes and motorcycles can be parked in interchange nodes (Macioszek & Kurek, 2020, 2021).

Despite the fact that transport-related social exclusion has been studied in Latin American cities (Hernandez, 2018; Vecchio, Tiznado-Aitken, et al., 2020), empirical and quantitative in-depth socio-spatial research is needed to identify whether transport systems include or exclude the people with transport disadvantages (Lucas, 2019). The analysis of the spatial and social contribution of SITEUR in the context of metropolitan mobility is relevant, given its quality service, contribution to multimodality and to the environmental quality of the city. This is even more pertinent, considering that the infrastructure of SITEUR has incurred great costs, a public debt that will be paid throughout future decades (Córdova España, 2010). In this context, the aim of this research was to calculate the level of coverage of the provision of SITEUR with regard to the social needs of transport to find out whether SITEUR contributes to achieving 11.2 SDG target. In order to facilitate this, three indexes were conceived, calculated, and mapped with geographic information system and principal component analysis methodologies. First, an Index of Mass Transport Provision (IMTP) was measured through proximity, frequency, and capacity. Then, an Index of Social Transport Needs (ISTN) was calculated by means of transport disadvantage indicators considered in the existing literature. Finally, the Index of Social Transport Needs Covered (ISTNC) was calculated.

Related work is described in the next section. Then the study area and the research object are described. The third section explains the methodology for all indexes, i.e., IMTP, ISTN, and ISTNC. Scientific and technological methods are applied through integration and analysis of statistical and spatial data. The results and discussions described in the fourth section highlight the spatial dimension of the social exclusion covered by the SITEUR. The final section shows the main conclusions of the research and presents some proposals for tackling social exclusion related to transport.

Literature review

The mass public transport system (MPTS) including light rail transit (LRT) and bus rapid transit (BRT), promotes sustainable mobility, with regard to environmental, economic, and social dimensions. Regarding environmental improvements, the MPTS contributes to the reduction of the number of private trips, therefore, they reduce greenhouse gas emissions. This is especially true in the current context of the promotion of electricity as clean energy for LRT (UITP, 2020). In addition, the urban quality is usually improved when integrating LRT or BRT, especially in the vicinity of the stations (Vuchic, 2017). In some cases, the MPTS even reduces crime (Cerda et al., 2012). In contrast, new conventional bus routes rarely promote improvements in urban environments or promote safer areas.

With respect to the economic dimension, at least two general perspectives support the relevance of analysing MPTS. Firstly, when MPTS is conceived within the development oriented transport paradigm, they drive neighbourhood revitalization, generate economic growth and development, promote the growth of affordable housing, and increase land values, rents, and real estate yields (S. Medina & Patlán, 2016; Quintero-González & Quintero-González, 2019, p.; Schlickmann et al., 2017). Secondly, the journey time is usually shorter with MPTS. Users recognize that LRT and BRT are more punctual and provide a faster overall journey time than conventional buses (D. A. Hensher et al., 2015). LRT or BRT stations are well established and respected: although the bus stops are officially designated in many Latin-American cities, buses usually stop randomly, whenever users call or flag so the journey time on conventional buses is hard to predict.

From the social dimension, it has been shown that the MPTS contributes to addressing transport social needs. This perspective deals with the reduction of disadvantages in transportation, largely explained by socioeconomic factors. The social needs of transport are the requirements to access jobs, goods, services and other essential activities by people whose motives and mode of transportation are determined, to a large extent, by their socioeconomic characteristics. Poor transport services can compound the problems of living on a low income (Clichevsky, 2000; Figueroa, 2005; Giraldo et al., 2009; Lazo, 2008; Vasconcellos & Mendoca, 2016). Transport disadvantage has a greater impact on particular groups whose condition of social exclusion is often reinforced by non-existent or low-quality public transport services (Bocarejo S. & Oviedo H., 2012; Currie, 2009; Hine & Mitchell, 2016; Jaramillo et al., 2012; SEU, 2003). In this respect, the MPTS offers higher quality services than conventional buses (Vuchic, 2017). Safe access for individuals to work, education, healthcare services and sociocultural activities is easier in areas with adequate public transport facilities. In particular, BRT improves mobility to low-income residents (Ferbrache, 2019).

Poor and low-income households in outlying locations have more difficulty accessing opportunities and services (Hine, 2003; Hine & Mitchell, 2016; Mackett et al., 2008; Schwanen et al., 2015; Yigitcanlar et al., 2010). These areas are usually far away from primary routes or corridors and have little or no public transport provision. In this regard, even though the MPTS mainly serves the central areas, where most of these activities occur, they connect these opportunities and services with the periphery via buses, usually through private services.

Guadalajara Metropolitan Area and SITEUR

The GMA is a conurbation in western Mexico with 4.8 million inhabitants spread over 2700 square kilometres. It is made up of nine municipalities: four central and five peripherals. An anarchic urbanization process and a metropolitan concentration has produced a scattered and fragmented city with a wide range of population density (Cruz Solís et al., 2008; Harner et al., 2018). Figure II.1 illustrates that density is Very High in the northwest and southwest urban areas, in addition to the central eastern area.

With respect to socioeconomic characteristics, more than 15% of the GMA inhabitants live in High and Very High levels of urban exclusion, and 40% of the inhabitants live in conditions of poverty (Calonge Reillo, 2017c; CONAPO et al., 2010; ECLA, 2019). The fact of not owning a refrigerator is an indicator of low household income, according to CONAPO (CONAPO, 2016). Remarkably, 30.9% of households do not own a refrigerator in the GMA. The poorest people must allocate more than 35% of the total income to transport (De Quevedo García Najar et al., 2017).

The mass public transport system (MPTS) in the Guadalajara Metropolitan Area (GMA) is operated by the urban electric train system, known as SITEUR. It is a public institution created in 1987. By 1992, the SITEUR operated the first light rail transit (LRT) in the area, connecting the north and south of the city. The second LRT line started operation in 1994 and travelled from the centre to the east through the densest areas of the GMA. The MPTS was complemented by a line of bus rapid transit (BRT), known as the *Macrobús* in 2006, running almost parallel to LRT Line 1 (Córdova España, 2010). Then four lines with high quality buses, known as *Sitren*, were integrated into the system. Finally, a third line of the LRT was included in SITEUR by September 2020. The SITEUR promotes advancement for public transport systems in the GMA in terms of quality, security and reliability.

Several more lines were contemplated in the metropolitan plans. In 2020, the construction of a second BRT line was started. It is aligned with a large avenue that links the central municipalities with those of the periphery. The improvement in the mobility within the city created by this line, will be assessed as soon as operational data is available. In general, SITEUR provides an improvement to the public transport system in the GMA in terms of quality and reliability. A study sponsored by UN-HABITAT refers to the good condition of vehicles, the attitude of the drivers and, in general, to the pleasant perception of the journey in SITEUR (Castañón Reyes, 2016). In addition, SITEUR's LRT lines contribute to good air quality, as they run on electricity and reduce trips by private motorized vehicles. Figure II.1 shows a bus network service in the non-central areas of the GMA. There are also low-quality transport services such as motorcycle taxis, minibuses and other unregulated alternatives that are not still integrated into SITEUR (CONAPO, 2016).

Just as the highest population density is concentrated in the four central municipalities, almost 95% of the generators of journeys on work-days are also located in that area (Programa General de Transporte del Estado de Jalisco, 2016). As illustrated in **Figure 3**, the three modes of SITEUR serve the urban area of these municipalities and the highest density areas, while the buses also serve the lowest density areas with microbuses and minivans. This kind of transport is slow, unreliable, and irregular (Calonge Reillo & Aceves Arce, 2019). Notwithstanding, they cover a lot of transport needs that are not reachable by SITEUR.

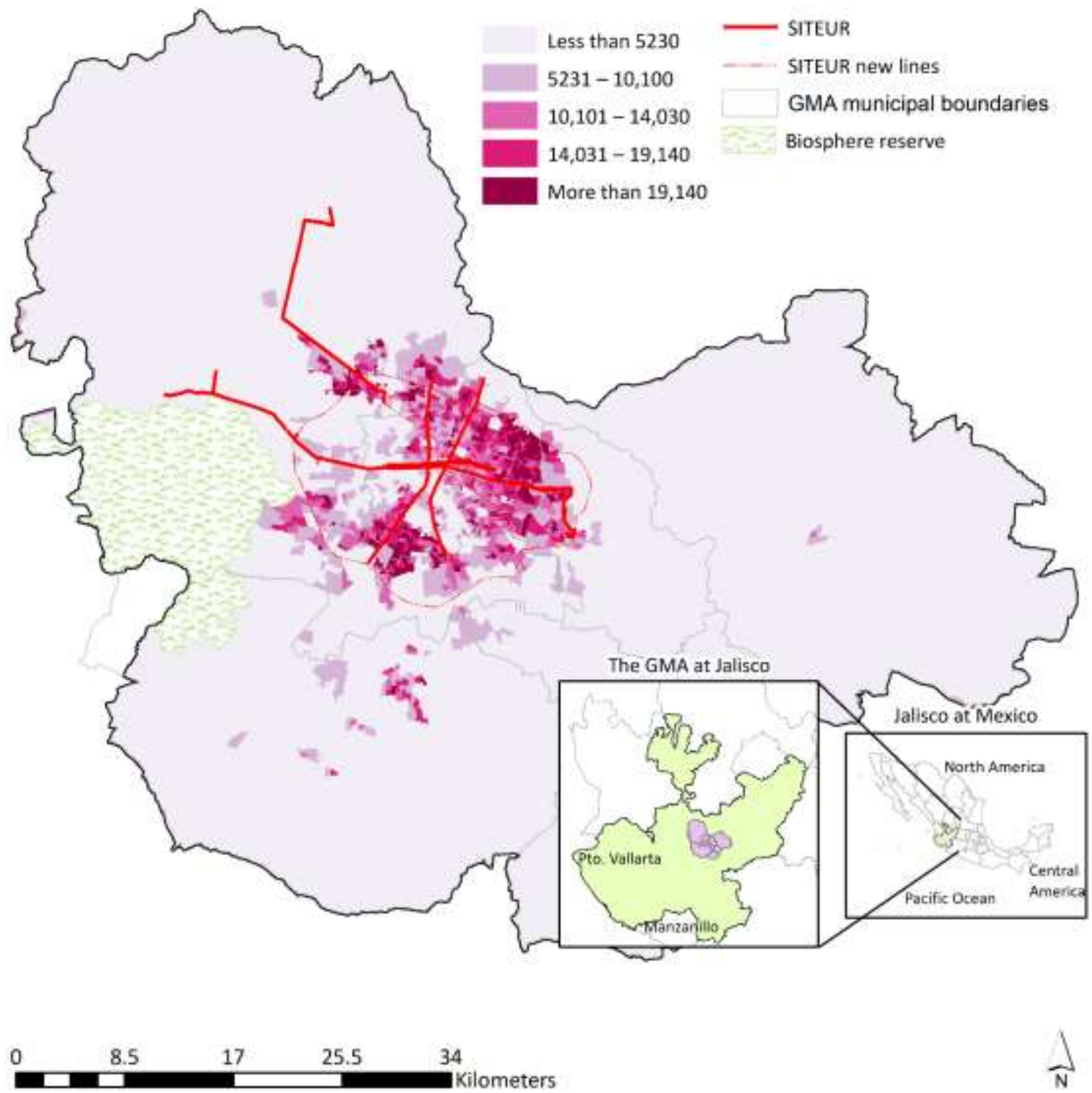

Figure 3. Population Density in the Guadalajara Metropolitan Area (inhab/sqkm)

Source: Authors based on (CONANP, 2017; INEGI, 2010a)

While the modal split of GMA has not been recently assessed, government estimates are shown in **Figure 4**. A third of the daily journeys are made by public transport, while less than a third of them are made by private motorized vehicle and almost half of the trips are made by non-motorized vehicles (Jalisco, 2019). From the 40% of non-motorized users, the 37% of the inhabitants who go by foot do so mainly for financial reasons (Aguirre Quezada, 2017).

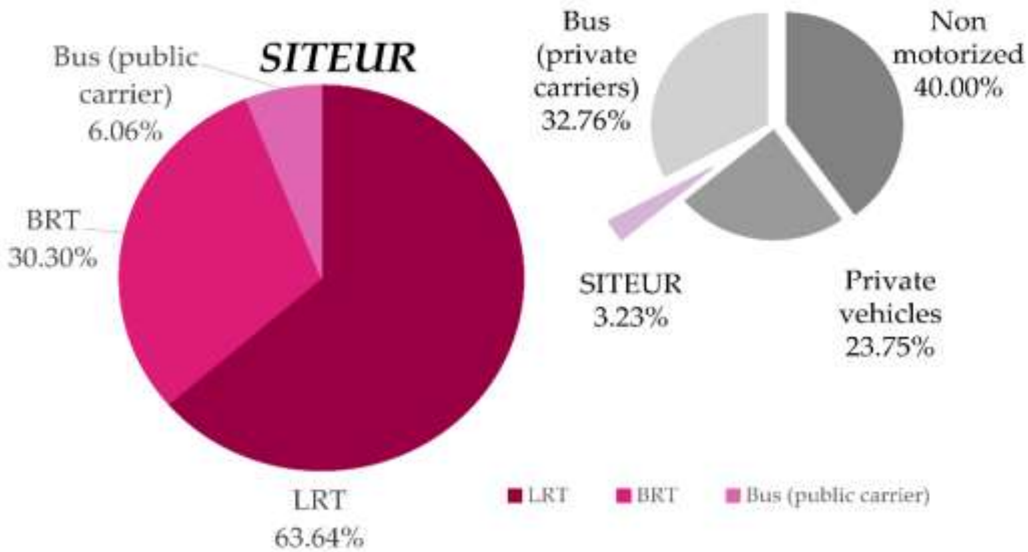

Figure 4. Modal Split in the Guadalajara Metropolitan Area (Percentage of Work-Day Journeys)

Source: Authors based on (Jalisco, 2019; S. de T. E. U. (Urban E. T. S. SITEUR Guadalajara), comunicación personal, 21 de junio de 2019; SITEUR, 2020a, 2020b, 2020c) .

Within the public transport system, SITEUR serves nearly one tenth of the journeys, i.e., nearly four hundred thousand trips on work-days (SITEUR, 2020a, 2020b, 2020c). Due to the large investments that a mass public transport system (MPTS) implies, SITEUR should increase its contribution to the modal split. In addition to SITEUR, private enterprises operate public transport services in the GMA. Although the fare is the same for SITEUR as it is for buses, the privately licensed operators provide poor transport services by bus and microbus and are not fare-integrated to the SITEUR.

As illustrated in **Figure 5**, SITEUR mainly serves the centre of the GMA. It represents an improvement in the intermodal transport in the GMA, through LRT, BRT, and high-quality bus services. Two of the higher capacity lines are north-south oriented through the centre of the city. The second LRT line and high-quality bus routes are east-west oriented. These buses serve some areas in the periphery of the city, where the lower socioeconomic dwellings are concentrated (Calonge Reillo & Aceves Arce, 2019; IMEPLAN, 2015, 2018; S. de T. E. U. (Urban E. T. S. SITEUR Guadalajara), comunicación personal, 21 de junio de 2019). As shown in **Table 1**

Characteristics of modes in the SITEUR

, there is a large difference between mode capacities of SITEUR vehicles. Nonetheless, the peak-time frequency (a.m.) does not differ greatly among the different modes, except for one bus line (S. de T. E. U. (Urban E. T. S. SITEUR Guadalajara), comunicación personal, 21 de junio de 2019).

Table 1

Characteristics of modes in the SITEUR

Mode	Name	Length [Km]	Number of Stops/Stations	Peak-Time Frequency [Minutes]	Capacity [Passenger/ Vehicle]
LRT	1	16	20	5.33	684
	2	9	10	4	600
	3	21	18	7	500
BRT	Macrobús	16	27	6	164
	MiMacro Periférico*	No data	No data	No data	No data
Bus	Sitren 1	12	29	6	47
	Sitren 1 B	12	30	8	80
	Sitren 2	13	26	7	47
	Sitren 3	18	54	7	80
	Sitren 4	22	88	15	80

* This BRT line was not included. It was under construction when the analysis was performed. Source: Authors based on (IMEPLAN, 2019; SITEUR, 2020a, 2020b, 2020c).

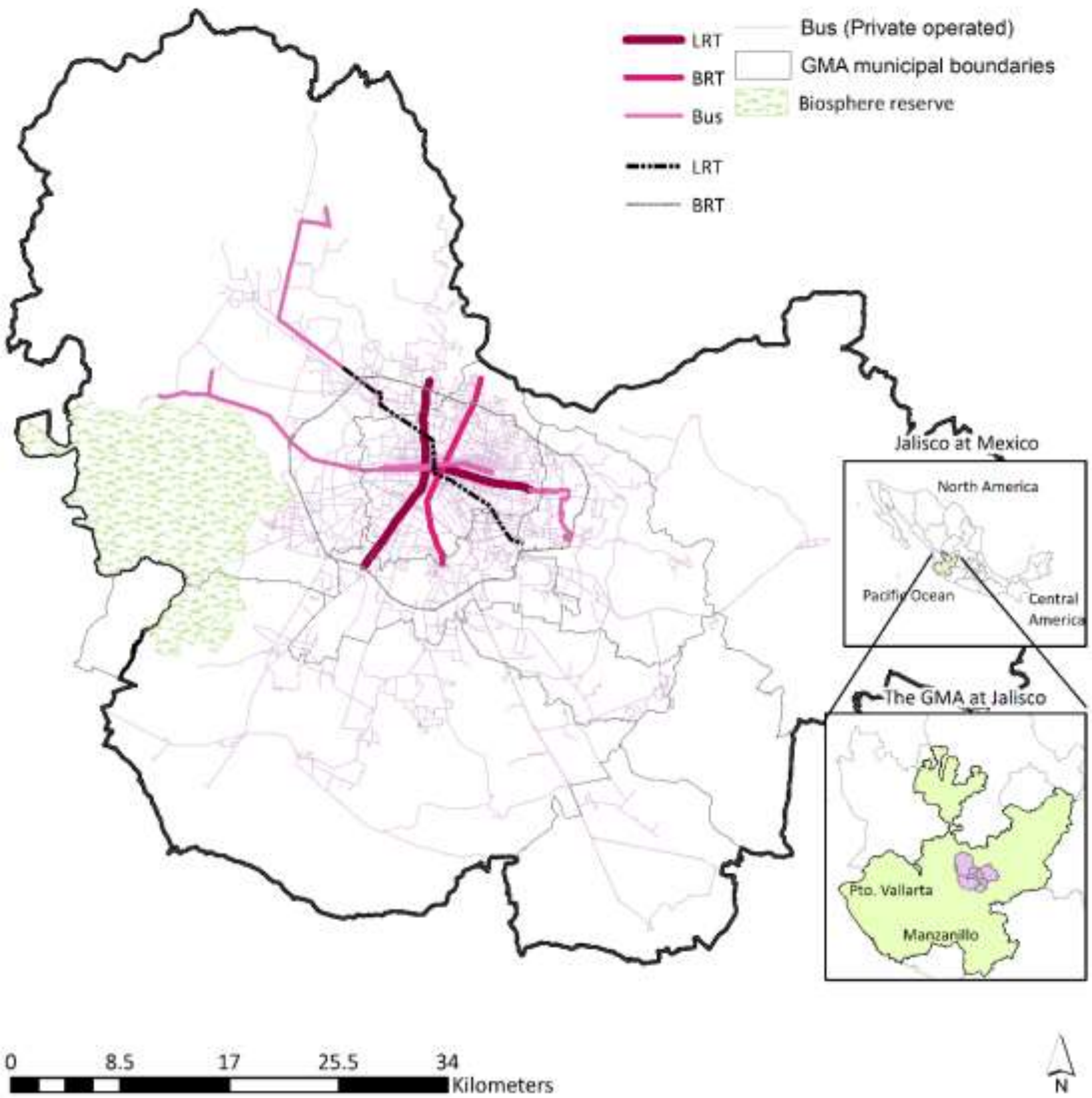

Figure 5. Mass Public Transport System in the Guadalajara Metropolitan Area

Source: Authors based on (CONANP, 2017; IMEPLAN, 2015, 2018, 2019; INEGI, 2010a; SITEUR, 2020b, 2020b, 2020c).

Methodology

In order to assess how SITEUR covers transport social needs in the Guadalajara Metropolitan Area (GMA), three indexes were proposed, calculated, mapped, and analysed. Firstly, an Index of Mass Transport Provision (IMTP) was measured through proximity, frequency, and capacity. Secondly, an Index of Social Transport

Needs (ISTN) was calculated by means of transport disadvantage indicators considered in the existing literature and listed in **Table 2**

Factors, indicators, and data sources used to assess the Index of Mass Transport Provision and the Index of Transport Social Needs

. Thirdly, a Social Transport Needs Covered (STNC) was calculated.

Data used were the newest available for the thematic and geographical scale that the methodology required (IMEPLAN, 2019; INEGI, 2010a, 2010b, 2017; S. de T. E. U. (Urban E. T. S. SITEUR Guadalajara), comunicación personal, 21 de junio de 2019). Social data were obtained from 2010 due to their geographically detailed scale, not available for later years. Thus, all indexes were calculated and mapped in 1834 geographic sections (GS). Scientific and technological methods, e.g., principal components analysis (PCA) and geographic information systems (GIS), supported the integration and analysis of statistical and spatial data through SPSS and ArcMap software.

Index of Mass Transport Provision

The Index of Mass Transport Provision (IMTP) was based on frequency, capacity, and proximity (Fransen et al., 2015; Jaramillo et al., 2012). **Table 2** describes data sources. Frequency used was at peak-time when most people commute to/from work (Vasconcellos & Mendoca, 2016). The vehicle capacity was used for the index calculations. Proximity was calculated through walking time from each of the GS centroids to the nearest stop/station. The distances were modelled by means of advanced spatial analysis (e.g., street network and nearest facility) and involved time as an innovative variable instead of traditional Euclidian distance. In accordance with Fransen et al. (2015), the distances were classified in ranges and normalized

Table 2

Factors, indicators, and data sources used to assess the Index of Mass Transport Provision and the Index of Transport Social Needs

Dimension	Indicator	Variable	Source
Transport	Proximity	Walking minutes to reach the nearest stop/station	Authors, based on the Statistical and Geographic Information Institute of the State of Jalisco (IIEGJal) (2012) and the National Institute of Statistics and Geography (INEGI) (2017)
	Frequency	Peak-time frequency, in minutes	SITEUR (comunicación personal, 21 de junio de 2019; 2020a, 2020b, 2020c) and Metropolitan Planning Institute (IMEPLAN) (2019)
	Capacity	Passenger per vehicle	
Social	Disability	People with motor, visual and auditory handicap	INEGI: Census Information Consultation System (SCINCE, from its initials in Spanish) (INEGI, 2010b)
	Educational level	People from 3 to 24 years assisting to an educational centre	
	Elderly	People of 65 years and over	
	Childhood	People of 5 years and under	
	Unemployment	Unemployed people	

Table 2 (continuation)

Dimension	Indicator	Variable	Source
Social	Illiteracy	People of 15 years and over without ability to read	INEGI: Census Information Consultation System (SCINCE, from its initials in Spanish) (INEGI, 2010b)
	Low income	Dwelling without refrigerator	
	Vehicle ownership	Dwelling without privately-owned vehicle	
	Gender	Dwelling with female-headed household	

As described in **Table 2**

Factors, indicators, and data sources used to assess the Index of Mass Transport Provision and the Index of Transport Social Needs

, the geometry of the road network was generated from two data sources. Given the differences in data generation criteria, the construction of the road network implied significant technical efforts. Finally, the resulting network achieved an acceptable topological quality for a metropolitan scale. Walking time was based on the street network distance assuming a speed of four kilometre per hour, since Mexican authorities recognize that children, the elderly and the motion-impaired walk at this speed (SEDATU et al., 2018). In addition, when two or more stops/stations were less than 50 m apart, this research assumed that users preferred the one that had a higher frequency or capacity in the following order: LRT, BRT, and then bus. This hierarchy served to eliminate the duplicated stops of 284 SITEUR stops/stations. **Table 3** describes the general characteristics of SITEUR considered for the IMTP calculations.

