MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

ANALYSIS OF TRANSPORT ACCESSIBILITY

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Análisis de Accesibilidad al Transporte

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

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ANÁLISIS DE ACCESIBILIDAD AL TRANSPORTE

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RESUMEN DEL PROYECTO

Palabras clave: accesibilidad, pobreza de transporte, transporte público.

1.- DESCRIPCIÓN DEL PROYECTO

Este capítulo presenta los fundamentos y el contexto del proyecto, cuyo objetivo es evaluar la accesibilidad al transporte público en el área metropolitana de Sevilla. El propósito principal es identificar las zonas donde los residentes enfrentan dificultades significativas para acceder a servicios esenciales como el empleo, la educación, la sanidad o el ocio. El estudio responde a la creciente relevancia de la pobreza de transporte como una forma multidimensional de exclusión social, y va más allá de la asequibilidad económica tradicional al considerar también barreras espaciales y temporales.

El trabajo se distingue por su enfoque basado en los tipos de desplazamientos diarios, considerando patrones como los viajes al trabajo o a centros educativos, desplazamientos frecuentes a lugares como gimnasios o supermercados, y salidas ocasionales o de carácter social. Esta perspectiva permite una comprensión más detallada de las desigualdades en la movilidad urbana.

El proyecto integra datos GTFS, análisis geoespacial y herramientas de programación en R para calcular tiempos estimados de viaje e indicadores de accesibilidad a nivel distrital. Sevilla se presenta como un caso de estudio relevante por su estructura urbana mixta y las notables diferencias en la cobertura del transporte público entre las zonas centrales y periféricas.

Asimismo, el proyecto se alinea con varios Objetivos de Desarrollo Sostenible (ODS), en especial los relacionados con la pobreza, la salud, la infraestructura, la desigualdad y la acción climática. Finalmente, el capítulo aborda el contexto de la pobreza de transporte en España, destacando su complejidad y los diferentes indicadores utilizados para cuantificarla, como el porcentaje de ingresos destinado al transporte o el acceso a servicios. El análisis refleja cómo los factores demográficos, espaciales y económicos se combinan para configurar desigualdades de movilidad, especialmente en áreas suburbanas y de bajos ingresos.

2.- ESTADO DE LA CUESTIÓN

El debate académico en torno a la pobreza de transporte pone de manifiesto lagunas persistentes en la forma en que se define y mide la accesibilidad. Aunque la asequibilidad económica ha sido con frecuencia el eje central, muchos investigadores sostienen que esta perspectiva es insuficiente por sí sola. La accesibilidad implica no solo el coste, sino también las características espaciales y temporales de los sistemas de transporte, que pueden limitar gravemente la capacidad de las personas para participar en la vida cotidiana cuando están mal diseñados o distribuidos.

Diversas metodologías han tratado de abordar estas limitaciones. Algunos estudios se basan en indicadores estáticos o aproximaciones financieras, mientras que otros incorporan enfoques más dinámicos, como el análisis de accesibilidad dependiente del tiempo o del espacio de actividad. Aunque estos métodos ofrecen aportes valiosos, con frecuencia pasan por alto la estructura física y el diseño territorial de la infraestructura de transporte, especialmente en entornos suburbanos o rurales con escasa cobertura de transporte público. La innovación y la tecnología también juegan un papel clave en la reducción de desigualdades en el transporte. Datos en tiempo real, aplicaciones móviles, plataformas de coche compartido y el desarrollo de vehículos eléctricos y autónomos representan nuevas vías para mejorar tanto la cobertura como la eficiencia del sistema. Los principios de diseño inclusivo, respaldados por herramientas políticas como el Fondo Social para el Clima de la Unión Europea, refuerzan aún más el potencial de soluciones de movilidad accesible, especialmente para grupos vulnerables.

A pesar de estos avances, sigue siendo necesario realizar estudios que analicen en detalle la infraestructura de transporte público. Integrar las dimensiones espaciales y de calidad del servicio en la evaluación de la pobreza de transporte permite una comprensión más precisa de las desigualdades existentes y puede servir de base para políticas orientadas a una movilidad urbana más equitativa y sostenible.

3.- METODOLOGÍA

La investigación aplica un marco metodológico en varias fases para evaluar la accesibilidad al transporte en el área metropolitana de Sevilla, integrando datos oficiales de movilidad, información sobre la red de transporte público, indicadores espaciales y variables socioeconómicas. El análisis se estructura en cinco etapas clave: recopilación de datos, depuración y limpieza, integración espacial, estimación de tiempos de viaje y construcción de indicadores de accesibilidad y coste.