Table 3

Social indicators weights

Social Indicator (S_i)	Weight (W_i)
S_1- Disability	$W_1 = 0.137$
S_2- Educational level	$W_2 = 0.125$
S_3- Elderly	$W_3 = 0.143$
S_4- Childhood	$W_4 = 0.113$
S_5- Unemployment	$W_5 = 0.128$
S_6- Illiteracy	$W_6 = 0.129$
S_7- Low income	$W_7 = 0.036$
S_8- Vehicle ownership	$W_8 = 0.066$
S_9- Gender	$W_9 = 0.123$

The Index of Mass Transport Provision (IMTP) was calculated as shown in **Equation** 1 and normalized through **Equation** 2.

Equation 1

Index of Mass Transport Provision (IMTP)

$$IMTP\,j = (1 - FMj) * Twj * CMj \qquad (1)$$

where

$IMTP_j$ = Index of Mass Transport Provision at GSj;

$_j$ = The GS analysed. Values are 1–1834;

FM_j = Frequency of mode M at the nearest stop/station from GS_j (minutes);

M = {LRT-line1, LRT-line2, BRT, bus-line1, bus-line1B, bus-line2, bus-line3, bus-line4};

Tw_j = Walking time to the nearest stop/station from GS_j (minutes);

CM_j = Capacity of the vehicle of mode M at the nearest stop from GS_j (passengers/vehicle).

Equation 2

Index of Mass Transport Provision Normalized (IMTP_N)

$$IMTP\_N_j = \frac{IMTP_j - IMTP_j^{min}}{IMTP_j^{max} - IMTP_j^{min}} \times 100 \qquad (2)$$

Index of Social Transport Needs

Based on previous methodologies (Currie, 2010; Fransen et al., 2015; Jaramillo et al., 2012; Lizárraga, 2012), the Index of Social Transport Needs (ISTN) incorporated socioeconomic and housing dimensions, following the wide evidence that social transport needs are different according to income, age, vehicle ownership, gender or education (De Quevedo García Najar et al., 2017; Graglia, 2016; Hine, 2009; Taylor et al., 2009; UN-Habitat, 2013). Transport disadvantage has a greater impact on particular categories that include the elderly, people with health problems, low incomes groups, those living in conditions of poverty, unemployed or disabled people (El-Geneidy et al., 2016; Grindlay et al., 2018; Hine, 2009; Jaramillo et al., 2012; Jirón, 2007; Lucas, 2019; Özkazanç & Özdemir Sönmez, 2017; Ricciardi et al., 2015; Schwanen et al., 2015; J. Xia et al., 2016). The ISTN incorporated nine transport disadvantage indicators with their variables: disability; educational level;

elderly; childhood; unemployment; illiteracy; low income; vehicle ownership and gender. The combination of the variables of these indicators provides an index of social transport needs, produced with the most important explanatory factors of transport disadvantage.

Interestingly, gender was incorporated through the variable “female-headed households”. Gender has a decisive influence on possibilities for moving through the non-central regions of the metropolis, as well as on ways of linking with the main metropolitan activities (Currie, 2010; Fransen et al., 2015; Ricciardi et al., 2015). In the case of the metropolis in developing countries, Calonge and Aceves (Calonge Reillo & Aceves Arce, 2019) showed that female-headed households make less use of the car and spend less on transportation than male-headed households, due to the prevailing conditions of poverty and the greater deficiencies in the public transport systems.

The ISTN were calculated as the weighted sum of these variables within the GS. **Equation 3** shows the algorithm used to compute this. It was normalized adapting

Equation 2.

Equation 3

Index of Social Transport Needs (ISTN)

$$ISTN_j = \sum_{i=1}^{8} S_{ij} \times W_i \qquad (3)$$

where

ISTNj = Index of Social Transport Needs at GS j;

Sij = Social indicator i at GSj;

Wi = Weight of the social indicator i.

The weighted values of socioeconomic and dwelling variables are listed in **Table 3**.

Principal component analysis (PCA) is a statistical technique usually used in academic studies concerning the social dimension of transport (Delbosc & Currie, 2011b; Jiang et al., 2021; Preston & Rajé, 2007; Tahmasbi et al., 2019), as well as in the evaluation of social public policies in Mexico (CONEVAL, 2019a). The PCA describes correlations between a set of variables by creating new components that propose weights for the original variables. The purpose of the PCA is to obtain a small number of linear combinations of the dataset that account for most of the variability in the data. Each component can be interpreted as one part of the social transport needs. A negative value means that this variable negatively affects the phenomenon. The variability of the original data is an indicator of the analysis performance. The higher the variability, the better the components account for the phenomenon. The component calculated in this study accounted for 76% of the social transport needs. Table 3 shows the factors which better explain transport-related social needs (STN) in the city.

Principal component analysis (PCA) was inputted with 214 socioeconomic and dwelling variables for the 1834 GS (CONEVAL, 2019a). The PCA reduced the dimensionality of the social data set. The fraction of variance explained by the first principal component accounted for 76%. The weights of the first principal component rotated matrix of PCA referred to transport disadvantage. The weights of the main component variables shown in Table 3 totaled 1.0, as they were previously normalized to be included in subsequent calculations. The weight values represent the contribution of each indicator to the social needs of transport in the GMA. These are valid only for the analyzed data set.

As shown in Table 3, the weight assigned to “vehicle ownership” represents only 6% of the indicators related to the disadvantage of transport for each GS. The number of inhabitants in the groups of “childhood”, “elderly” and “educational level” comprises 38% of the weight, while the other five socioeconomic indicators make up the remaining 56%. According to the social indicator weights used for the ISTN, results confirmed that in this case, the socioeconomic factors are much more relevant than the “vehicle ownership” indicator, which is consistent with other studies for Latin American cities (Jaramillo et al., 2012).

Index of Social Transport Needs Covered

The calculation of the spatial differences of the two indices mentioned above allowed us to understand the contribution of SITEUR to address the social needs of transport. The Index of Social Transport Needs Covered (ISTNC) is the difference between SITEUR’s transport provision and the social needs. It was calculated for every GS by means of **Equation 4**

Equation 4

Index of Social Transport Needs Covered (ISTNC)

$$ISTCNj = IMTP\_N_j - ISTN\_N_j \qquad (4)$$

where

$ISTNC_j$ = Provision–needs gap at GS_j;

$ITMPN_j$ = Index of Mass Transport Provision normalized at GS_j;

$ISTN\_N_j$ = Index of Social Transport Needs normalized at GS_j.

Results and discussion

Spatial and statistical analyses were performed to calculate the level of coverage of the provision of SITEUR with respect to the social needs of transport in the Guadalajara Metropolitan Area (GMA). The use of geographic information systems (GIS) highlighted not only the geographic dimension of SITEUR, but the social transport needs (STN) and their spatial patterns. The indexes calculated were the Index of Mass Transport Provision (IMTP), the Index of Social Transport Needs (ISTN) and the Index of Social Transport Needs Covered (ISNTC). All indexes were mapped with five graduated symbols calculated using quintiles of the geographic sections (GS) to create cut-off index levels: Very Low, Low, Medium, High, and Very High.

Index of Mass Transport Provision

The IMTP spatially illustrates the SITEUR transport supply. As shown in **Figure 6**, results confirm that the higher provision is naturally concentrated at the three main axes of the mass transport modes of SITEUR. The SITEUR high quality buses, known as *Sitren*, barely influence IMTP, since they have a very low capacity compared with LRT and BRT (**Table 1**

Characteristics of modes in the SITEUR

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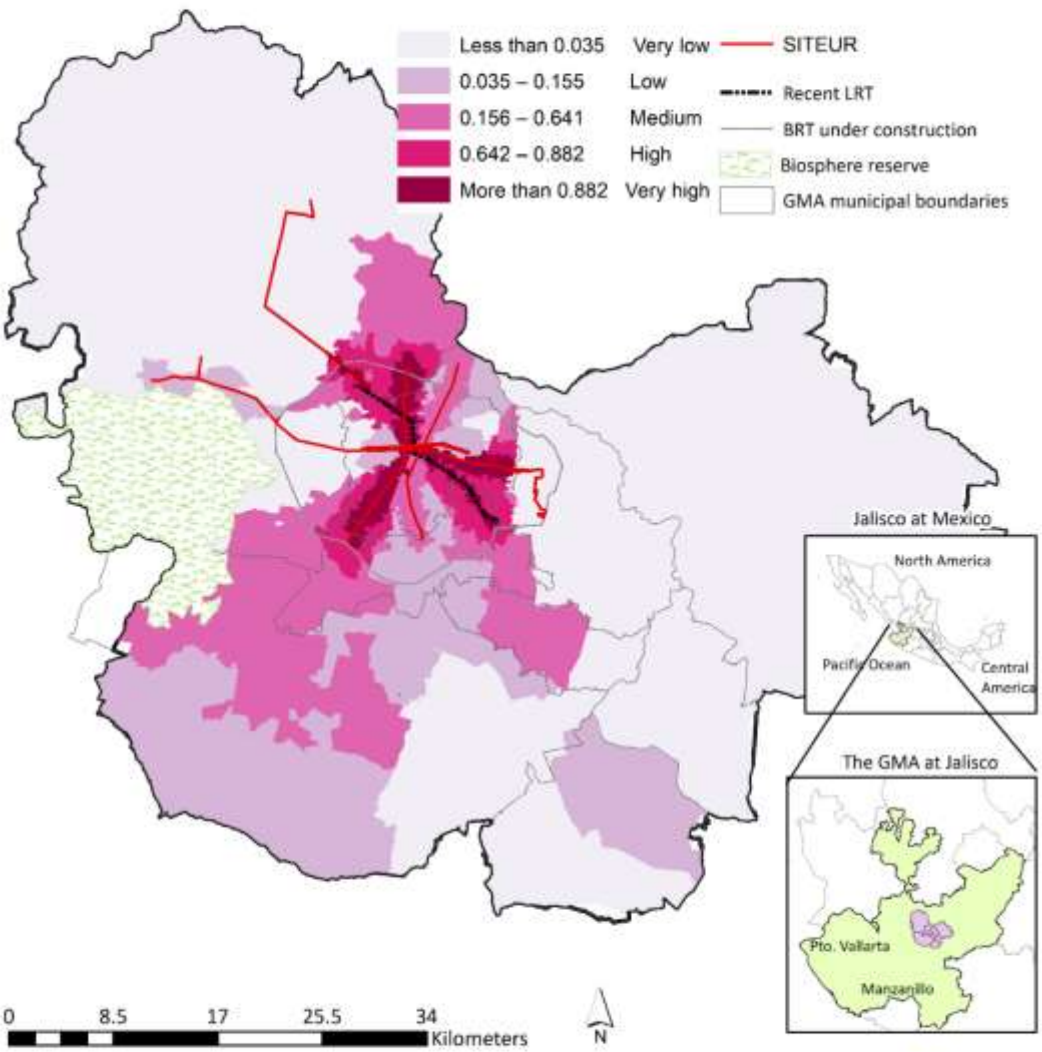

Figure 6. Index of Mass Transport Provision

Source: Authors, based on (CONANP, 2017; IMEPLAN, 2015, 2018, 2019; INEGI, 2010a; SITEUR, 2020b, 2020b, 2020c).

Index of Social Transport Needs

The Index of Social Transport Needs (ISTN) describes the spatial pattern of areas with higher social transport needs, as described in the methodology. Results mapped in **Figure 7** show that higher STN are concentrated in the periphery, as in other Latin America cities (Jaramillo et al., 2012; Jirón, 2007; Jirón & Mansilla, 2013), although the results also identified some areas in the centre of the metropolis with High social needs for transportation. Fortunately, the BRT under construction will largely serve areas with High and Very High STN.

Index of Social Transport Needs Covered

The Index of Social Transport Needs Covered (ISTNC) was calculated and mapped (**Figure 8**) to assess how adequately SITEUR covers or not social transport needs (STN). Positive values of ISTNC can be interpreted as STN adequately covered by SITEUR in the GS. Negative values refer to GS where STN are not covered by SITEUR. As stated by Calonge and Aceves (Calonge Reillo & Aceves Arce, 2019), most of the population in the periphery of the GMA have a limited choice of quality means of transport. According to current mobility public policy (IMEPLAN, 2016b), results highlight areas where mass transport lines should address STN, e.g., the BRT line, *MiMacro Periferico*, currently under construction. This future line may serve some of the west and eastern areas identified in this study as not covered by SITEUR.

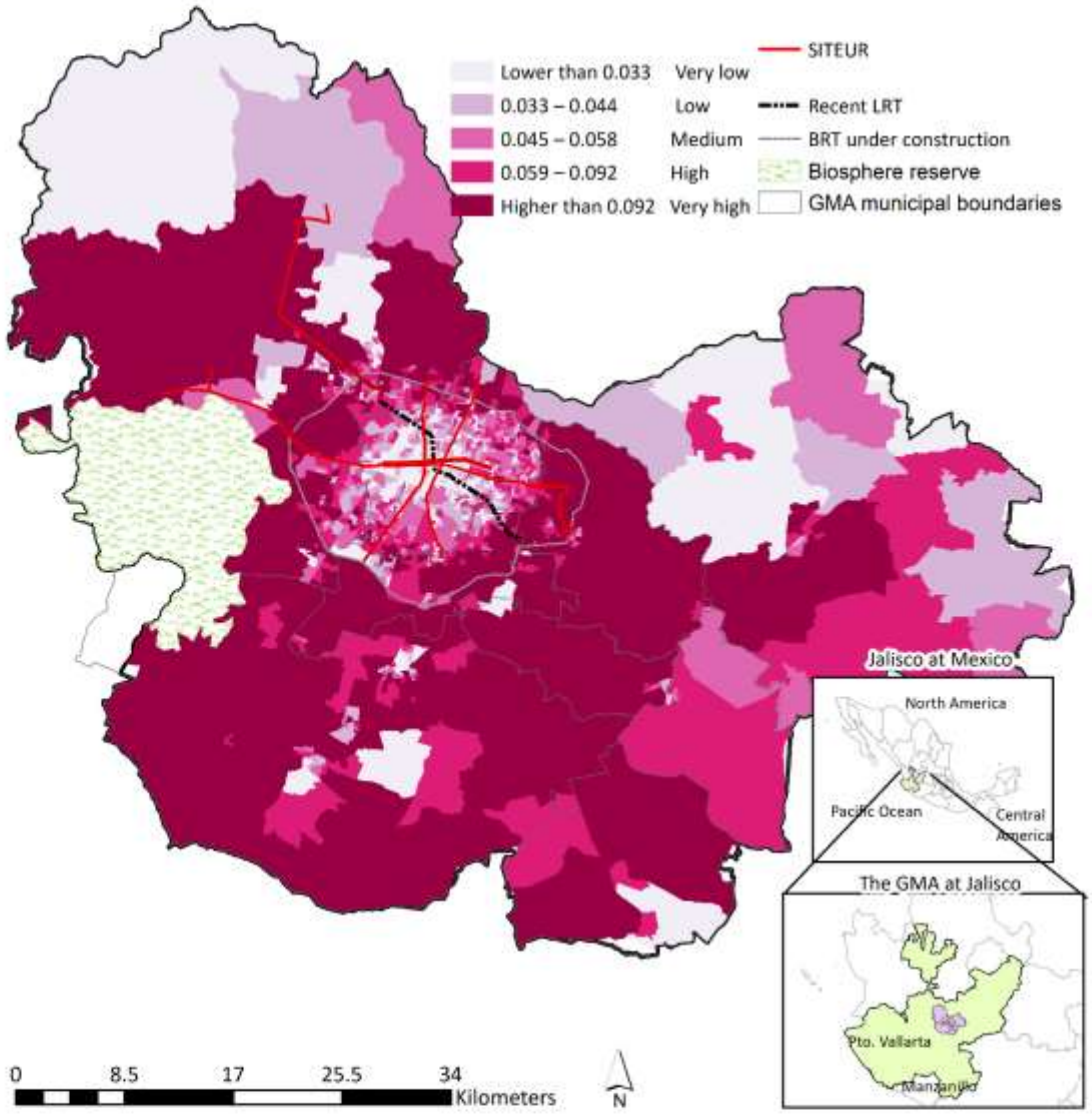

Figure 7. Index of Social Transport Needs

Source: Authors, based on (CONANP, 2017; IMEPLAN, 2015, 2018, 2019; INEGI, 2010a; SITEUR, 2020b, 2020b, 2020c).

As shown in **Table 4**, the proportion of the area where SITEUR exceeds the social needs of transportation is very small. This is due to the scarcity of the mass transportation lines within the system. Despite SITEUR addressing social transport needs in areas where more than half of the GMA population live, it contributes to only 3% of the total modal split. One possible reason is the lack of fare-integration between private buses and SITEUR. The bus network is closer than MPTS to most of the dwellings with higher STN (Figures **Figure** 5 and **Figure** 7). It can be assumed that users will prioritize their economy and will sacrifice journey quality and duration, thus not choosing to switch their mode of transport. In this context, target 11.2 SDG is far from being achieved.

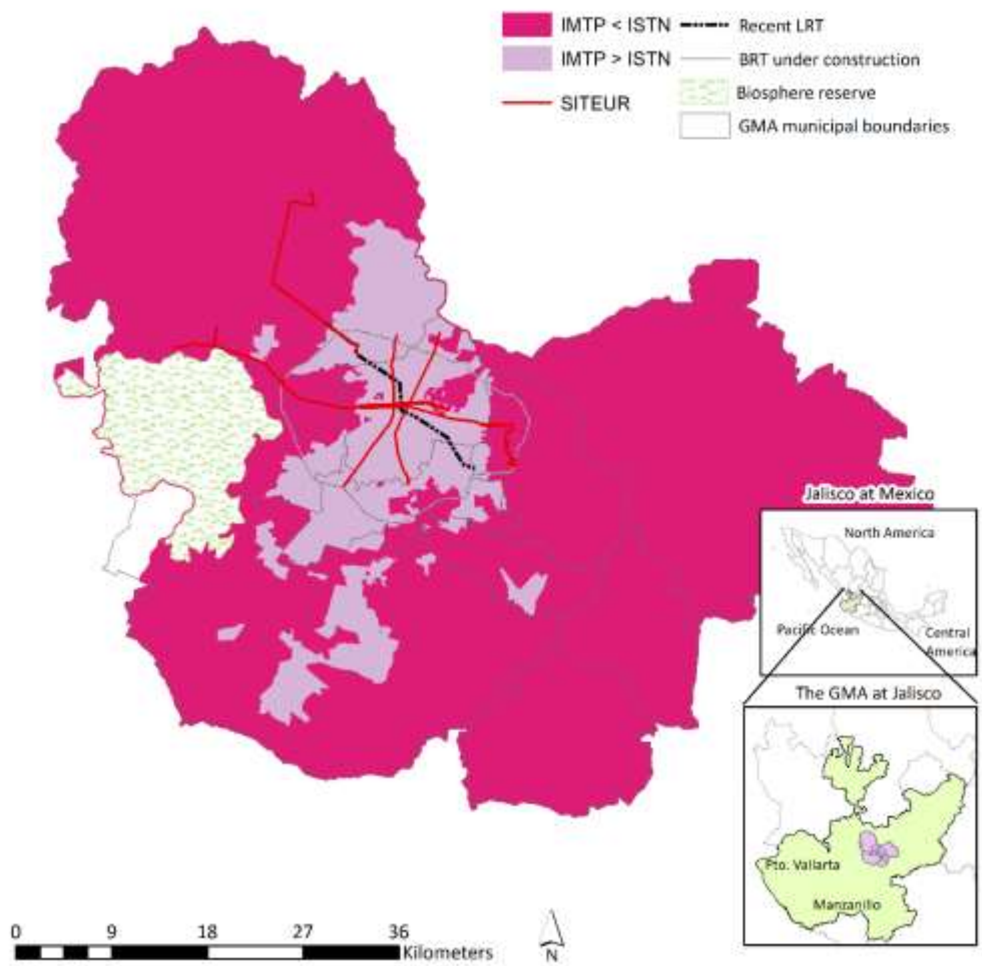

Figure 8. Index of Social Transport Needs Covered

Source: Authors, based on (CONANP, 2017; IMEPLAN, 2015, 2018, 2019; INEGI, 2010a; SITEUR, 2020b, 2020b, 2020c).

Table 4

Population and surface related to social transport needs covered by SITEUR

ISTNC	Inhabitants		Area		
	Value	%	GS	Ha	%
IMTP < ISTN	1,910,203	42%	511	293,265	87%
IMTP > ISTN	2,588,751	58%	1323	45,032	13%

After analysing data with and without the recent LRT Line 3, results show that it barely increases provision by 2% for the number of inhabitants with High transport needs living in areas already served by the SITEUR. The alignment of the line mainly overlaps areas already over-provided by SITEUR. Surprisingly, the new LRT Line 3 will contribute very little to the difference between SITEUR coverage and the enormous social transportation needs. This is regrettable, given the large public investment and the social and economic construction costs, i.e., costs of Line 1 exceeded more than one hundred million dollars (Herrera, 2018).

Figure 9 describes the percentage of the population with social transport needs. It shows the distribution of the levels of SITEUR's provision and of social transport needs in the 1834 GS, ranged by GS quintiles. Ideally, the transport provision curve is proportional, showing a high percentage of the population at the Very High provision level. In contrast, the ideal curve of the STN starts with a high percentage of the population for the lower levels of the index and a decreasing percentage of the population as it approaches the High levels of the index. However, the findings of this research reveal that the curve of the STN is almost inverse to the ideal. Furthermore, it presents a sharp slope in the last segment. This means that the highest STN are concentrated in the last quintile of geographic sections. These findings confirm the high inequality of the distribution of social transport needs and transport provision in the GMA.

Figure 9 also shows that the percentage of inhabitants with less than adequate transport provision is almost double that of people served with Very High values of the index. Results show that the transport need of less than a quarter of the population are covered by the SITEUR. It is worth noting that 50.3% of the inhabitants have a Very High level of STN, while only 6.8% of the population have Very Low social transport needs. Despite this, SITEUR only contributes 3% of the city's modal split (**Figure 4**). Furthermore, the SITEUR does not adequately serve more than half of the population. Notwithstanding that mass transport is scarce in the city, this population ratio is striking, given the high construction and operation costs of SITEUR.

Figure 9. Distribution of the Levels of MTP and of STN in the 1834 GS

Source: Authors.

Conclusions

The mass public transport system (MPTS) impacts the environmental, economic and social dimensions and is directly related to target 11.2 SDG aimed at providing access to sustainable public transport systems for all, with special attention to social needs. This paper contributes to the comprehension of public transport relationships with the spatial and social dimensions in the complexity of metropolitan areas. This study analysed how SITEUR, the MPTS, addresses social transport needs (STN) in the Guadalajara Metropolitan Area (GMA) and targets 11.2 SDG. In order to understand the complex multivariable phenomenon of STN, three indexes were designed, i.e., the Index of Mass Transport Provision (IMTP), the Index of Social Transport Needs (ISTN), and the Index of Social Transport Needs Covered (ISTNC). They were calculated for 1834 geographic sections (GS).

The IMTP was calculated with geographic information systems, using real walking distances and open-access data, such as network geometry, capacity, and frequency. The ISTN used social transport indicators assessed with principal component analysis, based on existing literature. The difference between IMTP and ISTN was used to assess the ISTNC, giving a positive or negative value, concerning the coverage or the disparity of STN in a GS.

It can be concluded that there is high inequality in the distribution of social transport needs and transport provision in the GMA. SITEUR does not meet the social transport needs in the peripheral areas. Results highlight that SITEUR mainly serves the central areas of the metropolis, as in other Latin American cities. Social transport needs do not match the spatial pattern that the mass transportation infrastructure provides in the city. The calculations reveal that the social needs are distributed, mainly, in the periphery, especially in the south-eastern municipalities.

The care of STN demands actions within both social and transport dimensions. The decrease of social transport disadvantages requires attention to the most significant social indicators, e.g., elderly and disabled, and the essential coordination of the public and private sectors. Addressing 11.2 SDG will not be solved solely with the increase of more mass transport lines, but by the reinforcement of connections and the improvement of transportation in the periphery (Duarte & Rojas, 2012). Public and private carriers cannot turn their backs, as they have done in recent decades. They must work towards a common sustainable goal: the improvement of mobility in the GMA, with special attention to social needs. This cooperation and integration must go beyond a simple homologation of bus/SITEUR fares. Carriers should reduce the gap between STN and the public transport provision with improved structural strategies. Although this integration implies the removal of longstanding political and economic handicaps, the public-private dialogue should address the important aspect of social exclusion in the city taking into consideration the SDG.

Although the methodology provides a quantitative approximation of a complex problem due to a considerable number of variables, the SITEUR transport supply is limited, so there is still room for improvement in the knowledge of social exclusion linked to public transport. The spatial analysis shows that SITEUR could have a great impact on the modal distribution of the city. However, this contradicts reality. Therefore, future research will integrate other modes of transport to the model to explore further the social needs of transport in the city from a more multimodal perspective. In particular, future research will include a new public transport supply index that considers, not only mass transport, but also the bus network managed by private carriers. This will support social dimension arguments to promote greater cooperation between all carriers with better integration of a more holistic approach to the transport system. This will facilitate social dimension arguments for decision makers to promote a more holistic approach to the transport provision in the GMA and to achieve transport-related SDGs.

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5. Air quality and active transportation modes: A spatio-temporal concurrence analysis in Guadalajara, Mexico

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Air Quality and Active Transportation Modes: A Spatiotemporal Concurrence Analysis in Guadalajara, Mexico

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Abstract: The protection of pedestrians, cyclists, and public transportation passengers from environmental pollution is a global concern. This study fills the gap in the existing knowledge of temporal exposure to air pollution in Latin American metropolises. The paper proposes a methodology addressing the relationship between two objects of study, i.e., the users of active modes of transport and air quality. This new methodology assesses the spatiotemporal concurrence of both objects with statistical analysis of large open-access databases, to promote healthy and sustainable urban mobility. The application of the empirical methodology estimated the number of users of active transportation modes exposed to poor air quality episodes in the Guadalajara metropolitan area (Mexico) in 2019. The study considered two pollutants, ozone (O_3) and particulate matter (PM_{10}), and two active modes, cycling and bus rapid transit (BRT). Spatiotemporal analyses were carried out with geographic information systems, as well as with numeric computing platforms. First, big data were used to count the number of users for each mode within the area of influence of the air quality monitoring stations. Second, the number of air pollution episodes was obtained using the air quality index proposed by the Environmental Protection Agency (USA) on an hourly basis. Third, the spatiotemporal concurrence between air quality episodes and active mode users was calculated. In particular, the air quality monitoring data from the Jalisco Atmospheric Monitoring System were compared to users of the public bicycle share system, known as MiBici, and of a bus rapid transit line, known as Mi Macro Calzada. The results showed that the number of cyclists and BRT passengers exposed to poor air quality episodes was considerable in absolute terms, that is, 208,660 users, while it was marginal when compared to the total number of users exposed to better air quality categories in the study area, who represented only 10%. To apply the results at the metropolitan scale, the spatial distribution of the air quality monitoring system should be improved, as well as the availability of data on pedestrians and conventional bus passengers.

Keywords: pedestrian; bicycle; active transportation modes; air quality; risk; health; mass transport system; bus rapid transit; GIS; big data

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1. Introduction

Air quality is a big concern in cities. Since 2016, 90% of worldwide city dwellers living in low- and middle-income countries have breathed air that did not meet the safety standards set by the World Health Organization (WHO), causing 4.2 million premature deaths due to air pollution [1,2].

Air pollution is the presence in the air of matter (solid particles and gases) or forms of energy that cause risk, damage, or serious annoyance for people and other living organisms. According to the WHO [2], PM, carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2),

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Keywords

Pedestrian; bicycle; active transportation modes; air quality; risk; health; mass transport system; bus rapid transit; GIS; big data

Introduction

Air quality is a big concern in cities. Since 2016, 90% of worldwide city dwellers living in low- and middle-income countries have breathed air that did not meet the safety standards set by the World Health Organization (WHO), causing 4.2 million premature deaths due to air pollution (ONU-Hábitat, 2021; World Health Organization, 2021).

Air pollution is the presence in the air of matter (solid particles and gases) or forms of energy that cause risk, damage, or serious annoyance for people and other living organisms. According to the WHO (World Health Organization, 2021), PM, carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) are the pollutants with the strongest evidence for being public health concerns.

The Environmental Protection Agency (EPA) proposed the universally recognized air quality index (AQI) (Environmental Protection Agency, 2021) to assess air pollution. The EPA defined six categories according to pollutant concentrations. The categories were labeled corresponding to the level of concern, that is, 1, 2, 3, 4, 5, or 6 for good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous concern, respectively.

Specifically, O_3 and PM pollution at ground level poses a high risk to health (De Jesus et al., 2020; Environmental Protection Agency, 2016a) and have multiscale temporal patterns. The concentrations may vary according to the hour of the day and the season, e.g., O_3 concentrations are higher during the daytime than at night, and particulate matter, such as PM_{10}, is more concentrated in the winter than in the summer. Precipitations also affect PM concentrations (De Jesus et al., 2020).

Exposure to excessive O_3 can cause breathing problems, trigger asthma, and reduce lung function, leading to lung disease. Additionally, breathing air with high concentrations of PM is considered the leading environmental cause of death and disease. Both long-term and short-term exposure to PM are associated with morbidity and mortality from cardiovascular and respiratory diseases (World Health Organization, 2021).

Different modes of transport are associated with specific effects of bad air conditions on health (Alemdar et al., 2021; Kahlmeier et al., 2017), for instance, the private car is recognized as the most polluting mode of transport (Grindlay et al., 2015; Instituto Nacional de Ecología y Cambio Climático, 2020, 2020). Recently, urban policies in large metropolises have promoted active transportation modes through investments in infrastructure, in particular, for improvements for pedestrians, cyclists, and users of mass transport systems. However, active modes, such as walking, cycling, and accessing public transport stations or bus stops, involve a physical effort (Mageau-Béland & Morency, 2021; Morency et al., 2011). Thus, the activity involved for these modes requires more inhalation and, consequently, users are more sensitive to air quality (Adams et al., 2016; Peng et al., 2021). The integration of public and nonmotorized transport networks in cities, as well as the reduction of the use of private cars, will contribute to minimizing the health risks to pedestrians, cyclists, and mass public transport users and promote sustainable cities (Balderas Torres et al., 2021).

This study proposes a novel methodology to estimate the exposure of users of active modes to air pollution. It also seeks to give information to these users on healthier threshold hours for walking or cycling. This new methodology involves addressing the relationship between two objects of study, i.e., the users of active modes and air quality, assessing the spatiotemporal concurrence of both objects with the statistical analysis of large open-access databases, to support healthy and sustainable urban mobility. This study carried out an empirical analysis in the Guadalajara metropolitan area (GMA), Mexico.

This metropolis is one of the most polluted in the country and in Latin America (Jalisco, 2019). Moreover, the city is susceptible to pollution impacts, since nonmotorized and public transport journeys predominate in the city’s modal split by

40% and 37%, respectively. This suggests that at least two-thirds of the population, the active mode users, may be vulnerable to poor air quality conditions.

This fact shows the importance of cross-temporal and spatial studies to identify the pollution impacts on city inhabitants. This is also recognized in existing literature (Achebak et al., 2021; Alemdar et al., 2021; Bhat et al., 2021; De Jesus et al., 2020; Iglesias-Merchan et al., 2021; Jia et al., 2021; Shogrkhodaei et al., 2021; Sullivan & Pryor, 2014; N. Xia et al., 2021). Despite studies in Europe (Alemdar et al., 2021; Cheng et al., 2021; Lejda et al., 2017; Qazi et al., 2021), there is a lack of analysis of large databases of temporal exposure to air pollution concerning active mode users in Latin American metropolises.

A great number of users were expected to be exposed due to the historical poor air quality episodes in the city and the high number of active mode users. Nevertheless, the results showed that this number was smaller than initially assumed. Even though the relative figures were low, the absolute number of users exposed should prompt the adoption of public policies to protect them, such as the reduction of automobile dependency and the promotion of active transportation modes in the city, benefiting the entire population.

This article is structured as follows. The study area is defined in Section 2, with a focus on the air quality monitoring system's areas of influence, the bicycle share system, and the bus rapid transit (BRT) system. The materials and methods are presented in Section 3, followed by the results in Section 4. The discussion and conclusions are included in Sections 4 and 5, respectively

Study area

The study area was defined by the overlap between the active mode stations where data were available and the area of influence of the air quality monitoring stations (AQSs) of the Jalisco Atmospheric Monitoring System (SIMAJ, from its initials in Spanish) in the GMA.

The Guadalajara Metropolitan Area: Geographical and mobility context

The GMA is the capital of the Jalisco province. It is an urban area of 5.2 million inhabitants in western Mexico (INEGI, 2020a), comprising nine municipalities: Guadalajara, Zapopan, San Pedro Tlaquepaque, Tonalá, El Salto, Tlajomulco de Zúñiga, Juanacatlán, Ixtlahuacán de los Membrillos, and Zapotlanejo. As shown in **Figure 10**, the city is surrounded by mountains to the northwest, west, and southeast. The prevailing wind circulates west-southwest, combined with a “chimney effect” caused by north-northeast winds (Secretaría del Medio Ambiente y Desarrollo Territorial, 2014), increasing the pollutant concentrations in the south-southeast sector of the city.

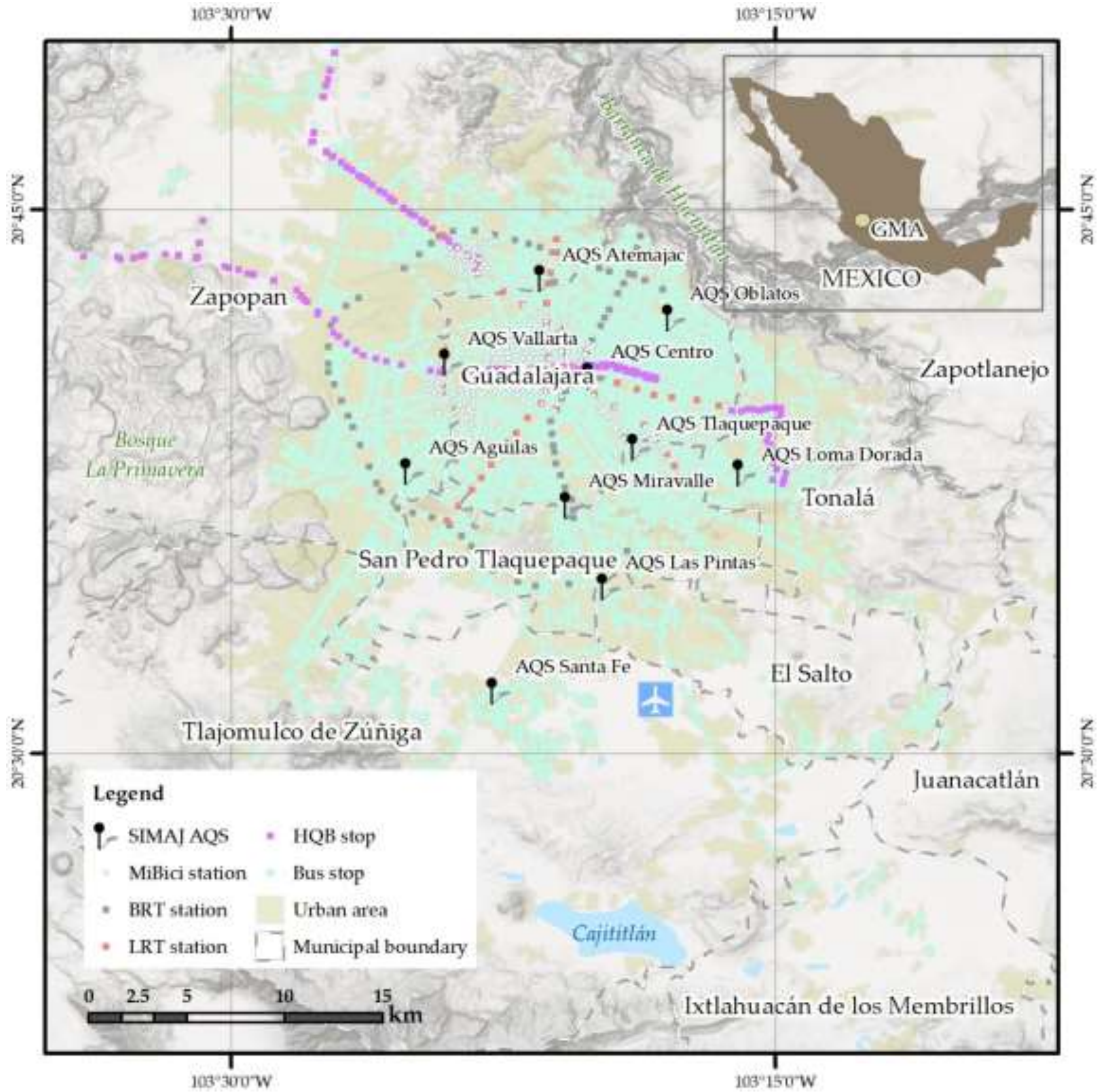

Figure 10. Air quality monitoring stations and active modes stations in the Guadalajara Metropolitan Area, Mexico

The Figure shows air quality monitoring stations (AQSs) of the Jalisco Atmospheric Monitoring System (SIMAJ, from its initials in Spanish) and their area of influence (AI), the stations of the bicycle share system (MiBici), conventional bus stops, and stations of the Urban Electric Train System (SITEUR, from its initials in Spanish), i.e., light rail transit (LRT), bus rapid transit (BRT), and high-quality buses (HQB). Source: authors based on (IMEPLAN, 2018, 2020; INEGI, 2014, 2015a, 2015b, 2020b).

The metropolitan area has a semiwarm climate, with some heat island episodes. There are temperature inversions in the city on 78% of the days of the year, mainly between November and June. This phenomenon favors the formation of O_3 and makes it difficult for volatile compounds such as PM_{10} to disperse. However, the situation improves in the rainy season (June–August) as the pollutants, mainly the PM_{10}, suspended in the atmosphere precipitate (Secretaría del Medio Ambiente y Desarrollo Territorial, 2014).

Air quality is a growing concern in the GMA. Quantifying and monitoring air pollution is the first step to reduce exposure to air pollution (World Health Organization, 2021). The local government monitors the air quality through the SIMAJ (Secretaría del Medio Ambiente y Desarrollo Territorial, 2021) and offers real-time air pollution measurements. **Figure 10** shows the ten fixed AQSs. The AQSs measure the concentration of five pollutants (CO, PM_{10}, O_3, SO_2, NO_2) as well as meteorological variables (ambient temperature, relative humidity, and wind speed and direction). The data are used as the input for the announcement of environmental alerts in the city

Figure 10 shows the heterogenous spatial pattern of the AQSs that partially assess the ambient pollution in the metropolis. Juanacatlán, Ixtlahuacán de los Membrillos, Tlajomulco de Zúñiga, and Zapotlanejo are mostly outside the SIMAJ's area of influence, while El Salto, Tonalá, Tlaquepaque, and Zapopan are only partly inside this area. Only the Guadalajara municipality has acceptable coverage by the SIMAJ.

According to the National Institute of Ecology and Climate Change (Mexico) (2020), in 2019, the number of days on which the maximum recommended thresholds were exceeded, in at least one parameter, for any pollutant in the GMA was 267 days. This is 6% more than the number registered in 2018 and represents two thirds of the year with excessive levels of air pollution. The figures in **Table 5**

Ambient pollutants in the Guadalajara Metropolitan Area in 2019 reveal that PM_{10} and O_3 are the pollutants that most frequently exceed the standards. Given these figures, this study focused on PM_{10} and O_3 as the pollutants to be analyzed.

Table 5

Ambient pollutants in the Guadalajara Metropolitan Area in 2019

Pollutant	Assessment	Unit	Value	Standard [NOM-Mexico]	Number of days above standard
O_3	8 hours	ppm	0.146	0.070	39.50%
PM_{10}	24 hours	$\mu g/m^3$	261	75	41.10%
CO	8 hours	ppm	3.6	11	N/A
NO_2	1 hour	ppm	0.203	0.210	N/A
SO_2	8 hours	ppm	0.013	0.2	N/A

N/A: Non-applicable; ppm = parts per million.

Source: authors, based on (Instituto Nacional de Ecología y Cambio Climático, 2020).

Private vehicles are recognized as the main source of ambient air pollution in cities (Landrigan, 2017), and the GMA is no exception (De Quevedo García Najar et al., 2017; Zuk et al., 2007). Between 1980 and 2010, the low-density urban development paradigm in the city increased individual motorized trips by more than 942% (Jalisco, 2019).

Mass transport systems are recognized as a solution for sustainable transport development (Lejda et al., 2017) and a catalyst for better air quality, despite the negative impacts during their construction (Qazi et al., 2021). Nevertheless, their contribution to the GMA modal share is very limited. According to the Jalisco State Government (2019), 37% of the trips in the GMA are made on foot, 3% by bicycle, 37% by public transportation, and 23% by private vehicles. The mass transport systems barely contribute, with only 3% of the modal share. It is recognized that commuting on foot and by bicycle can significantly reduce urban pollutant emissions

(Chen et al., 2021; Rojas-Rueda, 2021). According to the National Institute of Statistics and Geography (INEGI, from its initials in Spanish) (2020a), 25% of dwellings in the GMA have a bicycle as a potential means of transportation. This figure contrasts with the contribution of cycling to the modal split in the city (ITDP, Institute for Transportation and Development Policy. Mexico et al., 2021).

Historically, cars have been favored in the GMA with large infrastructure investments. Recently, the government, motivated by community associations and academic institutions, has promoted a sustainable mobility paradigm, particularly through active modes, e.g., improvements to the network of bike lanes, the expansion of the bicycle share system (known as MiBici), as well as the enhancement of the Urban Electric Train System (SITEUR, from its initials in Spanish).

MiBici is the public bicycle share system in the city, established in 2014 and recognized as one of the best bicycle share systems in the country in 2019 (ITDP, Institute for Transportation and Development Policy. Mexico et al., 2020). The system serves more than 86,000 cyclists through 3200 bicycles and 300 stations (Gobierno del Estado de Jalisco, s. f.) Balderas et al. (Balderas Torres et al., 2021) state that one of the main reasons users choose MiBici is the low cost compared with other transportation modes. The Ciclocities Ranking 2019 (2020) states that the local governments of Guadalajara, Zapopan, and Tlaquepaque have enhanced the cycling infrastructure by deploying public specialists in mobility and by giving it priority in planning bodies.

Figure 10 shows that the spatial distribution of MiBici is located mainly in Guadalajara, to a certain extent in Zapopan, and very little in Tlaquepaque. This network is nonexistent in the rest of the GMA municipalities. Cycling represents around 2% of the total modal split in the GMA (2021). The peak hours of use of the MiBici system are 8:00 a.m. and 6:00 p.m. According to Jalisco Cómo Vamos (2020), MiBici registered an average of more than 2.8 million annual cycling trips in the period 2014–2020. The same source reports that the kilometers of bicycle lanes increased five-fold between 2015 and 2020, totaling 182 km. The highest number of trips since the operation began was in 2019, with 4,660,470 trips taken by more than 27 thousand users, with an average travel time of 12:32 min (Gobierno del Estado de Jalisco, s. f.). The heterogeneous spatial distribution of MiBici shows a west–east pattern limited to the core of the city (**Figure 1**).

The SITEUR has operated since 1989. The public carrier serves more than 98.5 million passengers a year through 121 stations, i.e., 3.23% of the total modal split in the city, mainly with LRT and BRT (Jalisco, 2019). This study counted the BRT Line 1 passengers, due to the data availability when this research was conducted. The BRT Line 1, known as Mi Macro Calzada, is 16.6 km long with 27 stations, and has been in operation since 2009. It accounts for 30.3% of SITEUR trips. The main line plus the 15 feeding lines served 44.2 million passengers in 2020, (SITEUR, 2020a) with a five-minute frequency (morning peak hour) (SITEUR, s. f.). As shown in **Figure 10**, the BRT is north–south oriented and only serves the Guadalajara municipality up to the Tlaquepaque boundary.

The Jalisco Atmospheric Monitoring System's area of influence

The study area was determined by the SIMAJ's coverage and the data availability on an hourly basis. The spatial distribution of the AQSs does not cover the GMA's entire urban footprint, as shown in **Figure 10**. Moreover, according to the SIMAJ (Secretaría del Medio Ambiente y Desarrollo Territorial, 2018), the AQSs have a two-kilometer area of influence, for which real-time hourly measurements for PM_{10} concentrations in micrograms per cubic meter and O_3 in parts per million are recorded; these concentrations are used to calculate their related AQIs

The spatial concurrence between the AQSs' areas of influence and the active modes of transport stops/stations was identified through a geographic information system (ArcGis Pro, ESRI®). The calculations included 10 AQSs, 287 bike share stations, 9073 conventional bus stops, 77 BRT stations, and 48 light rail transit stations (IMEPLAN, 2018, 2020).

Air quality monitoring data affecting most of the active mode users were not available. **Figure 11** highlights the narrow coverage of the AQSs with respect to the active mode stops/stations. Thirty-seven percent of the MiBici stations, 28% of the conventional bus stops, 44% of the BRT stations, 22% of the high-quality bus stops, and 38% of the light rail train stations were outside the area of influence of the AQSs in the city. Only 107 of the MiBici stations were included in the area of influence of four AQSs: Atemajac, Centro, Tlaquepaque, and Vallarta. Similarly, only twelve BRT stations were considered for this study, as they fell inside of the AQSs' areas of influence. Specifically, the BRT stations located within the area of influence of the Centro AQS were Ciencias de la Salud (10), Juan Álvarez (11), Alameda (12), San Juan de Dios (13), Bicentenario (14), La Paz (15), and Niños Héroes (16). The stations in the area of influence of the Miravalle AQS were López de Legazpi (23), Clemente Orozco (24), Artes Plásticas (25), Esculturas (26), and Fray Angélico (27).

Unfortunately, no data for the conventional and high-quality buses or the light rail trains were available on an hourly basis. Thus, due to the SIMAJ's spatial pattern, together with the data availability, five AQSs, 107 MiBici stations, and 12 BRT stations were considered for the computations.

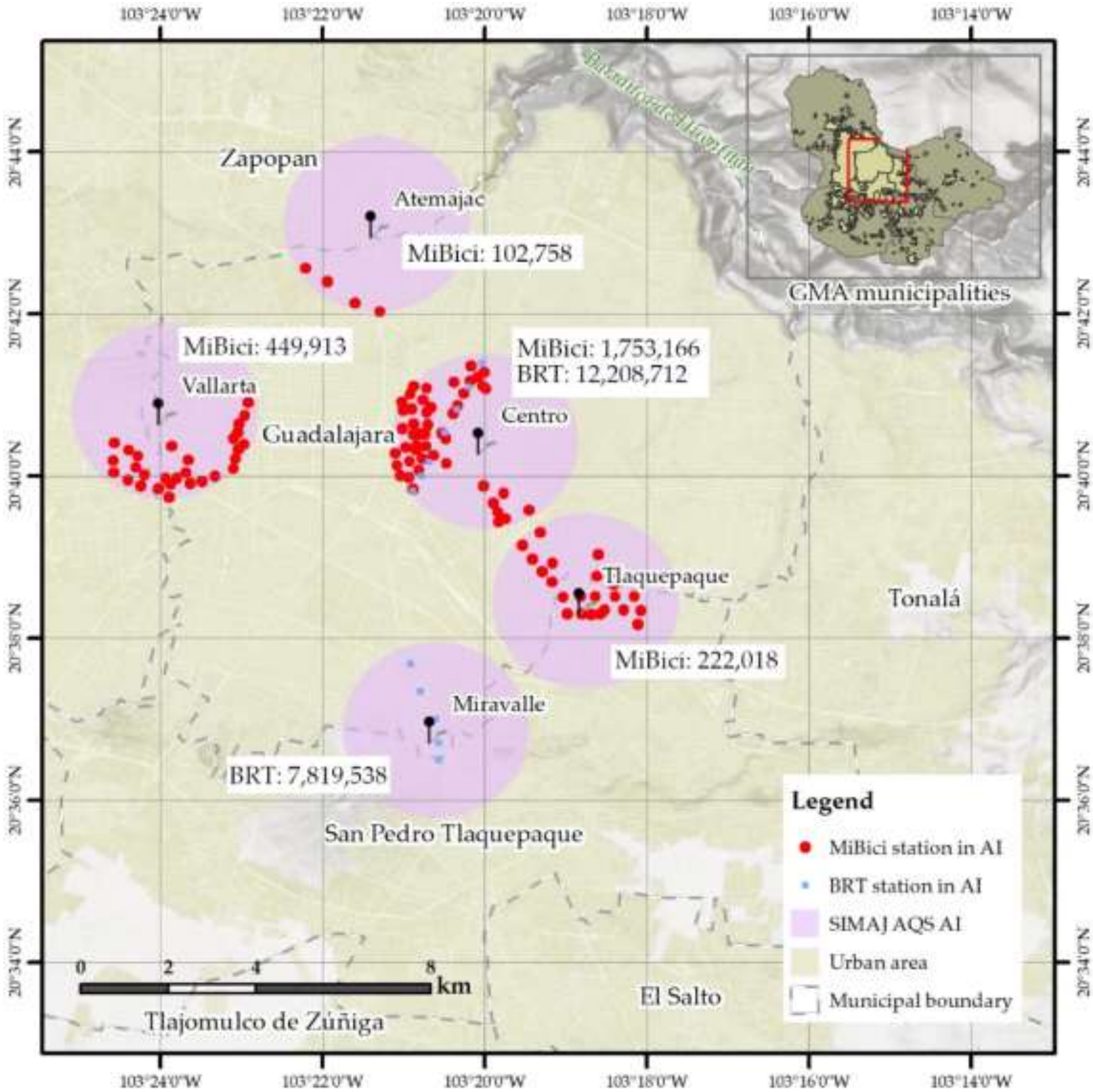

Figure 11. Study area

The figure shows the area of influence (AI) of the air quality monitoring stations (AQSs) managed by the Jalisco Atmospheric Monitoring System (SIMAJ, from its initials in Spanish). The map highlights the active mode stations considered in the study, i.e., 107 stations of the MiBici bicycle share system and 12 bus rapid transit (BRT) stations. Source: authors based on (IMEPLAN, 2018, 2020; INEGI, 2014, 2015a, 2015b, 2020b).

Data sources and methods

The WHO states that using large yearly databases allows outcomes to be refined, taking into account seasonal variations (Kahlmeier et al., 2017). The analysis assessed data from the selected stations in 2019. This year was chosen as the reference year to prevent misrepresentation due to changes in travel behaviors caused by the COVID-19 pandemic in 2020 and 2021. An hourly time scale was selected due to the O_3 and PM_{10} temporal behavior, and data availability. This study benefited from open data availability for all AQSs (Secretaría del Medio Ambiente y Desarrollo Territorial, 2018), particularly for O_3 and PM_{10}.

Nonmotorized modes and public transport account for 77% of trips in the city (Jalisco, 2019). Disappointingly, no data on pedestrian trips were available, nor trips made by privately owned bicycles. The MiBici open data system (Gobierno del Estado de Jalisco, 2021) was accessed to obtain the total trip registers to or from any of its anchoring stations for 2019. The SITEUR reported the number of passengers entering the BRT stations hourly (SITEUR, 2021b). No data for light rail trains were available at the required accuracy.

As a consequence of data availability, hereinafter, the term “active mode users” refers to trips via MiBici and pedestrians accessing BRT stations in the areas of influence of AQSs. **Table 6**

Sources of data on air quality monitoring and active transportation modes in the Guadalajara metropolitan area in 2019 shows data sources and recording frequency for each kind of station computed in this study, i.e., AQS, MiBici, and BRT.

Table 6

Sources of data on air quality monitoring and active transportation modes in the Guadalajara metropolitan area in 2019

Station	Data	Temporal Basis *	Number of Records	Source
Air quality	O_3 and PM_{10} concentration	Hour	87,600	Ministry of the Environment and Territorial Development (Semadet, Jalisco, Mexico) SIMAJ (Secretaría del Medio Ambiente y Desarrollo Territorial, 2018, 2021)
Active transportation mode	Bicycle in–out anchors	Minute	2,388,884	Government of the State of Jalisco, Mexico: MiBici (Gobierno del Estado de Jalisco, 2021)
	Passengers coming into the BRT station	Hour	105,120	Urban Electric Train System, Guadalajara (SITEUR, 2021b)

* For the year 2019.

A statistical spatiotemporal approach was used. The year 2019 was chosen as the most recent year without potential changes to travel behaviors due to the COVID-19 pandemic (Jalisco, 2019). **Figure 12** shows the conceptual model used to identify the number of active mode users exposed to poor air quality episodes in the reference year. First, the active mode database was organized to identify the number of active mode users in the AQSs' areas of influence, on an hourly basis. Then, the number of episodes per hour in each AQS area was assessed using the air quality index (Environmental Protection Agency, 2021). Finally, the concurrence between pollutants and users of active transportation modes was assessed.

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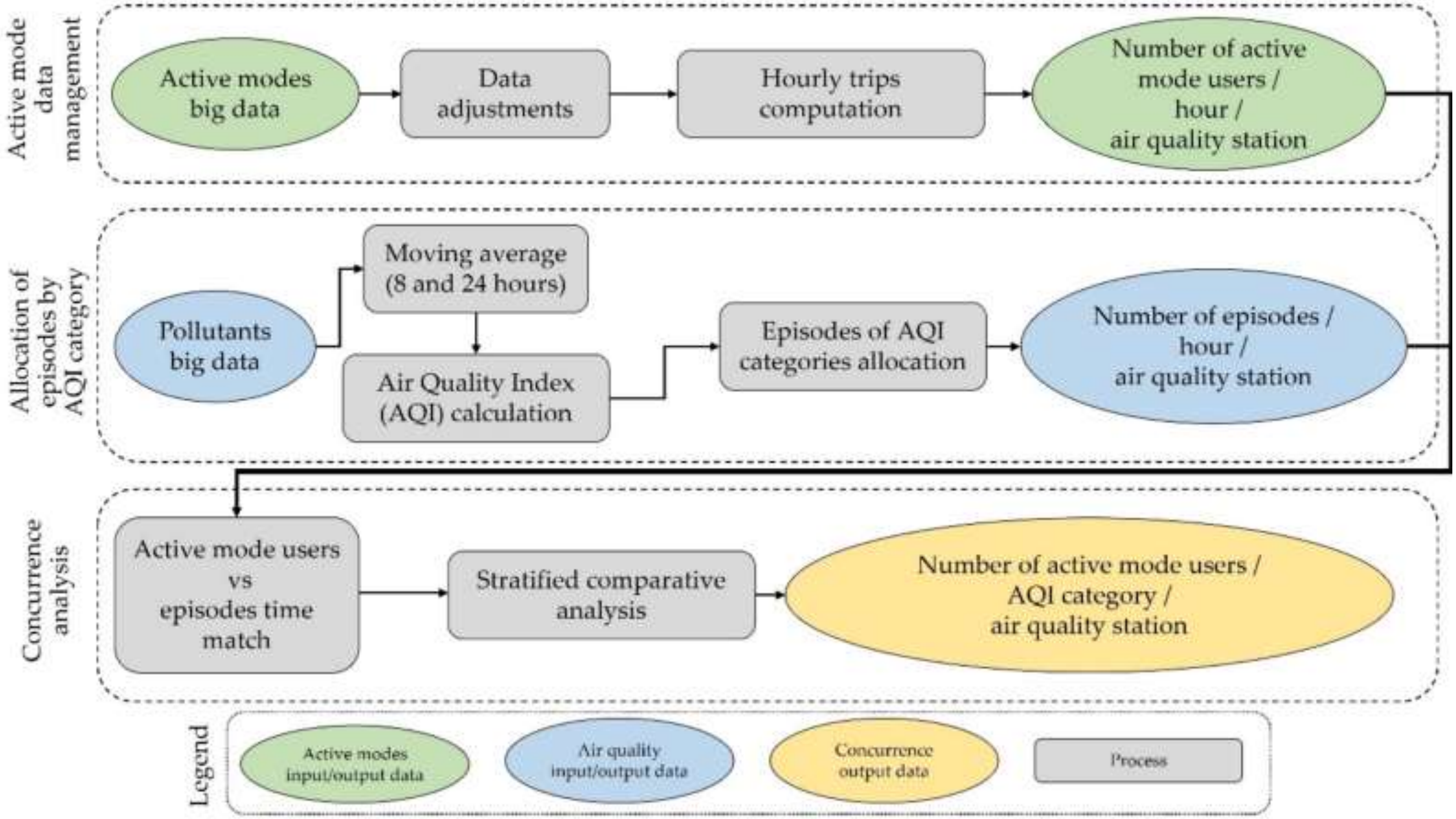


Figure 12. Conceptual model

Active modes analyzed were bicycle share system and bus rapid transit (BRT). Pollutants computed were ozone (O3) and particulate matter (PM10). Air quality index (AQI) refers to the Environmental Protection Agency index (2021). The word “users” refers to both bicycle trips and BRT passengers.

Active mode data management

Data from the 107 MiBici stations were used to calculate the number of trips per hour linked to each AQS. The data were managed using Python programming language and Pandas, among other libraries. The following assumptions were made to compute bicycle trips and create a database that would be compatible with AQS data. First, one hour was added to the temporal data. Second, bicycle trips traveling at least one minute inside the AQS's area of influence were quantified as one trip in the corresponding hour. Third, the cyclists were exposed to air quality episodes both when starting and ending the trip at the station, and thus counted twice. However, if a cyclist started and finished the trip at stations linked to the same AQS, it was counted as only one trip.

The SITEUR also provided hourly data on people accessing the 12 selected BRT stations. There were no data for passengers leaving the stations; these results were underestimated, since BRT users were only counted as passengers accessing the BRT and not as pedestrians after their transit journey.

Allocation of episodes by AQI category

AQI was assessed to allocate a category of O_3 and PM_{10} pollution in the five AQSs studied. The AQI was designed by the EPA (Environmental Protection Agency, 2016b), and calculations were performed using the MATLAB programming language.

First, moving averages of pollutant concentrations were calculated for 8 and 24 h time windows, for O_3 and PM_{10}, respectively. The AQI was calculated by substituting the moving averages directly in

Equation 5. Next, the AQI was classified according to the established categories described in the introduction (Section 1). Finally, the number of episodes in AQI categories 3, 4, and 5 were linked to AQSs for each hour of the year; these three categories correspond to poor air quality episodes.

Equation 5

Air Quality Index

$$AQI = [(AQI_{Hi} - AQI_{Lo})/(Conc_{Hi} - Conc_{Lo})] \times (Conc_i - conc_{Lo}) + (AQI_{Lo}) \qquad (5)$$

where

$Conc_i$ = Input concentrations for a given pollutant

$Conc_{Lo}$ = The concentration breakpoint that is less than or equal to $Conc_i$

$Conc_{Hi}$ = The concentration breakpoint that is greater than or equal to $Conc_i$

AQI_{Lo} = The AQI value/breakpoint corresponding to $Conc_{Lo}$

AQI_{Hi} = The AQI value/breakpoint corresponding to $Conc_{Hi}$

Concurrence analysis

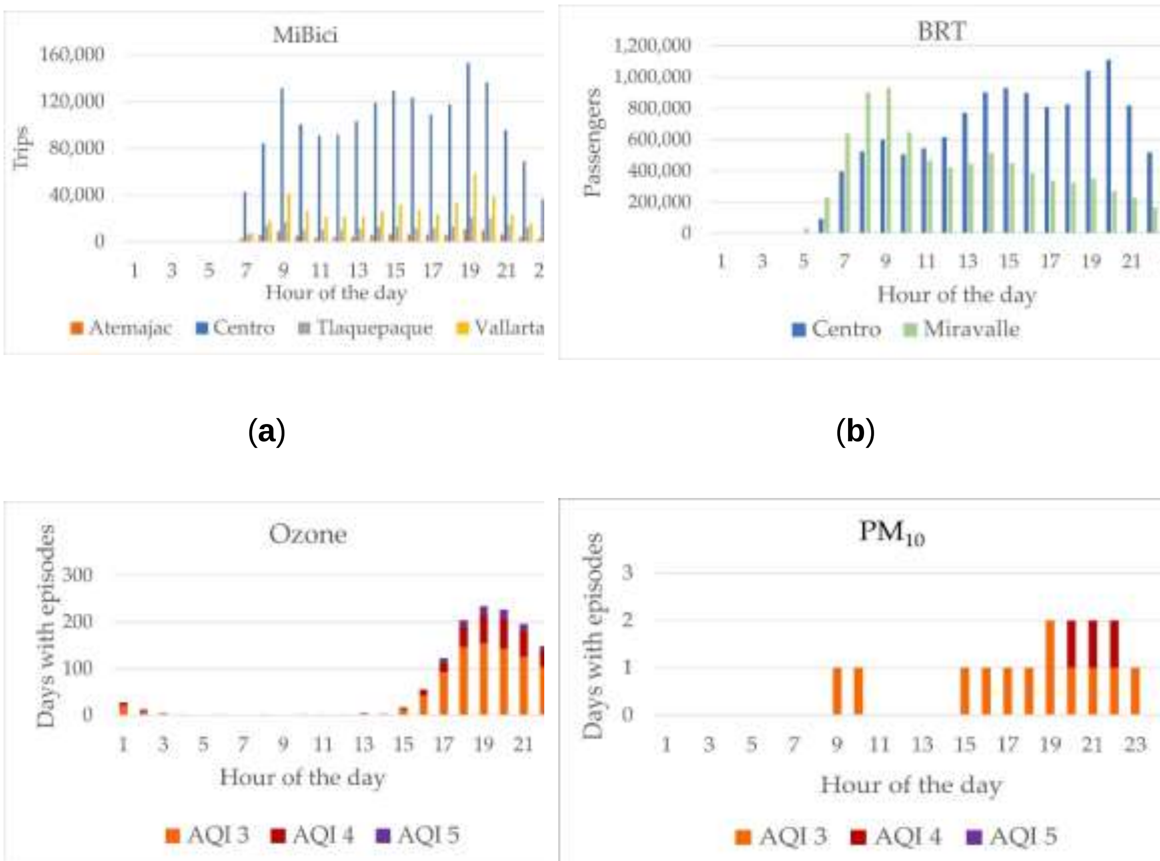
The concurrence analysis implied stratified computations of two inputs: first, for the number of MiBici trips and BRT passengers per hour in the five AQSs' areas of influence; then, for the number of poor air quality episodes falling into categories 3, 4, or 5. It was assumed that the entire study area had the same compensation to calculate exposure to pollutants. The concurrence analysis was computed with dynamic tables on a spreadsheet (Excel, MSOffice®), associating spatiotemporal correspondence. As a result, the number of active mode users exposed to category 3, 4, or 5 episodes was estimated, both for O_3 and PM_{10}.

Results

Active mode data management

As expected, the number of passengers who walked to access the 12 mass transport BRT stations was higher than the number of trips logged at the 104 MiBici stations, that is, 20,028,250 and 2,388,884, respectively. **Figure 13** displays the number of annual active mode users studied on an hourly basis. **Figure 13a** shows that most of the MiBici trips were in the area of influence of the Centro AQS. All stations registered two peak hours, i.e., 9:00 and 19:00. At 9:00, there were 131,608, 17,005, and 41,602 trips in the area of influence of AQS Centro, Tlaquepaque, and Vallarta, respectively. These figures increased at 19:00 in the same areas of influence, that is, 153,314, 21,062, and 58,179 trips, respectively This was concurrent with the standard working hours in the city. In addition, the trips linked to the Centro station also showed a peak hour at 14:00 (lunch time), i.e., 129,274 trips

The spatial pattern of the BRT passengers was similar, although the stations that contributed to the peak hours were clearly distinguished. **Figure 13b** shows the three peak hours at the BRT stations in the area of influence of the Centro and Miravalle AQSs, that is, between 8:00 and 9:00, between 14:00 and 15:00, and between 19:00 and 20:00. Of the 20 million passengers using these stations, 60% were in the area of influence of the Centro AQS and 40% in that of the Miravalle station, i.e., 12,208,712 and 7,819,538, respectively. Moreover, it was shown that 1,832,788 passengers walked to reach BRT stations in the vicinity of the Miravalle AQS between 8:00 and 9:00, and 2,152,791 passengers accessed BRT stations around the Centro AQS between 19:00 and 20:00. This can be explained by the fact that the former AQS serves a mostly residential area, while the latter serves areas with a high density of workplaces, particularly retail trade and public services.



(**a**) (**b**)

(**c**) (d)

Figure 13. Active mode users and poor ozone (O_3) or particulate matter (PM_{10}) episodes in the study area on an hourly basis

The order of magnitude between figures must be considered to properly compare them. (**a**,**b)** refer to the annual number of MiBici trips and Bus Rapid Transit (BRT) passengers, respectively. (**c**, **d**) show the number of days with episodes within the worst air quality index (AQI) categories for O_3 and PM_{10}, respectively.

Allocation of episodes by AQI category

The AQI calculations emphasized categories three, four, and five. According to the EPA, categories four and five strongly affected users in active modes. No consensus was found regarding the impact of category three episodes on active mode users.

Even though the Environmental Protection Agency does not explicitly include cyclists as a sensitive group, some organizations promote the use of face masks for cyclists riding within areas in AQI category three. Thus, this category was computed to account for cyclists' exposure to pollutants

For the studied area, only the Tlaquepaque AQS recorded PM_{10} data in 2019. Thus, the PM_{10} results are not included in this section, since the calculations were not representative of the phenomenon in the study area. However, it is important to note that in the south-southeastern AQSs of the city (Santa Fe, Las Pintas, and Tonalá), more high-PM_{10}-concentration episodes are usually recorded but there were no available records of users of active modes of transport for their areas of influence. **Figure 13c** shows the temporal pattern of the AQI on an hourly basis. The results showed that the worst O_3 concentrations were between 17:00 and 23:00, as expected for O_3 behavior. The worst air quality episodes, adding the three AQI categories together, were recorded at 19:00 on 227 days. **Table 7** shows the total number of episodes in the three AQI categories and the percentage of episodes accounted for by the five SIMAJ stations in the study area with respect to the entire GMA. PM_{10} was not representative of the phenomenon, due to the scarce data assessed, and hence was dismissed.

Table 7

Days with poor air quality episodes in 2019 on an hourly basis

Pollutant	AQI 3[1]		AQI 4[1]		AQI 5[1]	
	[episodes[2]]	[% [3]]	[epipsodes[2]]	[% [3]]	[episodes[2]]	[% [3]]
O_3	993	55.19	342	52.31	96	59.26
PM_{10}	1	7.14	3	100	0	0

[1] Air quality index (AQI) category according to EPA; [2] number of episodes in the corresponding AQI category, on an hourly basis in 2019.

Concurrence analysis

Few MiBici and BRT users within the study area were exposed to O_3 and PM_{10} episodes in categories three, four or five of the AQI during 2019, that is, less than 1.48% and 0.87%, respectively. **Table 8** shows the spatiotemporal match between the pollutant episodes and the active mode users. The difference between the two modes in the order of magnitude of the figures is explained by the modes' attributes: MiBici is unipersonal and BRT is mass transport.

Table 8

Active transportation users exposed to O3 and PM10 in the study area

		MiBici		BRT		MBici + BRT	
Total users	AQI[1]	2,388,884		20,028,250		22,417,134	
O_3	3	28,469	1.19%	145,468	0.73%	173,937	0.78%
	4	6,467	0.27%	27,761	0.14%	34,228	0.15%
	5	43	0.00%	18	0.00%	61	0.00%
	Total	*34,979*	*1*.48%	*173,247*	0.87%	*208,226*	0.93%
PM_{10}	3	431	0.02%	0	0.00%	431	0.00%
	4	69	0.00%	0	0.00%	69	0.00%
	5	0	0.00%	0	0.00%	0	0.00%
	Total	*500*	0.02%	*0*	0.00%	*500*	0.00%
O_3 + PM_{10}	All categories	35,479	1.50%	173,247	0.87%	208,726	0.93%

[1] Air quality index (AQI) category according to EPA.

The results show that only 0.24% and 0.14% of MiBici and BRT users in the study area were exposed to unhealthy or very unhealthy levels of concern, i.e., categories four and five. However, the figures become relevant when analyzed in absolute terms. More than 200,000 active users were exposed; this is almost 35,000 and

173,000 MiBici and BRT users, respectively. Only 22 cyclists were riding and 18 pedestrians were accessing BRT stations while category five O_3 episodes occurred, and this occurred only in the area of influence of the Miravalle AQS, as shown in **Figure 14**. Nevertheless, more than 30,000 active mode users were exposed to category four O_3 episodes.

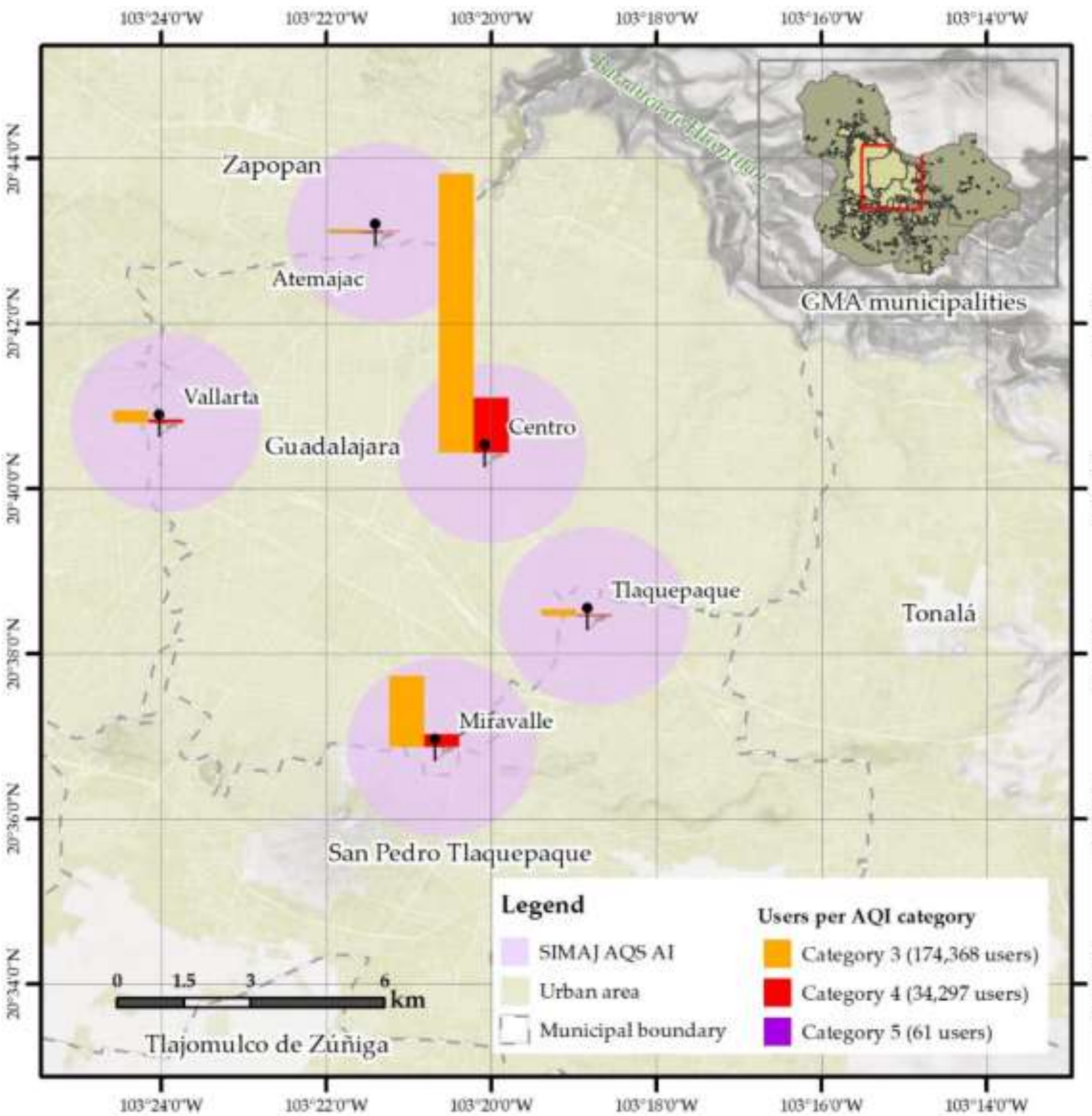


Figure 14. Spatiotemporal concurrence of air quality episodes and active mode users in 2019.

Figures summarize ozone (O_3) and particulate matter (PM_{10}). Source: authors based on (IMEPLAN, 2018, 2020; INEGI, 2014, 2015a, 2015b, 2020b).

Although these figures are modest in the context of the metropolitan area's overall trips, it should be considered that, in this study, active transportation modes only served a small fraction of the urban area in the metropolis, due to the limited area of influence of the AQSs in the city (**Figure 14**).

More than two hundred thousand active users were exposed to O_3. In contrast, the exposure to PM_{10} affected fewer than 500 passengers, due to the lack of data for this pollutant in most of the AQSs. According to the daily temporal pattern, most of the exposure occurred in the afternoon. Fewer than 10% of the total users were exposed to pollutant episodes in categories three, four, or five.

Discussion

According to the novel methodology proposed, the data availability determined the estimation of the exposure of active mode users to air pollution. In the case of the GMA, the spatial and temporal data accuracy of active modes and air quality was limited. On the one hand, MiBici data were accessible and well structured. Thus, the spatiotemporal data precision allowed deep analyses of this active mode. In contrast, no data on pedestrian flows were available at all. Additionally, regardless of the great potential of data analysis from smart cards already proved in other cities (Pelletier et al., 2011), neither bus nor light rail train data were available at the required accuracy. Only data on passengers accessing BRT stations were obtained on an hourly basis. All these active modes data limitations led to an underestimation of the real situation

On the other hand, the gaps in the air quality data were a consequence of the heterogeneous spatial distribution, the small number of AQSs, and their temporal lack of operation (Jalisco, 2019). First, the spatial distribution and the 2 km area of influence of the AQSs resulted in the assessment of only 18.63% of the GMA urban fabric. This spatial restriction dismissed most of the MiBici and BRT stations. Second, PM_{10} was assessed only by the Tlaquepaque AQS; thus, the results of this pollutant were underestimated.

Despite the data availability limitations in the GMA, the results allowed the trends of the mobility and the temporal exposure of cyclist and BRT users to air pollution to be successfully identified. Concerning the mobility patterns, two tendencies were identified. First, the BRT stations located in residential areas were largely used in the morning, while the downtown stations were predominantly used at lunchtime and in the evenings. The trips are generated by the concentration of economic activity (INEGI, 2019a). This trend confirms other studies' results showing that cycling and BRT trips are mainly used for commuting to work (Rosas Gutiérrez et al., 2020). Second, results showed that active mobility was concentrated around the central AQSs, confirming that a high centrality in cities promotes mobility concentration in the downtown area where the main economic activity is concentrated (D. A. Hensher et al., 2015), as in other metropolises in Latin America (Mora et al., 2021; Rosas-Satizábal et al., 2020).

The results for the temporal exposure of cyclists and BRT users to air pollution showed that users traveling in the evenings, i.e., from 18:00 to 21:00, were more exposed to air pollution than users travelling at other hours of the day, similar to other empirical cases in Latin America (Beleño Montagut & Colegial Gutierrez, 2018; Pinzón & Arias, 2013).

Conclusion

The link between air quality and active transportation modes assessed in this study is recognized locally and worldwide (Alemdar et al., 2021; Lejda et al., 2017). When using active transportation mode systems, such as MiBici and SITEUR, people perform physical activity, contributing to their health (Rojas-Rueda, 2021, p.). However, cyclists, pedestrians, and transit users are susceptible to traffic injuries (P. Xu et al., 2019; X. Xu et al., 2016) and environmental pollution (Y. Sun & Mobasheri, 2017). This research focused on the latter.

The study estimated the exposure of active mode users to air pollution and identified the healthier threshold hours for walking or cycling in the GMA. It is extremely important to protect pedestrians, cyclists, and passengers of public transport from ambient pollution in a context such as the GMA, where more than 70% of trips are made on foot or by nonmotorized vehicles, buses, or mass transport systems.

The number of exposed users was small, since the results revealed that 208,660 users of MiBici or BRT, i.e., less than 10%, were exposed to the worst categories of the AQI in the study area, mainly within category three. Furthermore, according to the results, cyclists and pedestrians may reduce their exposure to poor air quality episodes when traveling before 18:00 and after 21:00.

The 13th Sustainable Development Goal (SDG) seeks to bring down the levels of atmospheric pollution by shifting from private motorized modes to active transportation (Shogrkhodaei et al., 2021; United Nations (UN), 2015). The proposed methodology can be applied in other metropolitan areas to provide key information for sustainable mobility and air quality contingency plans in the context of this SDG (Figueredo et al., 2018).

The empirical application of the methodology led to three general suggestions for cities seeking to reach SDGs. First, spatiotemporal data of active mode users should be recorded and made available as open-access data, according to worldwide trends (Glaeser et al., 2015; «The Promise of Open-Source Intelligence», 2021). Next, air quality monitoring systems should properly assess the air quality in the metropolis. Finally, urban planning, mobility, and environmental and public health policies should be coordinated and should fully adopt the current urban sustainability paradigm (Landrigan, 2017; Ochoa-Covarrubias, Molero-Melgarejo, et al., 2021).

The results did not apply to the whole metropolitan area due to methodological and data deficiencies: the limited area of air quality monitoring due to the spatial distribution of the AQSs; the lack of active mode users' data; the underestimated calculations as a consequence of the gaps in the PM_{10} data; and the lack of data from pedestrians, conventional buses, and light rail train users. Despite the limitations in the data availability for the study area, this methodology can be replicated in other urban areas to support decision making in the generation of public policies for the benefit of active mode users and to promote safe and healthy active mode trips, thus contributing to sustainable mobility in cities.

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6. (In)equitable Accessibility to Sustainable Transport from Universities in the Guadalajara Metropolitan Area, Mexico

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(In)Equitable Accessibility to Sustainable Transport from Universities in the Guadalajara Metropolitan Area, Mexico

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Abstract: The equitable accessibility to higher education favours social fairness in economic opportunities. This paper provides an empirical approach to the assessment of the (in)equity of accessibility from universities to sustainable transport modes: Light Rail Transit, Bus Rapid Transit, buses, and bicycle infrastructure in the Guadalajara Metropolitan Area (Mexico). In particular, the study designed and calculated an Access to Sustainable Transport from University Index by combining governmental and crowdsourced Open Access Data. It used spatial analysis techniques within a Geographic Information Systems environment, and multivariate statistical methods such as Principal Component Analysis and Cluster Analysis. The findings highlight the weakness in the accessibility to sustainable transport modes from the universities in the Metropolitan Area. Furthermore, this study revealed an unfavourable bias in the location of sustainable transport stations/stops in the vicinity of public universities. The results provide a methodology and empirical evidence for transport policy makers to reduce inequalities and therefore transport-related social exclusion in this under-represented, but socially relevant, student community.

Keywords: accessibility; social exclusion; university; inequity; sustainable transport; principal component analysis; geographic information system; crowdsourcing; open access data

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1. Introduction

Equitable accessibility to university facilities (UFs) guarantees social fairness in economic opportunities [1]. Students suffer transport-related social exclusion when transport services are non-existent or severely restricted [2] due, for example, to the distance to reach them [3] or the limited multi-modal transport options [4]. According to Litman [5], equity refers to the fairness with which benefits are distributed. The spatial equity of accessibility is the provision of consistent access throughout a geographic space. Since Wachs and Kumagai [6], up to the present day, the equity of accessibility has been a subject of research interest [7–10] and, more recently, public policies [11].

The literature concerning accessibility is extensive [7,8,12–18], along with empirical reviews worldwide [19–25] and in Latin America [26–39]. Nevertheless, there is no consensus on the definition of accessibility [15,40], mainly due to its relationship to the multidimensionality of transport equity. In this study, accessibility was defined as the possibility to reach a station/stop (henceforth 'node') of a sustainable transport mode from UFs. Three elements are included in this definition, i.e., the number of destinations around the UFs; the ease to reach them by walking or cycling within a walking-time threshold; and the quality of each node, as defined by the number of routes and bicycle lanes.

Access to sustainable transport mode (STM) infrastructure from universities is fundamental in order to reduce the social exclusion of students in the current era of the sustainable mobility paradigm [41]. The promotion of STMs in the vicinity of UFs, e.g.,

Abstract

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infrastructure in the Guadalajara Metropolitan Area (Mexico). In particular, the study designed and calculated an Access to Sustainable Transport from University Index by combining governmental and crowdsourced open-access Data. It used spatial analysis techniques within a Geographic Information Systems environment, and multivariate statistical methods such as Principal Component Analysis and Cluster Analysis. The findings highlight the weakness in the accessibility to sustainable transport modes from the universities in the Metropolitan Area. Furthermore, this study revealed an unfavourable bias in the location of sustainable transport stations/stops in the vicinity of public universities. The results provide a methodology and empirical evidence for transport policy makers to reduce inequalities and therefore transport-related social exclusion in this under-represented, but socially relevant, student community.

Keywords

Accessibility; social exclusion; university; inequity; sustainable transport; principal

component analysis; geographic information system; crowdsourcing; open-access data

Introduction

Equitable accessibility to university facilities (UFs) guarantees social fairness in economic opportunities (Astakhova et al., 2016). Students suffer transport-related social exclusion when the transport service is non-existent or severely restricted (Kelobonye et al., 2019) due, for example, to the distance to reach it (J. Xia et al.,

2016) or the limited multi-modal transport options (Guthrie et al., 2019). According to Litman (2002) equity refers to the fairness with which benefits are distributed. Spatial equity of accessibility is the provision of consistent access throughout a geographic space. Since Wachs and Kumagai (1973) up to the present day, the equity of accessibility has been a subject of research interest (Kenyon, 2002; Kenyon et al., 2002; Litman, 2012; Lucas, 2019) and, more recently, public policies (SEU, 2003).

The literature concerning accessibility is extensive (Bertolini et al., 2005; Cervero, 1997; Guthrie, 2018; Handy, 2020; Kamruzzaman et al., 2016; Kenyon, 2002; Kenyon et al., 2002; Schwanen et al., 2015; Talavera-Garcia & Valenzuela-Montes, 2018), along with empirical reviews worldwide (Cheng et al., 2020; Ermagun & Tilahun, 2020; Gutiérrez-Puebla et al., 2002; Guzman et al., 2017; Lamíquiz Daudén, 2011; Pritchard et al., 2019; Stępniak et al., 2019) and in Latin America (Bocarejo S. & Oviedo H., 2012; Calonge Reillo & Aceves Arce, 2019; Esquivel-Cuevas et al., 2013; Grindlay et al., 2018; Guzman & Oviedo, 2018; Jaramillo et al., 2012; Lizárraga, 2012; S. Medina & Patlán, 2016; Montoya-Robledo & Escovar-Alvarez, 2020; Pereira, 2019; Shirahige & Correa, 2015; Terán-Hernández, 2017; UN-Habitat & Jalisco, 2017; Vecchio, Tiznado-Aitken, et al., 2020). Nevertheless, there is no consensus on the definition of accessibility (Cohen, 2020; Handy, 2020) mainly due to its relationship to the multidimensionality of transport equity. In this study, accessibility was defined as the possibility to reach a station/stop (henceforth node) of sustainable transport modes from UFs. Three elements are included in this definition, i.e., the number of destinations around UFs; the ease to reach them by walking or cycling within a walking time threshold; and the quality of each node, as defined by the number of routes and bicycle lanes.

Access to sustainable transport mode infrastructure (STM) from universities is fundamental to reduce the social exclusion of students in the current era of the sustainable mobility paradigm (Vuchic, 2017). The promotion of STMs in the vicinity of UFs, e.g., Light Rail Transit (LRT), Bus Rapid Transit (BRT), buses and bicycle infrastructure, greatly benefits not only the students, but the city as a whole (UEA, 2012). First, students need STMs to commute to UFs, due to limited incomes and transport choices (Allen & Farber, 2018; Jalisco, 2020a). Second, the promotion of STMs contributes to shifting the future travel behaviour of current students (Cattaneo et al., 2018). Third, the sustainable mobility paradigm promotes more equity and liveable cities (Oviedo & Guzman, 2020; UEA, 2012; Vecchio, Porreca, et al., 2020; Vuchic, 2017).

The sharing mobility paradigm, e.g., park and ride (P&R) systems or bike-sharing systems (BSS), are growing worldwide as a solution for sustainable mobility in cities as a complete system. Macioszek and Kurek (2020) and Ibrahim et at. (2020) analysed the use of P&R in Cracow (Poland) and Putrajaya (Malaysia), respectively, as an option for improvement of accessibility to STM. In Warsaw (Poland), the BSS is an element enhancing sustainable mobility (Macioszek et al., 2020). Politis et al. (2020) studied the willingness to shift to BSS in Thessaloniki (Greece). They found that BSS promotes sustainability since they are an active mode of transport. Moreover, in the current COVID-19 pandemic, BSS is a safe mobility option (Nikiforiadis et al., 2020). In accordance with these global trends, the individual transport systems, e.g., assisted bicycles, segways and scooters, have been integrated to the public policies in the GMA and they must operate in the city under the principles of accessibility, equity and security (Criterios para la Prueba Piloto relativa a la Implementacion de los Sistemas de Transporte Individual en Red en sus diferentes modalidades para el Área Metropolitana de Guadalajara, s. f.; Criterios para la prueba piloto relativos a la implementación del sistema de bicicletas sin anclaje en el Área Metropolitana de Guadalajara, s. f.).University students' transport-related inequities have been studied in developed countries (Allen & Farber, 2018; Cattaneo et al., 2018; Hancock & Nuttman, 2014; Lien et al., 2020; Miralles-Guasch & Domene, 2010; Nash & Mitra, 2019; Pitsiava-Latinopoulou et al., 2013; Ricciardi et al., 2015; Soltani et al., 2019; Stein & Grigg, 2019; Whannell et al., 2012). Some authors have tackled the conceptual frame (Guthrie, 2018; Kamruzzaman et al., 2016; Kenyon et al., 2002, 2002; Litman, 2002; Schwanen et al., 2015; Wachs & Kumagai, 1973), while others have improved the concepts through empirical studies worldwide (Cui et al., 2019; Guthrie et al., 2019; Hine & Mitchell, 2016; Kathuria et al., 2019; Özkazanç & Özdemir Sönmez, 2017; Ricciardi et al., 2015) and in Latin America (E. J. Miller, 2018; Pereira, 2019). Little scholarly research was found to be published regarding this subject in developing countries (Ansarey, 2016; Centro Mario Molina, 2016; Franco Cordero, 2014; C. Sun et al., 2018), andvery little scientific evidence was found with regard to the (in)equity of accessibility to sustainable transport means from UFs in Latin American cities. In particular, few quantitative studies have explored university students' travel needs in the Guadalajara Metropolitan Area (GMA) (García-Morales, 2020) where the urban transport system clearly generates social inequities (Calonge Reillo, 2017c) in one of the largest metropolitan areas in Latin America (UN-Habitat, 2012).

The aim of this empirical study was to measure inequity of accessibility to sustainable transport as an indicator of student transport-related social exclusion in the GMA. An Access to Sustainable Transport from University Index (ASTUI) was calculated by measuring the access, in the vicinity of UFs, to ST nodes, i.e., LRT, BRT and bicycle-sharing stations, as well as high-quality and conventional bus stops. The ST nodes were weighted by means of Principal Component Analysis. Thus, the ASTUI included the two main aspects of the broader concept of accessibility, i.e. walking/cycling distance, and the number of nodes and their quality, in terms of the quantification of the number of routes at each node.

This study provides methodological and empirical contributions. On the one hand, the methodology included advanced spatial and statistical analyses using crowdsourced open-access Data, i.e., data which was produced and reviewed by the community. On the other hand, it also contributes to the understanding of mobility in the GMA. The findings highlight the weakness in accessibility to sustainable transport from the universities in the metropolitan area. Furthermore, this study reveals an unfavorable bias in the location of sustainable transport stations / stops in the vicinity of public universities.

This paper includes five sections. After this introduction, Section Two describes the state of the art, the study area, the methodology and data for calculations of the (in)equity of spatial accessibility from UFs to STMs. Section Three presents findings of horizontal and vertical (in)equity by means of maps and charts. Next, Section Four includes discussions. Finally, Section Five provides conclusions, implications and recommendations for further research.

Materials and Methods

Study area

The Guadalajara Metropolitan Area (GMA), the capital of the state of Jalisco -one of 32 states of the Mexican Republic-, has 4.5 million inhabitants spread over 3,365 square kilometres (IMEPLAN, s. f.) (**Figure 15**). The GMA is served by a multimodal transport system network. In accordance with international trends, sustainable transport means are promoted by university authorities as a way to reduce environmental impacts to cities (Franco Cordero, 2014). Thus, the modes of transport considered in this study were the LRT, the BRT, high-quality buses, conventional buses and bicycles. According to SEDATU (2018), Jalisco is among the states with the highest federal and local public investment in sustainable mobility projects, particularly in public transport (PT) and bicycle lanes.

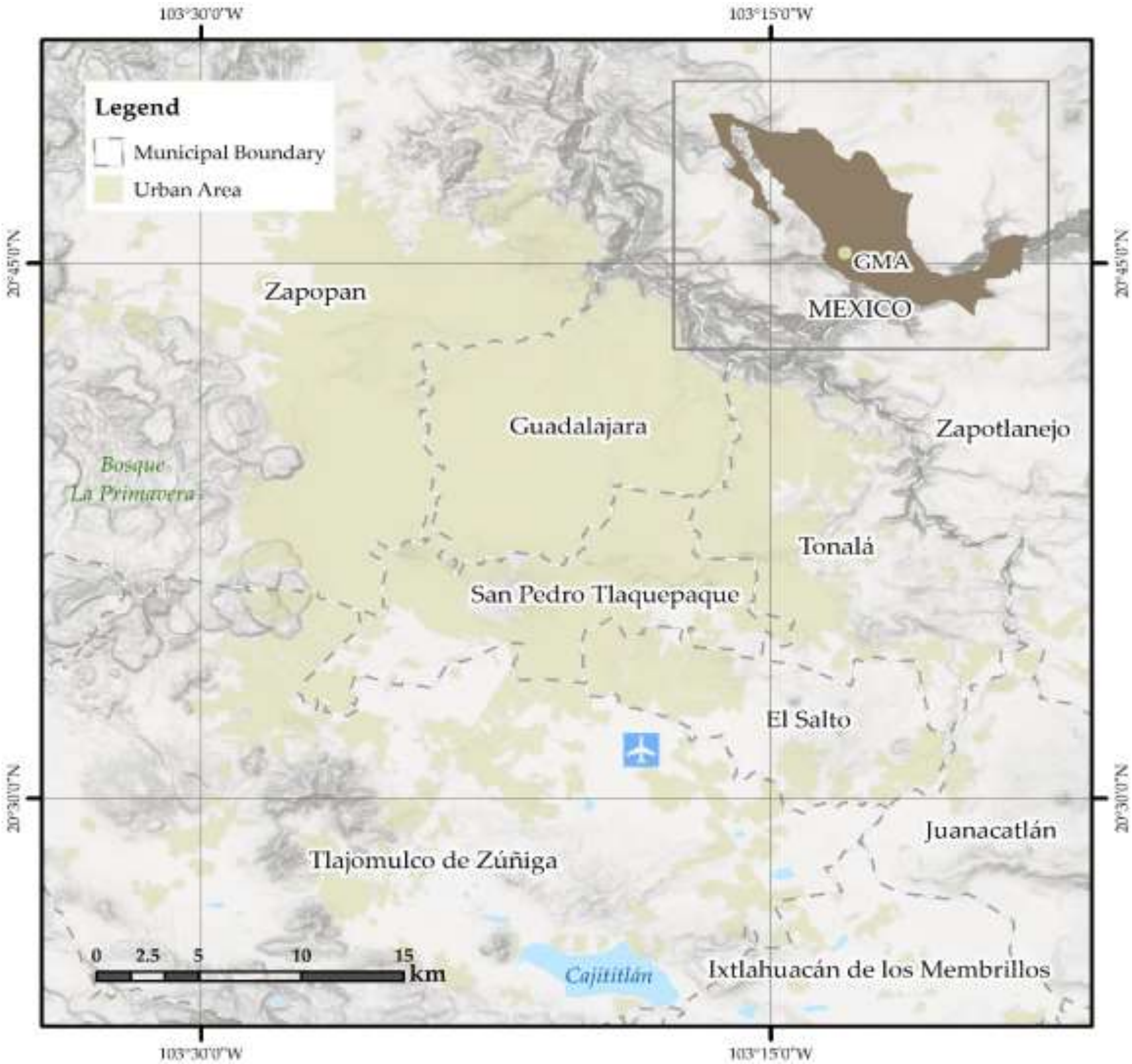

Figure 15. The Guadalajara Metropolitan Area (GMA)

Source: Authors based on (INEGI, 2014, 2015a, 2015b, 2019b)

Figures **Figure 16**,**Figure** 17 and **Figure** 18 illustrate STM in the GMA. First, the mass transport system known as SITEUR consists of three LRT lines, one BRT line —a second BRT line is currently under construction—, known as *Tren Ligero* and *Macrobús*, respectively. Second, high-quality buses, known as *Sitren,* and conventional buses serve the city with 255 routes. Third, the bicycle-sharing system, known as *MiBici*, encompasses 287 docking stations and a 194-km bicycle lane network. The outer suburbs are also served by other private on-demand transport modes that are beyond the scope of this study.

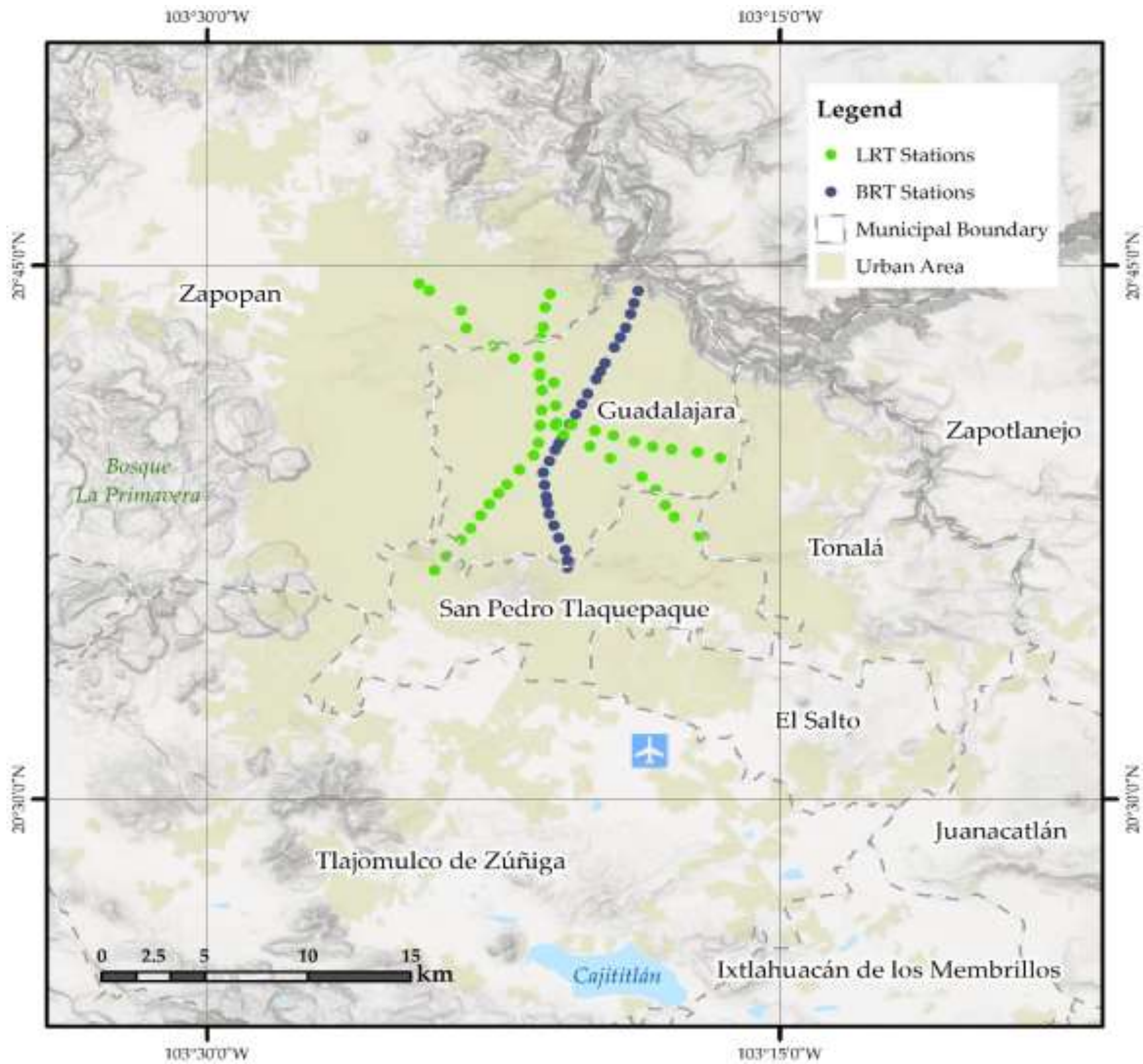

Figure 16. Mass Transport System in the Guadalajara Metropolitan Area (GMA).

Source: Authors based on (INEGI, 2014, 2015a, 2015b, 2019b; SITEUR, 2021a)

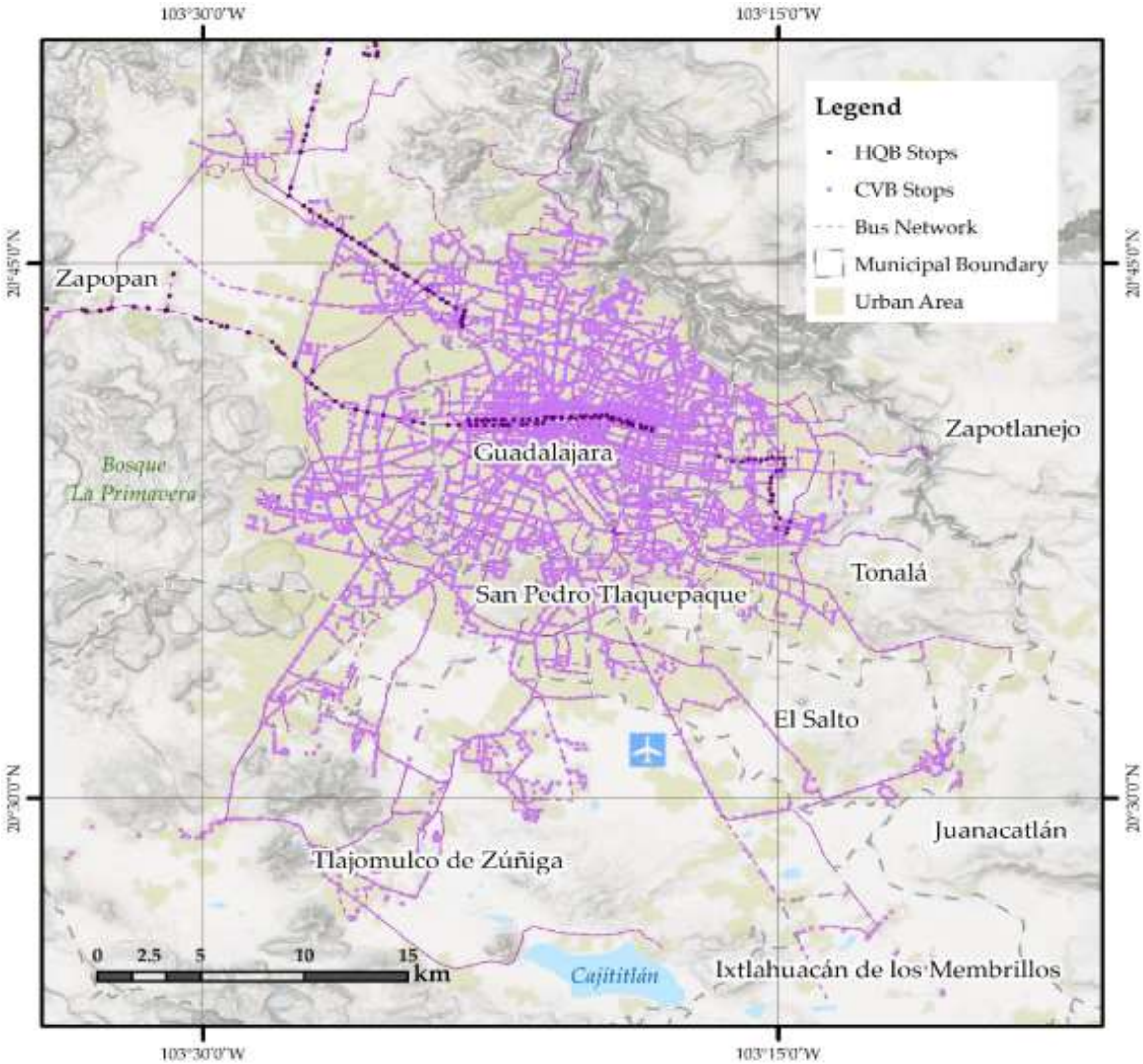

Figure 17. High-quality and conventional bus network in the Guadalajara Metropolitan Area (GMA)

Source: Authors based on (IMEPLAN, 2018; INEGI, 2014, 2015a, 2015b, 2019b; SITEUR, 2021a)

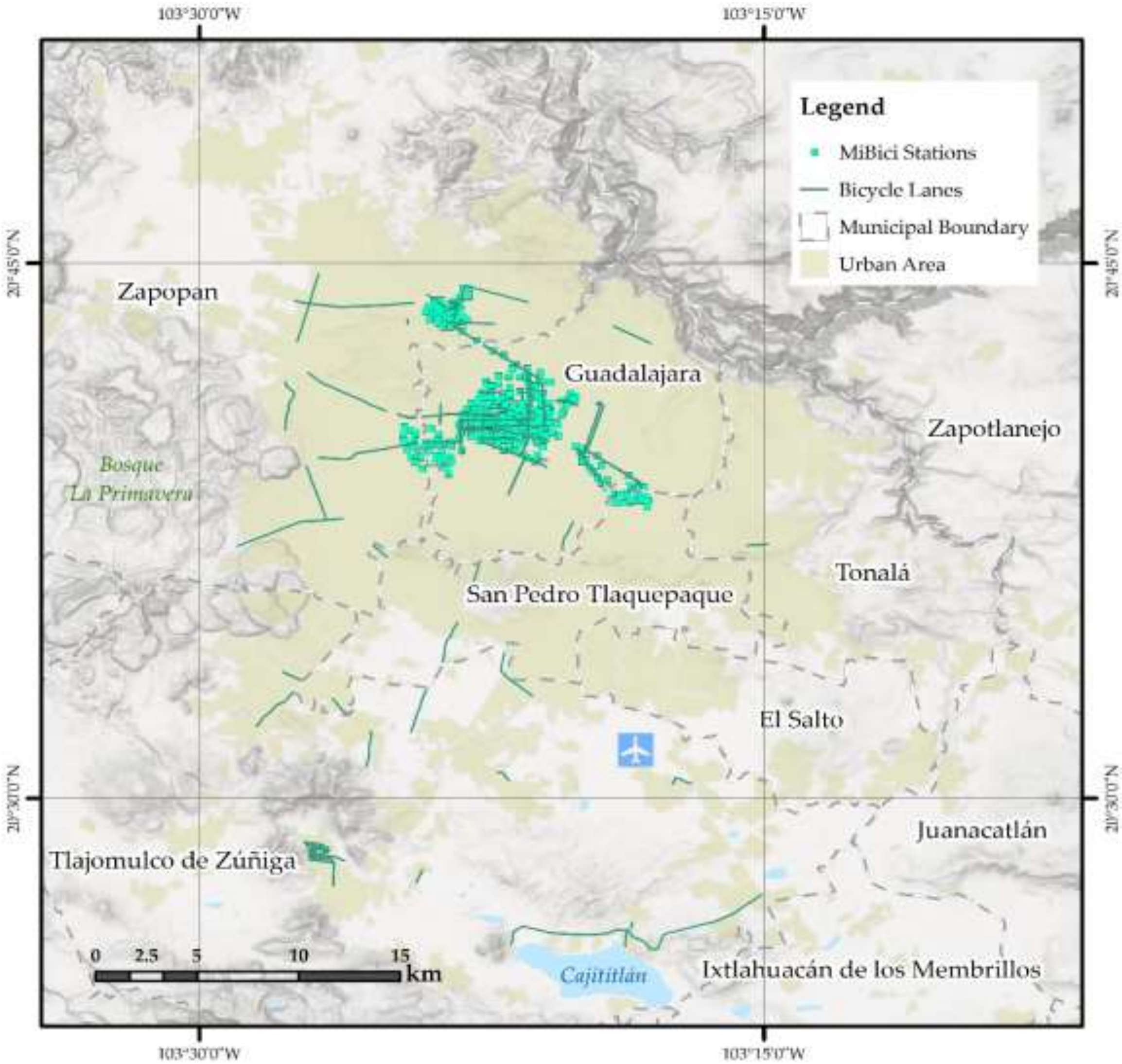

Figure 18. Bicycle system network in the Guadalajara Metropolitan Area (GMA)

Source: Authors based on (IMEPLAN, 2020; INEGI, 2014, 2015a, 2015b, 2019b)

In contrast with students' transport modal split in North American universities (Franco Cordero, 2014), students in other regions have to rely on public transport or bicycle for their commute to universities (C. Sun et al., 2018). Few modal split studies of university students in the GMA were found. In accordance with the Jalisco Government (2018), 20.5% of PT users in the GMA are students, but only 8.9% use PT for school commuting there. Most students walk between 1 and 15 minutes to reach their destination. Many students use their bicycles to complement their trips.

Half of the students suggest improvements to schedules and frequency. García-Morales (2020) studied a sample of three universities with respect to their modal split. The author states that the modal split varies from one university to another, depending mainly on the accessibility to public transport and bicycle lanes in the vicinity of the facility, as well as on the type of administration, i.e. public or private organisation.

There are different sources regarding university statistics. According to INEGI (2019a), there are 274 UFs in the GMA (**Figure 19**). Only 26% of them are publicly financed, even though public and private universities serve 163,678 and 86,738 students, respectively (SEP, 2020). Both public and private universities provide service to students with financial difficulties and most of the private universities have scholarship programmes for underprivileged students, e.g. ITESO, where almost half of the students receive financial aid. As shown in **Figure 19**, though the UFs are distributed in the central municipalities of the GMA, there is a concentration of public UFs in the central area and private ones are located mainly in the municipalities of Guadalajara and Zapopan. The mid-south of the city is served by only a few public UFs and the south, east and north of the GMA have few UFs.

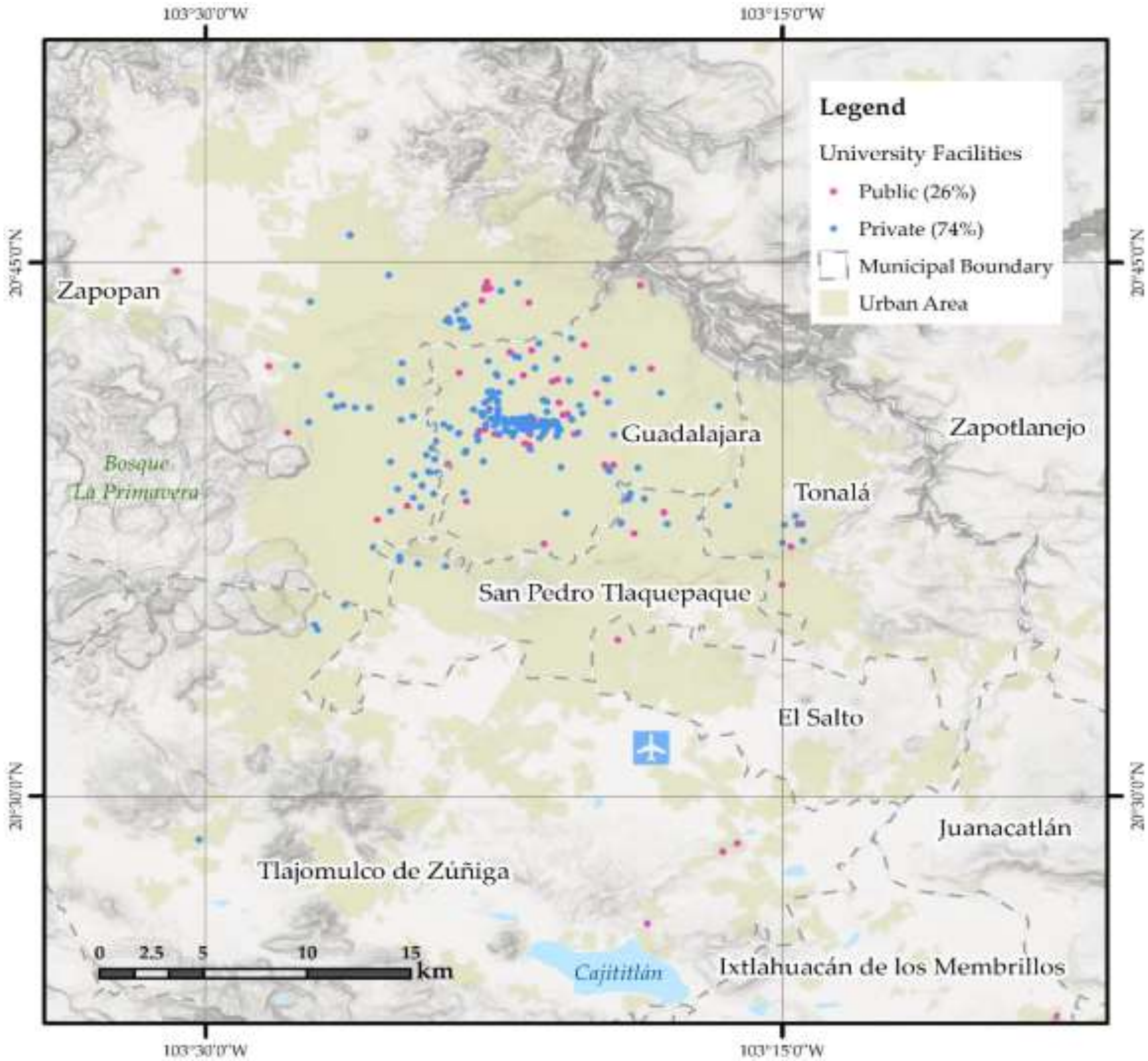

Figure 19. University facilities (UFs) in the Guadalajara Metropolitan Area (GMA)

Source: Authors based on (INEGI, 2014, 2015a, 2015b, 2019a, 2019b).

Methodology

Transport-related (in)equity is usually measured by means of accessibility (J. Xia et al., 2016). Several methods for accessibility assessment were identified in the literature to date. Most of the authors refer to four approaches, i.e., proximity-based (Litman, 2002; UEA, 2012), also referred to as cumulative-based (Handy & Niemier, 1997; Pereira, 2019); gravity-based; user-based; and space-time approaches (Kelobonye et al., 2019). In addition, Sun et al (2018) refer to “competition-based” assessment at transport nodes. For further discussion of approaches to accessibility measurement, readers are referred to, among others, these authors (Al Mamun & Lownes, 2011; Ben-Elia & Benenson, 2019; Delbosc & Currie, 2011b; Ghorbanzadeh et al., 2020; Handy & Niemier, 1997; Levine, 2020; Litman, 2012; Martinez & Viegas, 2017; E. J. Miller, 2018; Pritchard et al., 2019; Stępniak et al., 2019).

In this study, the nodes, routes and bicycle lanes were counted as STMs. The ASTUI was calculated by the proximity and competition-based methods. These methods not only measure the total transport nodes available in an area within a desirable walking or cycling time (Guthrie et al., 2019; Litman, 2002; UEA, 2012), but also estimate the intensity of opportunities or their attractiveness (Handy, 2020). The more routes there are at a stop, the more attractive it is. Thus, the ASTUI was assessed by calculating the number of sustainable transport nodes, as well as the number of routes or bicycle lanes available in the area of influence of each UF (Litman, 2002; UEA, 2012).

Figure 20 illustrates the conceptual model of the ASTUI. First, the service areas were calculated from the 274 UFs through the street network, which is a better predictor of human behavior than just a Euclidian distance (Yenisetty & Bahadure, 2020). Then the accumulation of nodes and routes for each mode and service area were spatially joined through a ModelBuilder® model within a Geographic Information System. Next, these variables were examinated in a Principal Component Analysis (PCA) from which principal components were proposed, interpreted and selected. This method is used by the National Council for the Evaluation of Social Development Policy (CONEVAL, 2019b). Finally, the ASTUIs were calculated by means of weighted variables from the PCA.

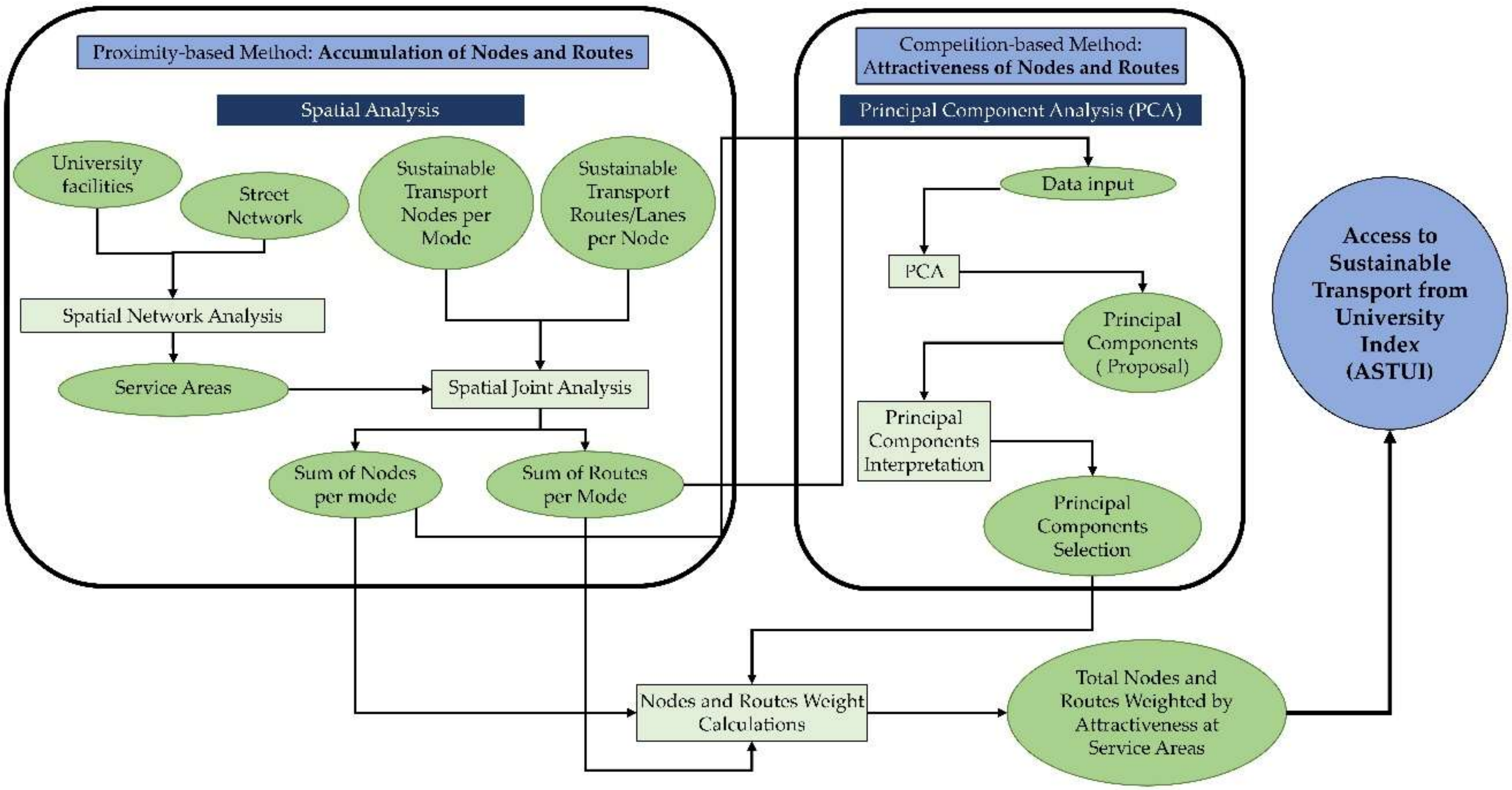

Figure 20. Access to Sustainable Transport from University Index (ASTUI) Conceptual Model

Source: Authors.

The data required for the ASTUI calculation were the street network, the UFs and STM infrastructures. **Table 9**

Data sources lists the data used and the Open Data produced by the government and crowdsourcing. The latter are continually verified by volunteers and improved by peer reviewers. The software used to calculate the ASTUIs was a Geographic Information System (GIS), well recognised as an effective modelling technique to explore accessibility and network distances (O'Sullivan et al., 2000; J. Xia et al., 2016; Yenisetty & Bahadure, 2020), particularly the Network Analyst module of ArcMap Esri®. The StatGraphics® software was employed for the Principal Component Analysis as well as the cluster analysis. First, the service areas and the number of STM infrastructures were computed by means of Network Analysis. Then, the weightings of variables were computed with StatGraphics®. Finally, the inequities were analysed, through clusters.

Table 9

Data sources

Data	Source
Street Network	OpenStreetMap, October 2020 (OpenStreetMap contributors, 2020)
University Facilities	National Statistical Directory of Economic Units (INEGI, 2019a)
Mass Transport* and High-quality Buses	Light Rail System (SITEUR, from its initials in Spanish) (SITEUR, 2020b, 2020a, 2020c)
Conventional Buses	Metropolitan Planning Institute (IMEPLAN, 2018)
Bicycle-sharing Stations and Lanes	Metropolitan Planning Institute (IMEPLAN, 2020)

*Mass Transport data included lines, stations, stops, frequency and vehicle capacity.

The calculation of the ASTUIs required specifying the time threshold that the students are willing to walk or cycle, and the attractiveness of each node and route. Despite the sensitivity and importance of this criterion, there is a lack of consensus on the distance that people are willing to walk to reach public transport in a complex context such as the GMA (Talavera-Garcia & Valenzuela-Montes, 2018). To the authors' best knowledge, there is no standard of accessibility that is broadly accepted and used in urban and transport planning. Since the Transit Oriented Development (TOD) paradigm has already been applied in some areas of the city (ITDP, 2018), this study used the time threshold defined most often by the TOD and already applied in other regions (UEA, 2012). As shown in **Table 10**

Maximum time thresholds by mode of transport, the ASTUIs included the fulfilment of the TOD standard for distance from universities to the STMs, i.e., fifteen minutes walking for mass transport, such as LRT and BRT; five minutes walking for high-quality and conventional buses; and two minutes cycling for *MiBici* stations and cycle lanes.

Table 10

Maximum time thresholds by mode of transport

Sustainable Transport Mode	Sustainable Transport Mode Infrastructure (STM)	Walking or cycling time threshold (Minutes)
LRT *	Station	15
BRT *	Station	15
High-quality Bus *	Stop	5
Conventional Bus	Stops and Routes **	5
Bicycle	Stations and Bicycle Lanes **	2

Source: Authors adapted from (Talavera-Garcia & Valenzuela-Montes, 2018; UEA, 2012).

*SITEUR: Tren Ligero, Macrobús and Sitren. ** The conventional buses and the bicycle sharing stations are the only modes with more than one route/lane at the stations/stops

Figure 21 illustrates the numerical model for the ASTUI calculation. It includes three particularities of the study area. First, given that people are willing to walk up to 5 minutes to reach buses, they would also walk this distance to reach a bicycle-sharing station to complete the journey cycling. Therefore, the *MiBici* stations were counted within this service area. Second, bicycles are allowed on LRT and the high-quality buses, *Sitren*. Consequently, these two types of stations and stops were computed for the service area of 2 minutes cycling. This is not the case for BRT or conventional buses. Third, there is only one route at the LRT, BRT and *Sitren* stations. Thus, the routes for these modes were not counted, in order to avoid biases in the PCA. In contrast, there is usually more than one route at the conventional bus stops and more than one cycle lane at the *MiBici* stations. Thus, routes and cycle lanes were counted for both modes. Based on these particularities, the spatial analysis for service areas and the number of STMs were computed by means of Network Analyst, with the ModelBuilder from Esri®.

The Principal Component Analysis (PCA) describes correlations between the STM infrastructure variables referred to in **Table 11** by creating new components that propose weights of the original variables for the 274 UFs (CONEVAL, 2019b; Delbosc & Currie, 2011b; Harris, 2001; Nwachukwu, 2014; Tahmasbi et al., 2019; Vicente & Reis, 2018). The purpose of the PCA is to obtain a small number of linear combinations of the 12 variables that account for most of the variability in the data. Each component can be interpreted as one part of the accessibility phenomenon. A negative value means that this variable negatively affects accessibility. Three components have been retained, since their eigenvalues were greater than or equal to 1.0, as shown in **Table 12**. Together they account for 72.4925% of the variability in the original data.

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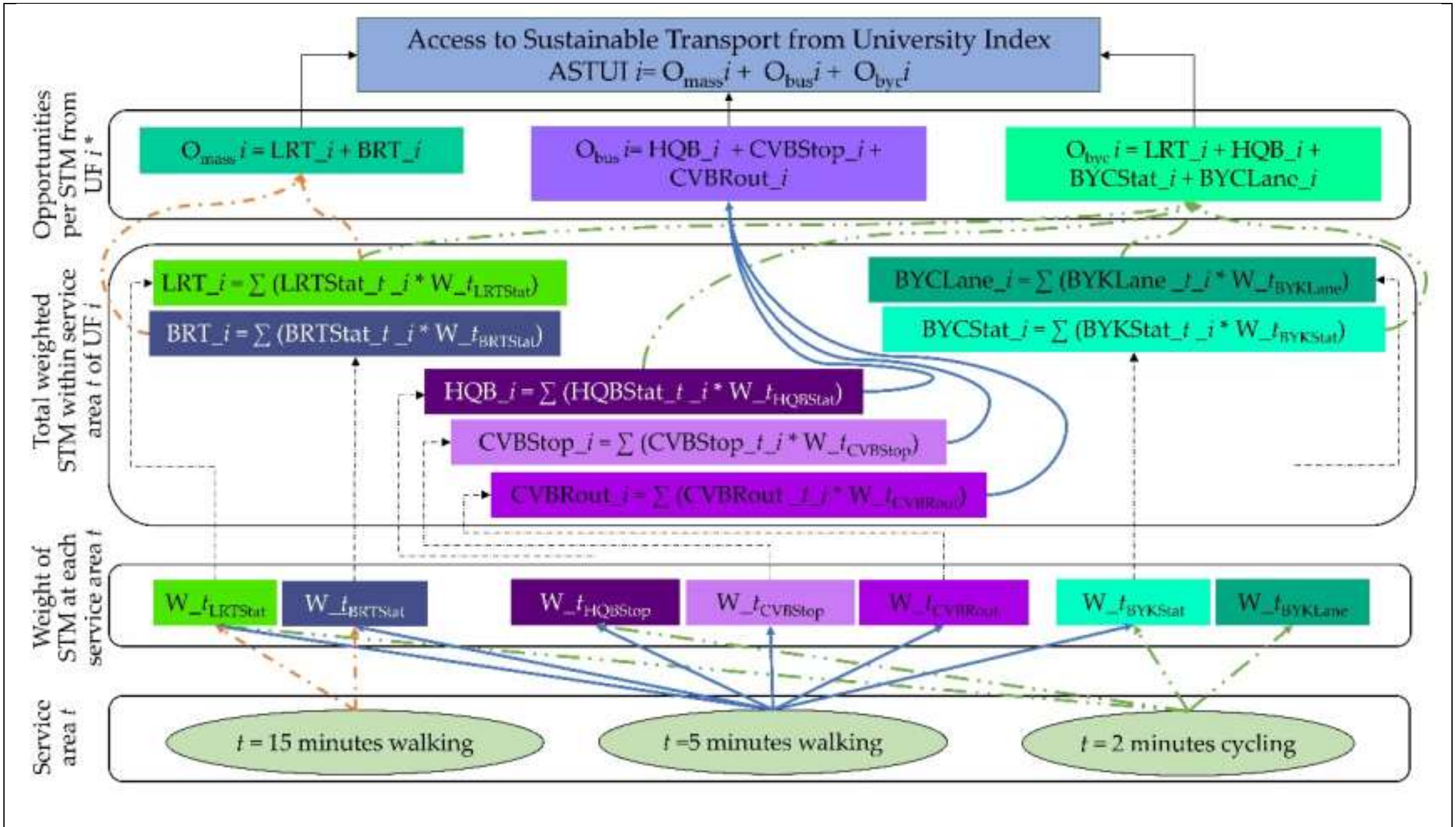

Figure 21. Access to Sustainable Transport from University Index (ASTUI) Numerical Model

Source: Authors.

Table 11

Input variables of the service area and the Principal Component Analysis

STM id [ST_{id}]	Sustainable Transport Mode infrastructures	*t* = 15 [walking minutes]	*t* = 5 [walking minutes]	*t* = 2 [cycling minutes]
A B C	Number of LRT Stations in Service Area *t* (*Tren Ligero*)	F15_LRT	F5_LRT	B2_LRT
D E	Number of BRT Stations in Service Area *t* (*Macrobús*)	F15_BRT	F5_BRT	
F G	Number of High-quality Bus Stops in Service Area *t* (*Sitren*)		F5_HQB	B2_HQB
H	Number of Conventional Bus Stops in Service Area *t*		$F5\_CNB_s$	
I	Number of Conventional Bus Routes in Service Area *t*		$F5\_CNB_r$	
J K	Number of *MiBici* Stations in Service Area *t*		$F5\_ BYK_s$	$B2\_ BYK_s$

Table 11 (Continuation)

STM id [ST_{id}]	Sustainable Transport Mode infrastructures	*t* = 15 [walking minutes]	*t* = 5 [walking minutes]	*t* = 2 [cycling minutes]
L	Number of Bicycle Lanes in Service Area *t*			$B2\_BYK_l$

Source: Authors.

The factorability tests provide an indication of whether or not it is likely to be worthwhile attempting to extract factors from a set of variables. The Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) statistic delivers an indication of how much common variance is present. For factorisation to be worthwhile, KMO should normally be at least 0.6. Since KMO = 0.786828, factorisation is likely to provide meaningful information about any underlying factors.

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Table 12

Principal Component Analysis Components

Component Number	Eigenvalue	Variance [%]	Cumulative Variance [%]
1	5.19051	43.254	43.254
2	2.21364	18.447	61.701
3	1.29495	10.791	72.493
4	0.966089	8.051	80.543
5	0.7064	5.887	86.430
6	0.404834	3.374	89.804
7	0.319993	2.667	92.470
8	0.288061	2.401	94.871
9	0.240288	2.002	96.873
10	0.218669	1.822	98.695
11	0.0839818	0.700	99.395
12	0.072579	0.605	100.000

Source: Authors.

The three retained components were interpreted by the variable weights shown in **Table 13**. They represent the relation between the original variables and the principal components. Component 1, named the ‘Multimodal Transport System,’ represents all modes of transport retained in the study with less importance than the BRT, as the values of its variables are smaller than the other ones. Component 2, named the ‘Mass Transport System’, favours mass modes of transport, i.e., the *Tren Ligero* and the *Macrobús*, and gives negative or Very Low values to modes linked to bicycles and buses, both *Sitren* and conventional. Component 3, named the ‘Bus

Rapid Transit' component, prioritises this mode, and thus it complements Component 1.

Table 13

Component Weights

Component weight ID [id]	Variable	Component_1	Component_2	Component_3
W_A	F15_LRT	0.318819	0.296047	-0.197854
W_B	F5_LRT	0.225533	0.302996	-0.383931
W_C	B2_LRT	0.288487	0.224921	-0.386717
W_D	F15_BRT	*0.135682*	0.443007	0.488484
W_E	F5_BRT	*0.047106*	0.311531	0.576449
W_F	F5_HQB	0.255624	-0.380555	0.174918
W_G	B2_HQB	0.283082	-0.378544	0.155742
W_H	$F5\_CNB_S$	0.352379	0.0976065	0.0679395
W_I	$F5\_CNB_R$	0.329129	0.225656	0.00105742
W_J	$F5\_ BYK_S$	0.361178	-0.140043	0.106823
W_K	$B2\_BYK_S$	0.378923	-0.207403	0.116437
W_L	$B2\_BYK_L$	0.3027	-0.255853	-0.0924796

Source: Authors.

Equation 6 shows an example of the first principal component, where the values of the variables in the equation must be standardised by subtracting their means and dividing by their standard deviations.

Equation 6

Example of the first principal component

$$Component\ 1 = 0.318819 * F15\_LRTStat + 0.225533 * F5\_LRTStat + 0.288487 * B2\_LRTStat + 0.135682 * F15\_BRTStat + 0.047106 * F5\_BRTStat + 0.255624 * F5\_HQBStop + 0.283082 * B2\_HQBStop + \quad (6)$$

$$0.352379 * F5\_CVBStop + 0.329129 * F5\_CVBRout + 0.361178 * F5\_BYKStat + 0.378923 * B2\_BYKStat + 0.3027 * B2\_BYKLane$$

The three components were calculated by means of **Equation 7**.

Equation 7

Components calculation

$$Component\_n = A*WAn + B*WBn + C*WCn + D*WDn + E*WEn + F*WFn + G*WGn + H*WHn + I*WIn + J*WJ\,n + K*WKn + L*WLn \quad (7)$$

where

n = number of components from **Table 12**, i.e., {1, 2, 3}

A to K = the variables listed in **Table 10**, standardised by subtracting their means and dividing by their standard deviations

$W_{A\_}n$ to $W_{L}n$ = the weight of each variable A – L at component n, as shown in **Table 12**.

An average of the three components was retained for the ASTUI calculation at UF i, as shown in **Equation 8**.

Equation 8

Average of the three components

$$ASTUI\ i = [(Eigenvalue\_1 * Component\_1) + (Eigenvalue\_2 * Component\_2) + (Eigenvalue\_3 * Component\_3)] / [Eigenvalue\_1 + Eigenvalue\_2 + Eigenvalue\_3] \quad (8)$$

Recent literature refers to statistics to measure (in)equity of spatial accessibility (Kelobonye et al., 2019; Pereira, 2019; C. Sun et al., 2018), particularly, cluster analyses (CONEVAL, 2019b; Pritchard et al., 2019). These computations served to identify homogeneous areas, reducing the number of the 274 UFs by classifying 5 strata, thus simplifying the data interpretation of the (in)equity of accessibility to STMs from UFs.

The clustering method was Ward's with the squared Euclidean distance metric and non-standardised observations. According to the StatGraphics ® report, the procedure began with each observation in a separate group. It then combined the two observations that were closest together to form a new group. After recomputing the distance between the groups, the two groups now closest together were combined. This process was repeated until only 5 groups remained. The computations served to identify homogeneous areas, reducing the number of the 274 UFs by classifying the limited number of strata shown in **Table 14**. Then, the vertical equity of spatial accessibility was calculated by statistical comparisons of the ASTUIs at private-public universities.

Table 14

Cluster analysis results

Strata	Centroid of ASTUI	Cluster	Members	Percent [%]
Very Low	-1.26353	2	105	38.32
Low	-0.349644	4	62	22.63
Medium	0.686179	3	60	21.90
High	1.54135	1	25	9.12
Very High	3.39289	5	22	8.03

Source: Authors.

Results and discussion

According to Litman (2002) and recent literature (Gori et al., 2020; Kelobonye et al., 2019; Oviedo & Guzman, 2020), transport equity can be horizontal or vertical. Horizontal equity assumes that everyone has the same right to access basic goods, or that the group has equal abilities and needs. Since accessibility to UFs is recognised as a basic good (Caywood & Roy, 2018), horizontal equity means that the STMs do not favour any UF. Every student should have equitable access to sustainable transport means from their UF, in the current era of the Sustainable Development Goals.

Figure 22 shows the ASTUI spatial pattern for the analysis of horizontal (in)equity. Even though the public UFs seem to be "near" SITEUR, this study ascertained that the vicinity is not within the standards recommended in the ASTUI. The figure also shows that almost half of the UFs have Low and Very Low accessibility, while less than 10% of the UFs meet the standard of the Transport Oriented Development paradigm. This is empirical evidence of the transport-related social exclusion of university students, who have traditionally been under-represented in public transport policies.

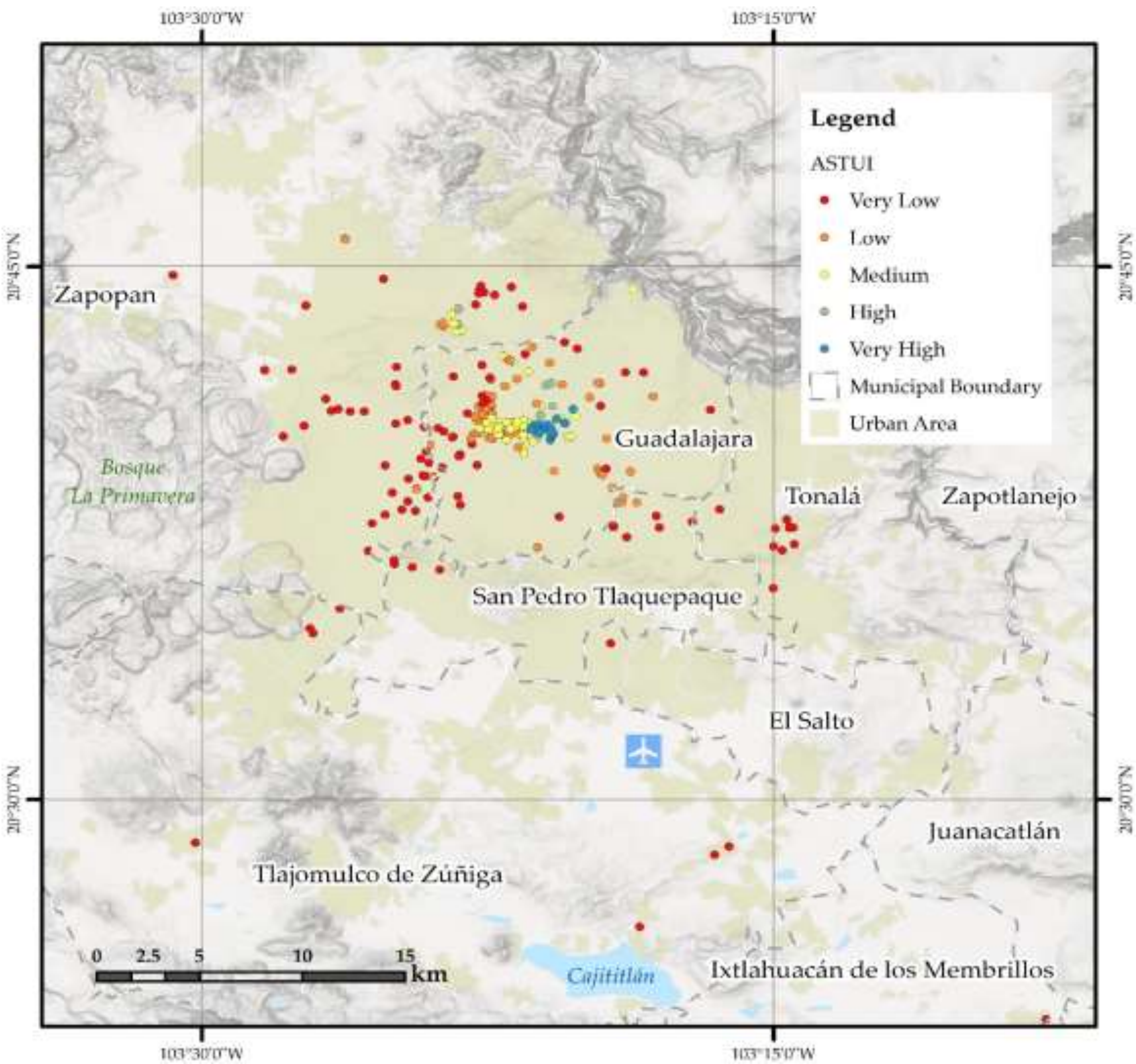

Figure 22. Access to Sustainable Transport from University Index (ASTUI) in the Guadalajara Metropolitan Area (GMA)

Source: Authors, based on (INEGI, 2014, 2015a, 2015b, 2019b).

Vertical equity refers to social and/or income class (Delbosc & Currie, 2011b; Litman, 2002). It suggests that the distribution of STMs should favour a specific group of students. The ASTUIs were compared across the public and private UFs. Therefore, an egalitarian accessibility policy should ensure that the location of the STMs does not negatively impact students attending universities with public funds. Other factors, such as number of students and gender, are relevant to transport equity analyses. However, only financial source was computed in this project, given the data availability.

According to the calculation of the ASTUIs and their classification by clusters, most of the university infrastructure has Low and Very Low ASTUI values, i.e., 62.0% and 42.3% for public and private infrastructure, respectively. Nevertheless, as shown in **Figure 23**, there is no spatial pattern of inequity between public and private infrastructure. Although more private infrastructure is observed in the three most disadvantaged strata, the relative difference between them is small, i.e., 5%, 8%, and 3% for Very Low, Low and Medium, respectively. There are 14 percentage points of difference in the High stratum that favours public infrastructure. In the Very High stratum, private infrastructure is favoured over the public infrastructure by 9 percentage points.

Figure 23. Inequity distribution of the Access to Sustainable Transport from University Index (ASTUI)in the Guadalajara Metropolitan Area (GMA)

Source: Authors.

According to Guthrie et al. (2019), the results highlight that university students in the GMA are under-represented in transport planning. In spite of the investments in the SITEUR and the governmental subsidies for students to use public transport (SEDATU et al., 2018) and *MiBici*, this study reveals that transport-related social exclusion persists within this disadvantaged group. Several reasons were identified that discourage the use of sustainable transport by university students. First, despite the extensive area served by conventional buses, they offer low-quality service (De Quevedo García Najar et al., 2017). Second, most of the UFs are further away than a 2-minute bicycle ride from *MiBici* stations and bicycle lanes. And third, notwithstanding the high-quality service offered by *SITEUR* (UN-Habitat & Jalisco, 2017), the LRT, BRT and *Sitren* cover only a small proportion of the GMA.

The public transport system is considered as a promoter of social inclusion. This is more relevant in areas traditionally characterised by high levels of structural inequalities, such as the GMA. This research identified low access levels for the university student population, which means that the study detected transport-related social exclusion (Lizárraga et al., 2020). The authors propose general actions to enhance the equity of opportunities not just for university students, but for other groups with transport-related disadvantages. Guaranteeing the quality of the conventional buses and building a safe, interconnected and larger bicycle lane network will reduce the transport disadvantages of university students. Researchers also propose the incorporation of university students and authorities in the decision-making process for transport planning and policies, in order to reduce the accessibility disparities experienced by this under-represented, but socially relevant (Gibbons, 1998) community.

Conclusion

According to this research, the promotion of sustainable transport modes in the vicinity of UFs is not supported by the GMA's public transport policies, nor is the intention to modify the future travel behaviour of current students. Indeed, the GMA is very far from the paradigm of a more equitable and livable city when it comes to sustainable mobility in the vicinity of UF. As expected, university students in the GMA suffer transport-related social exclusion when they access LRT, BRT, buses and bicycles. It affects all students, since the ASTUI is similar in the public and private UI, except for the average values of the index, where the public UI is favoured.

The analysis does not fully confirm the inequity between private and public UFs and a deeper analysis must be made in future research, since this study has some limitations. First, the number of students at each UF was not available in Open Data sources, and thus the analysis did not distinguish according to the "size" of each UF. Second, the results may be significantly different as the service areas vary. Third, the ASTUIs did not include walking or travel impedances, such as transport fees, topography, security or other urban quality indicators. Fourth, (in)equity is difficult to measure due to the subjective (individual) nature of accessibility. Therefore, the results of this research are plausible, but not yet completely established.

Although this paper represents a significant advancement of prior work in the GMA, there is still room for improvement. Future tasks could enhance this research:

- Considering the topography and urban environment as elements of effective mobility for the measurement of hindrances affecting the walking time to the stops/stations.
- Computing a sensitivity analysis for different service areas.
- Including the BRT line currently under construction. According to Jalisco (2020b), this line will serve more than 49,000 students.
- Considering income, gender, physical ability or other vulnerabilities in the student population.
- Accounting for the impact of transport fees in the model.
- Including data from smartcards and General Transit Feed Specifications, as soon as they are available.
- Transferring the proposed methodology to the calculation of indices for other basic goods, such as health, cultural or basic educational infrastructure.

It is necessary to shift the mobility paradigm, taking advantage of the adaptation inertia in the Post-COVID era. This study proposed a simple and powerful approach to improve the practice of transport planning and policies. It is easy to understand, interpret and replicate by policy makers in metropolitan areas similar to the GMA who seek to reduce inequality in the form of transport-related social exclusion.

III. DISCUSION AND CONCLUSIONS

This chapter summarizes the confirmation of the general hypothesis and specific research questions. Here the case studies are outlined and structured by hypothesis, data processing and answers to research questions referred to in Sections I and IV (**Tabla 5**, **Tabla 6**, **Tabla 7** y **Tabla 8**). This facilitates the interpretation of the methodological and empirical contribution of this thesis to the field of knowledge. Finally, potential uses and limitations of this type of research are presented, and future work suggested.

7. Discussion

Regarding the estimation of socio-spatial dimensions of mass transport systems

The hypothesis of this dissertation was that socio-spatial dimensions of mass public transport can be estimated through accessibility, specifically by identifying areas with different degrees of transport-related social exclusion by means of open-access data and spatial and multicriteria analysis. To prove this hypothesis, the general aim of the thesis was to propose an innovative methodology to estimate access to public transport system, using open-access data, spatial and multicriteria analysis.

The application of the methodology proposed in Chapter 3 was applied to the Guadalajara Metropolitan Area (GMA), Mexico, thereby confirming the general hypothesis. First, the availability of open-access data was sufficient to be able to estimate Transport related social exclusion (TRSE) in the study area. Second, spatial analysis enabled the identification of areas with different degrees of social transport needs, an estimation of the degree of access to the public transport system, as well as the calculation of the spatial or spatiotemporal concurrence between social transport needs, transport provision, active transport users and air quality episodes. Third, socioeconomic and transport data were rich and complex, thus multicriteria analyses, e.g., principal component analysis, were pertinent to decrease correlation and this assisted interpretation.

Regarding the fulfillment of the social transport needs (STN) by the mass public transport system (MPTS) in the city (CS_1)

The CS assessed the level of fulfillment of STN by the MPTS provision. The ISTN was estimated based on socioeconomic georeferenced factors weighted with PCA. The Index of Mass Transport Provision (IMTP) was calculated with a simplified gravity method by means of frequency, capacity and walking time using GIS. The gap was then assessed by indexes difference. All indexes were mapped to communicate results more easily. The findings confirm the inequality of the distribution of STN and MTP in the city.

The PCA results confirm that the intrinsic factors best explain the STN (Boisjoly et al., 2020; Vecchio, Tiznado-Aitken, et al., 2020). After analyzing 216 variables from the 2010 population and housing census, socioeconomic factors represented 56% of the variables characterizing the STN in the city, while age and schooling contributed 38%. This confirms the relevance of the efficiency of subsidies that SITEUR grants to students and the elderly. In addition, the ownership of a vehicle only represented 6% (**Table 3**), already found in other Latin American studies (Jaramillo et al., 2012). The findings highlight inequalities in the city, since 50.3% of the population had High STN, while only 6.8% had Very Low STN

Results also show that the spatial pattern of transport disadvantage in the Guadalajara Metropolitan Area (GMA) was fragmented. On the one hand, the STN were located in the outskirts of the city (**Figure 7**). Furthermore, 13% of the population lived in transport deserts, mainly in non-central areas. The disadvantage in peripherical areas is similar to other Latin American cities (Jaramillo et al., 2012; Jirón, 2007; Jirón & Mansilla, 2013) and corresponds to the spatial pattern of an official indicator of social exclusion known as marginalization (IIEGJal, 2016).

On the other hand, results also show an unexpected outcome, i.e., Medium and High grades of STN were also located in central areas. This finding highlights the importance of focusing the analysis of the social dimension of transport in the central areas of the city, since existing scholarly publications in the GMA are mainly focused on non-central areas (Asprilla Lara et al., 2018; Calonge Reillo, 2016, 2018b, 2019; Calonge Reillo & Aceves Arce, 2019).

The results regarding the IMTP prove a spatial inequity in access to MPT (**Figure 6**), as observed in other Latin American cities (Jaramillo et al., 2012; Vasconcellos & Mendoca, 2016). The predominance of LRT over BRT was clearly identified, while the service in the outskirts was limited.

When comparing the spatial correlation of STN with access to PT, the positive gap, i.e., IMTP higher than ISTN, was located in 13% of the surface of the metropolitan area where 58% of inhabitants lived (**Table 4**). It can be concluded that MPTS adequately served central areas, mainly where Low and Very Low STN were located. However, MPTS was inadequate to satisfy needs in peripherical areas. This spatial gap confirms the pertinence of the location of the recent BRT connecting the central area with the outskirts. This is not the case with the new LRT line 3. After comparing the gap both with and without Line 3, this line increased access to just 2% of inhabitants living in areas with High grades of STN. LRT line 3 served areas where High and Very High IMTP were already achieved.

Inequality was observed in the distribution of access to MPTS and STN by population percentage (**Figure 9**), since the curves are almost the opposite of the ideal: the highest needs were concentrated in the last quintile of the geographical sections analyzed. In addition, it was shown that the people who suffered from low transport access were almost double the amount of those who benefited from better access. When analyzing inequity by population percentage, the SITEUR covered the needs of a quarter of the inhabitants with High and Very High levels of provision.

Regarding spatiotemporal concurrence of active mode users and air quality (CS_2)

The CS analyzed the spatiotemporal concurrence of air quality and the users of active transport modes. The methodology enabled an estimation of the number of users exposed to episodes of Low air quality, using large open-access databases, GIS and numerical computer platforms. The Air Quality Index was calculated according to the Environmental Protection Agency (2016b) standard. BRT and the public bicycle system were included in the model, because of the availability of open-access data on an hourly basis. Particulate meter (PM10) and ozone were computed, since these are the pollutants that most frequently exceed the standards.

The findings show pendular movements in accordance with work hours from/to residential and trip generation areas. Peak usage times for active modes in the study area were 9:00 a.m. and 7:00 p.m. at three of the monitoring stations. These stations correspond to the intuitively identified origin-destination pendulum, since the residential and commercial/industrial stations are clearly distinguishable.

Surprisingly, only 0.24% and 0.147% of users were exposed to episodes of poor quality of one of the two pollutants, for MiBici and BRT, respectively. However, this becomes relevant when observed in absolute terms, since there are 35,000 and

173,000 users of each mode (**Table 8**). Unfortunately, results are not conclusive, given the spatial heterogeneity and temporal inconsistency in the air quality measurement and the limited availability of transport data on an hourly basis. To apply the methodology to the metropolitan scale, the distribution of monitoring stations should be improved and data on an hourly basis from LRT and conventional buses should be available.

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Regarding access to sustainable transport from university facilities (CS_3)

The CS provided an empirical assessment of the inequity of access from university facilities (UF) to a public transport system, i.e., LRT, BRT, buses and bicycles. The Access to Sustainable Transport from University Index (ASTUI) was calculated with GIS and PCA with time thresholds based on TOD paradigm and weighted nodes by mode and number of lines.

The results confirm the weakness of access to PTS from UF. Astonishingly, most UF in the city had limited access to public bicycle, conventional bus, or mass transit stations and stops. Less than 10% of the UF had a Very High ASTUI value. Half of both public and private universities have a Low and Very Low access rate, that is, 59.2% and 61.5%, respectively. Less than 2% and 11% of public and private facilities, respectively, had access to 274 stops/stations within the TOD standard walking time. Results are consistent with other horizontal inequity studies showing UF with a deficit in access to PT (Miralles-Guasch & Domene, 2010; C. Sun et al., 2018).

Results show no clear pattern of vertical inequality between public and private UF. ASTUI values were similar for both public and private UF, i.e., a higher proportion of UF for lower grades of ASTUI and vice versa (**Figure 23**). Although private university facilities apparently suffer from a greater disadvantage, the relative difference is Very Low, that is, 5%, 8% and 3% for Very Low, Low and Medium ratings, respectively. In contrast, public infrastructure benefited from High access, while the Very High access favored private infrastructure. Nonetheless, differences were not considered sufficiently robust to declare vertical inequity, that is, no consistent differences were found between public and private university facilities.

8. General conclusions

A public transport system is recognized as a promoter of social inclusion. This is particularly important in urban areas with structural inequities, such as the GMA. This thesis contributes to the limited quantitative research on transport-related social exclusion (TRSE) in the GMA in particular, and to the TRSE in Latin American metropolises, in general. It provides methodologies and empirical evidence for transport policy makers to reduce inequalities and, in consequence, TRSE.

This dissertation proposes that socio-spatial dimensions of transport may be estimated through access to PTS by means of open-access data and multicriteria analysis. The methodological proposals of this paper are a relevant contribution to the transdisciplinary approach of TRSE in Latin America. Theoretical and earlier empirical knowledge from the disciplines of Geography, Urban Planning, Economics and statistical and spatial analysis sciences were considered, from the identification of the problem through to the methodological proposal and its application.

The CS proved that the socio-spatial dimension of transport can be explained with open data, spatial analysis and multi-criteria methods. In particular, the pertinence of using the simplified gravity method to estimate access to public transport was confirmed for contexts with technical and financial limitations.

CS_1 confirmed the inequality in the distribution of social transport needs and access to a public transport system in the GMA. The results also proved that the SITEUR only covered the social transport needs of a quarter of the population.

CS_2 highlighted the low percentage of active mode users exposed to poor air quality episodes in the year of reference in the study area. This case also confirmed the need for more accurate air quality data to properly estimate this spatial dimension of transport.

CS_3 showed that the university community in the metropolis suffers from social exclusion due to a deficit in access to transportation.

The traditional approach to designing and operating PTS has been supported on a technical and financial basis, with few social subsidies. The results of this thesis confirm that, even though the capacity and arrangement of the network are key elements of accessibility (Souto Rodrigues et al., 2016), it is also necessary to take into account STN to properly reduce the TRSE (Handy, 2020; Jaramillo et al., 2012; Litman, 2002; Vecchio, Tiznado-Aitken, et al., 2020). The CS' findings may contribute to reducing the negative impact of transport in Latin American cities (Manrique et al., 2020), characterized by urban contexts of inequality, chaos urbanization and limited regulation (Jaramillo et al., 2012).

Proposals

Based on the results of this thesis, two general actions are proposed in order to reduce TRSE in the GMA. First, the design and operation of PTS should permanently integrate a social approach. Accordingly, four considerations are suggested:

1. Areas with more social needs should be considered when expanding the PT network with mass, collective or on-demand PT modes.
2. Private carriers should be properly regulated since they serve most of the areas with High and Very High STN. This may improve access to the entire system if issues of accuracy, frequency and capacity are addressed.
3. The fare-integration of PTS may promote intermodality (Mendo-Gutiérrez, 2008) and reduce transport poverty, since income was among the relevant variables explaining the STN.
4. Non-motorized transport should also be promoted. Recent data revealed that 25% of households have bicycles as a mode of transport and that they are located mainly on the outskirts. To promote these active transport modes, the expansion of a safe and connected cycling infrastructure is required.

Second, the relevance of considering socio-spatial dimensions of transport in multisectoral public policies is indisputable (Jalisco Cómo Vamos et al., 2020; Jaramillo et al., 2012). Since socioeconomic factors, such as, gender, disability, illiteracy, unemployment and low income comprised most of the explanatory variables of STN in the area, the consideration of these factors in multisectorial policies may reduce transport disadvantage, and, in consequence, TRSE.

Public transport policies should also be coordinated with other sectors. The socioeconomic determinants of STN identified in CS_1 proposed that economic and social policies may decrease STN, thus TRSE. CS_2 established the need for accurate air quality data to properly estimate exposure of active mode users to pollutants. This data is produced by the environmental public sector, thus coordination with the transport sector is crucial. CS_3 showed that land use policies may also contribute to TRSE when they are not coordinated with transport policies. In consequence, four proposals are suggested regarding the variables explaining STN:

1. Gender perspective should be integrated when designing and operating the PTS.
2. Universal accessibility to the entire PTS should be pursued.
3. Economic policies should decrease unemployment, and so also reduce the transport disadvantage.
4. The absolute values of transport users exposed to episodes of poor air quality call for improvement of the air quality monitoring system throughout the city.

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9. Potential and limitations

Regarding the potential to estimate the socio-spatial dimensions of transport

The methodology is transferable to other contexts with limited technical capacities and financial resources, because of the following characteristics:

1 The methodology was based on previous scholarly studies and verified by peer reviews, then accepted by the scientific community and general public.

2 The methodology is affordable as open-access data sources are utilized.

3 The methodology may be applicable in Mexican metropolises. The national government provides socioeconomic data every five [survey] and ten years [census]. It also updates the location of urban facilities on a quarterly basis. The transport operators offer data on capacity, frequency and passengers per station, as well as public bicycle system large databases. In addition, the environmental authority publishes air quality monitoring data on an hourly basis.

4 The methodology allows the inclusion of different transport modes and amenities in the model according to the context.

5 Results were presented on maps, so they were easy to understand by non-specialized public.

Parameters according to each context should be adjusted to apply the methodology, such as, the weight of the socioeconomic factors (CS_1) and of stations/stops (CS_2); the walking time thresholds; the minimum unit of spatial analysis; or the modes of transport to be modeled.

Regarding the limitations to estimating the socio-spatial dimensions of transport

Data availability is one of the difficulties involved in modeling complex phenomena. The methodology proposed is highly sensitive to the availability of open-access data. Moreover, this type of data that is systematically generated is still scarce in some contexts.

Data sensitivity may be observed in relation to these three dimensions:

1. The spatial dimension of data
    a. The study area. Results show that spatial patterns may vary when analysing metropolitan, municipal or neighbourhood areas.
    b. The spatial unit of analysis. Results vary according to big units of analysis (CS_1), survey units, or blocks. The smaller the unit, the higher the precision of the ITMP. This is not the case with the ISTN, since social phenomena do not vary from one block to another, but variations can be seen in larger areas.
2. The thematic dimension of data
    a. The transport modes. The application of the methodology to various modes to achieve their contribution to reducing TRSE depends on transport data availability. Open-access data policies vary between public and private carriers. Moreover, data on paratransit and on-demand modes are scarce, and generation of this data requires high human and financial resources (Goldwyn & Vergel-Tovar, s. f.; Lesteven & Boutueil, 2018; Vergel-Tovar et al., s. f.).
    b. The socioeconomic factors. The PCA is intrinsically sensitive to the input data base analysed. To determine the variables to be processed, a deep knowledge of the context is necessary to properly adapt existing empirical studies of TRSE to the study area.
3. The temporal dimension of data
    a. The walking time. The methodology is highly sensitive to time thresholds. The time an individual is willing to walk varies according to urban environment, cultural context, security and perception, among other intrinsic and extrinsic factors (Boisjoly et al., 2020; Talavera-García & Valenzuela-Montes, 2018; Wachs & Kumagai, 1973).

Although the availability of open-access data is imperfect in Latin American cities, government institutions have aligned with the global trend and are increasingly willing to share data, thus improving figures on all three dimensions mentioned above.

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10. Future work and scientific challenges

To improve the methodology proposed in this dissertation, several research tasks may be carried out in the future:

- To develop Phyton programming code to apply the methodology to other transport modes, amenities or contexts efficiently.
- To include intrinsic and extrinsic travel impedance parameters in the gravity model, such as security, fees, topography or urban quality.
- To compute sensitivity analyses for different dimensions: spatial, i.e., different metropolises and different spatial units of analysis; thematic, that is, different modes and amenities; and temporal, i. e., different walking time thresholds and in different socioeconomic surveys.

For the future, scientific challenges have been identified to be able to facilitate the research proposed above. First, the determination of intrinsic and extrinsic input variables in the PCA. Second, the definition of walking time thresholds for specific urban contexts. Third, the election of spatial, temporal, and thematic data for a comprehensive estimation of the phenomenon and to simplify the computations. In general, the methodology should remain as simple as possible to explain a complex phenomenon.

IV. REFERENCIAS Y ANEXOS

Este capítulo contiene el resumen de los casos de estudio (CE), el listado de la producción académica durante la formación doctoral y las referencias que sustentaron los capítulos anteriores.

11. Resumen de casos de estudio

IV. REFERENCIAS Y ANEXOS

Esta sección resume las principales características de los casos de estudio (CE) por medio de cinco tablas generales que complementa la (**Tabla 1**) que refiere la traducción de los títulos originales de las publicaciones, las hipótesis particulares y las preguntas de investigación y fue incluida en de la sección 1 de este documento. La **Tabla 5** enlista los datos utilizados y sus fuentes. La **Tabla 6** refiere la aproximación metodológica, los métodos, índices y fórmulas/ algoritmos utilizados. La **Tabla 7** señala los principales hallazgos y la **Tabla 8** responde de forma sintética las preguntas de investigación.

Tabla 5

Datos utilizados en los casos de estudio y sus fuentes

CE[1]	Datos	Fuente
1	LRT, BRT, HQB: localización de estaciones/paradas, frecuencia y capacidad de los vehículos	SITEUR[2] (2021c) /IMEPLAN[3] (2019, 2020)
1	Ejes viales con topología de red	OpenStreetMap (2020)
1	Variables socioeconómicas con referencia geográfica	INEGI[4] (2010b)
2	BRT y bicicleta pública: localización de estaciones y número de usuarios/hora en 2019	SITEUR[2] (2021b)
2	Concentraciones de ozono y partículas suspendidas (PM10) por hora durante 2019	SEMADET[5] (2021)
3	LRT, BRT, autobuses convencionales y bicicleta pública: localización de estaciones/paradas y número de líneas en cada una.	IMEPLAN[3] (2020) /Gobierno del Estado de Jalisco (2021) /EPA (2016b)
3	Edificios universitarios: localización	INEGI (2019c)

[1]CE: Caso de estudio; [2]Sistema de Tren Eléctrico Urbano (México); [3]Instituto de planeación y gestión del desarrollo del Área Metropolitana de Guadalajara (México); [4]Instituto Nacional de Estadística e Informática (México) y [5]Secretaría del Medio Ambiente y Desarrollo Territorial (México).

Tabla 6

Métodos, índices, algoritmos, herramientas y datos utilizados en los casos de estudio

CE[1]	Acercamiento / Método	Índices / algoritmo	Herramientas
1	Dual[2] Acumulativo / Gravitatorio simplificado	Índice de provisión de transporte masivo (IMTP[3]) $IMTP_j = CM_j * (1/FM_j) * Tw_j$	SIG[4]
1	Ponderación / Suma ponderada	Índice de necesidades sociales de transporte (ISTN[5])/ $ISTN_j = \sum_{i=1}^{n} S_{ij} \times W_i$	ACP[6]
1	Equidad horizontal / Diferencia	Brecha entre el potencial y las necesidades sociales del transporte $ISTNCj = IMTP_j - ISTN_j$	SIG[4]
2	Comparativo por tiempo y espacio	Índice de calidad del aire[7] / $AQI = [(AQI_{Hi} - AQI_{Lo})/(Conc_{Hi} - Conc_{Lo})] \times (Conc_i - conc_{Lo}) + (AQI_{Lo})$	SIG[4] y Tablas dinámicas

Tabla 6 (continuación)

CE[1]	Acercamiento / Método	Índices / algoritmo	Herramientas
3	Prime[8], Acumulativo / Gravitatorio simplificado y ponderado por grado nodal	Índice de acceso a transporte sostenible desde universidades (ASTUI[9]) $$ASTUI_i = \sum_{i=1}^{n} STAT_{imt} \times W_{mt}$$	SIG[4] y ACP[6]

[1]Caso de estudio; [2]Estima el tiempo/distancia, para llegar a estaciones/paradas definidas; [3]Índice de provisión de transporte masivo, por sus siglas en inglés; [4]Sistema de Información Geográfica; [5]Índice de necesidades sociales de transporte, por sus siglas en inglés; [6]Análisis de Componentes Principales; [7]Conocido como AQI, por sus siglas en inglés; [8]Estima el número de estaciones/paradas a una distancia/tiempo definida; [9]Índice de acceso a transporte sostenible desde universidades, por sus siglas en inglés.

Tabla 7

Principales hallazgos de los casos de estudio

CE1	Hallazgos generales
1	Tras analizar 216 variables del censo de población y vivienda 2010, los factores socioeconómicos representan el 56% de las variables determinantes de las necesidades sociales del transporte en la ciudad, mientras que la edad y escolaridad aportan el 38%. Además, la propiedad de un vehículo solamente representa el 6%. Esto confirma lo encontrado en otros estudios latinoamericanos; El 50.3% de los habitantes tienen muy altos niveles de necesidades, mientras que solo el 6.8% tiene bajos niveles. El 42% de los habitantes de la ciudad sufren de exclusión social por transporte presente en el 87% de la superficie del área metropolitana (mayor necesidad que provisión). El SITEUR cubre las necesidades de un cuarto de los habitantes con grados alto y muy alto de provisión. Se observa desigualdad en la distribución espacial de las necesidades sociales del transporte pues la curva es casi opuesta a la ideal: las más altas necesidades están concentradas en el último quintil de las secciones geográficas analizadas. Además, se observa que las personas que sufren de un índice bajo de provisión de transporte son casi el doble que las que disfrutan de mejor provisión.
2	Las horas pico de uso de modos activos en el área de estudio son las 9 y las 19 hr en tres de las estaciones de monitoreo. Estas corresponden al péndulo de origen destino intuitivamente identificado, pues las estaciones residenciales y comerciales/industriales son claramente distinguibles..

Tabla 7 (continuación)

CE1	Hallazgos generales
3	El 0.24% y 0.147% de los usuarios fueron expuesto a episodios de mala calidad de uno de los dos contaminantes, para MiBici y BRT, respectivamente. Sin embargo, esto toma relevancia cuando se observa en términos absolutos, pues son 35,0000 y 173,000 usuarios de cada modo. El estándar de tiempo de caminata previsto por el TOD (ITDP, 2018) es alcanzado por menos del 2% y 11% del equipamiento público y privado, respectivamente. En contraste, la mitad desde las universidades tanto públicas como privadas presentan un índice de acceso bajo y muy bajo, esto es, 59.2% y 61.5%, respectivamente.

[1] Caso de estudio.

Tabla 8

Respuestas sintéticas a preguntas de investigación de los casos de estudio

CE1	Acercamiento a las respuestas de investigación
1	Las variables socioeconómicas son las que mejor explican las necesidades sociales del transporte en la metrópoli, particularmente, la movilidad reducida, el analfabetismo, el desempleo y la renta.
	Se observa una gran desigualdad en la distribución de las necesidades del transporte como en la provisión del transporte masivo en la ciudad
2	Los valores absolutos de usuarios del transporte expuestos a episodios de mala calidad del aire demandan acciones inmediatas
	Los resultados no son definitivos, dada la heterogeneidad espacial y la inconsistencia temporal en la medición de calidad del aire
	La limitación de datos del LRT a escala temporal del día dificulta la consideración de los usuarios de este modo de transporte masivo en los cálculos.
3	El colectivo universitario está en desventaja de transporte respecto a otros colectivos de la ciudad y es susceptible de exclusión social.
	La inequidad vertical no es identificable con esta metodología

[1] Caso de estudio.

12. Producción académica

Esta sección refiere la producción académica desarrollada durante la formación doctoral. La **Tabla 9** lista los productos publicados ordenados cronológicamente. Destaca la mejora continua de la producción de acuerdo con parámetros reconocidos por la comunidad científica, tales como la indexación y la revisión por pares. Además, la coautoría demuestra el trabajo en equipo y la colaboración internacional.

Tabla 9

Producción académica publicada durante la formación doctoral

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Ochoa-Covarrubias, G.	Urban planning and mobility as promoters of healthy cities	2019	GraWHO 2019. World Health Organisation Simulation, Escuela Andaluza de Salud Pública, Granada	Presentación no publicada	No	No	Comunicación de congreso
Ochoa-Covarrubias, G., Molero-Melgarejo, E., Grindlay-Moreno, A., & Falcon Meraz, J. M.	Planeación y movilidad como promotores de ciudades saludables en España y México	2019	Congreso Iberoamericano para la fundamentación y práctica de la ciudad sostenible, 155-172, Universitat Politècnica de Valencia, Valencia	http://dx.doi.org/10.4995/CSOS.2021.6588_01	No	Sí	Comunicación de congreso

Tabla 9. (Continuación)

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Lizárraga, C., Grindlay, A. L., & Ochoa-Covarrubias, G.	Evaluating public transport social exclusion in Guadalajara, Mexico	2020	WIT Transactions on the Built Environment, WIT, online	Presentación	SJR	Sí	Comunicación de congreso
Grindlay, A. L., Ochoa-Covarrubias, G., & Lizárraga, C.	Urban Mobility and Quality of Public Spaces: the Case of Granada, Spain	2020	WIT Transactions on the Built Environment, WIT, online	Presentación	SJR	Sí	Comunicación de congreso

Tabla 9. (Continuación)

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Lizárraga, C., Grindlay, A. L., & Ochoa-Covarrubias, G.	Evaluating public transport social exclusion in Guadalajara, Mexico	2020	WIT Transactions on the Built Environment. (Vol. 200, 195–203)	https://www.wessex.ac.uk/2011/HBNFE452/UT20-9781784664091.pdf	SJR	Sí	Capítulo de libro
Grindlay, A. L., Ochoa-Covarrubias, G., & Lizárraga, C.	Urban Mobility and Quality of Public Spaces: the Case of Granada, Spain	2020	WIT Transactions on the Built Environment. (Vol. 200, 37–48)	https://www.wessex.ac.uk/2011/HBNFE452/UT20-9781784664091.pdf	SJR	Sí	Capítulo de libro

Tabla 9. (Continuación)

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Grindlay, A. L., Ochoa-Covarrubias, G., & Lizárraga, C.	New Rail-Based Public Transport Systems and their Urban Impacts in Andalusia (Spain)	2021	Global Summit on Civil, Architectural and Environmental Engineering, Barcelona	https://www.thescientistt.com/civil-structural-environmental-engineering/conference-book.pdf	No	No	Comunicación de congreso
DeAlba-Martínez, H., Grindlay, A. L., & Ochoa-Covarrubias, G	(In)Equitable Accessibility to Sustainable Transport from Universities in the Guadalajara Metropolitan Area, Mexico	2021	Sustainability, 13(1), 55	https://doi.org/10.3390/su13010055	JCR	Sí	Artículo científico

Tabla 9. (Continuación)

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Ochoa-Covarrubias, G., Grindlay, A. L., & Lizarraga, C.	Does the Mass Public Transport System Cover the Social Transport Needs? Targeting SDG 11.2 in Guadalajara, Mexico	2021	Applied Sciences, 11(16), 7709	https://doi.org/10.3390/app11167709	JCR	Sí	Artículo científico
Ochoa-Covarrubias, G., Gonzalez-Figueredo, C., DeAlba-Martínez, H. & Grindlay, A. L.	Air Quality and Active Transportation modes: A Spatiotemporal Concurrence Analysis in Guadalajara, Mexico	2021	Sustainability, 13(24), 13904	https://doi.org/10.3390/su132413904	JCR	Sí	Artículo científico

Tabla 9. (Continuación)

Autores	Título	Año	Editorial, volumen, página / Nombre del congreso, organizador, lugar	DOI o URL	Index	Revisión por pares	Tipo
Grindlay, A. L., Ochoa-Covarrubias, G., & Lizárraga, C.	Sustainable mobility and urban space quality: the case of Granada, Spain	2021	International Journal of Transport Development and Integration, 5(4), 309-326	https://doi.org/10.2495/TDI-V5-N4-309-326	SJR	Sí	Artículo científico

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