Las fuentes de datos principales incluyen la matriz origen-destino del Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA), que ofrece información detallada sobre los flujos de viajes entre distritos, incluyendo variables como el propósito del viaje, la distancia recorrida y segmentaciones demográficas. Se integraron cuatro conjuntos de datos GTFS (autobuses, metro, tranvía y cercanías) para reconstruir el sistema multimodal de transporte público de Sevilla. Además, se utilizaron los centroides geográficos para anclar espacialmente los desplazamientos y se incorporaron datos socioeconómicos sobre ingresos por hogar y por persona, obtenidos del Servicio de Estadística del Ayuntamiento de Sevilla. El área de estudio abarca toda la región metropolitana de Sevilla, elegida por su diversidad morfológica urbana y la disponibilidad de datos de transporte de alta calidad. Se aplicó un proceso de limpieza y filtrado para eliminar registros inconsistentes o incompletos y se enfocó el análisis en los desplazamientos entre distritos, con el fin de reflejar la accesibilidad estructural. Todos los conjuntos de datos fueron georreferenciados y armonizados para permitir análisis espaciales y cálculos realistas de rutas multimodales.
Los tiempos de viaje en transporte público se estimaron mediante simulaciones basadas en GTFS, correspondientes a un lunes laborable en hora punta (6:00 h). Estas simulaciones calcularon el tiempo total estimado de viaje, el número de transbordos y las líneas utilizadas para cada par origen-destino. Si no se encontraba una conexión factible, el viaje se excluía del análisis posterior. Se empleó procesamiento en paralelo para acelerar el cálculo de rutas en los flujos de viaje de mayor volumen.

Para ofrecer una visión más completa de la accesibilidad, se incorporó el contexto socioeconómico a través de indicadores de renta por distrito. Se identificaron notables desigualdades de ingreso entre distritos, siendo las zonas de menor renta las que presentan, en general, mayores tiempos de viaje y servicios menos frecuentes, lo que refuerza la importancia de la equidad en la planificación del transporte urbano.
La matriz MITMA fue enriquecida con coordenadas espaciales y datos de cada viaje sobre distancia recorrida, duración y coste según el modo de transporte. Las distancias fueron ajustadas con índices de desvío (1,3 para coche y 1,5 para transporte público) para reflejar trayectorias no lineales. Posteriormente, se estimaron los tiempos de viaje utilizando velocidades medias de referencia: 30 km/h para coche y 25,77 km/h para transporte público, basadas en estadísticas oficiales.

Los costes de transporte se calcularon usando tarifas por kilómetro: 0,35 €/km para vehículo privado y 0,24 €/km para transporte público, este último derivado de un promedio ponderado entre tarifas y distancias reales obtenidas del Metro de Sevilla y los servicios de Cercanías de RENFE. Esto permitió construir tres conjuntos de datos comparativos: uno para el tiempo de viaje, otro para la distancia, y otro para el coste, todos desagregados por tipo de viaje y modo de transporte.

Mediante la combinación de eficiencia de red, distribución espacial y vulnerabilidad socioeconómica, este diseño metodológico permite una evaluación multidimensional de la accesibilidad y pone de manifiesto las desigualdades existentes en el sistema de transporte urbano. Los resultados sirven de base para identificar distritos en situación de desventaja y apoyar una planificación basada en datos que promueva la movilidad equitativa.

4.- RESULTADOS

PATRONES DE TIEMPO DE VIAJE EN SEVILLA

PERFILES FUNCIONALES DE LOS DESTINOS ENTRE DISTRITOS

Dentro del apartado más amplio de resultados, este subcapítulo se centra en el análisis de los patrones de tiempo de viaje en el área metropolitana de Sevilla, con especial atención al propósito funcional de los desplazamientos interdistritales. El objetivo es entender cómo distintos municipios actúan como destinos para diferentes tipos de actividades —como trabajo, educación, gestiones cotidianas o visitas esporádicas— y, con ello, identificar el papel que desempeñan dentro del sistema de movilidad urbana. Este enfoque desagregado permite una interpretación más profunda de las dinámicas espaciales que configuran la accesibilidad, así como detectar variaciones en la demanda y en el uso del suelo.

La Figura 1 presenta los diez municipios que reciben el mayor volumen de desplazamientos interdistritales, identificados a partir de la agregación de datos de toda la matriz de movilidad. Cada barra descompone el porcentaje de viajes según cuatro categorías de actividad en destino: trabajo/estudios, viajes frecuentes, viajes no frecuentes y regreso a casa. Esta visualización permite realizar comparaciones tanto cuantitativas como cualitativas entre municipios según la naturaleza funcional de los desplazamientos que atraen.

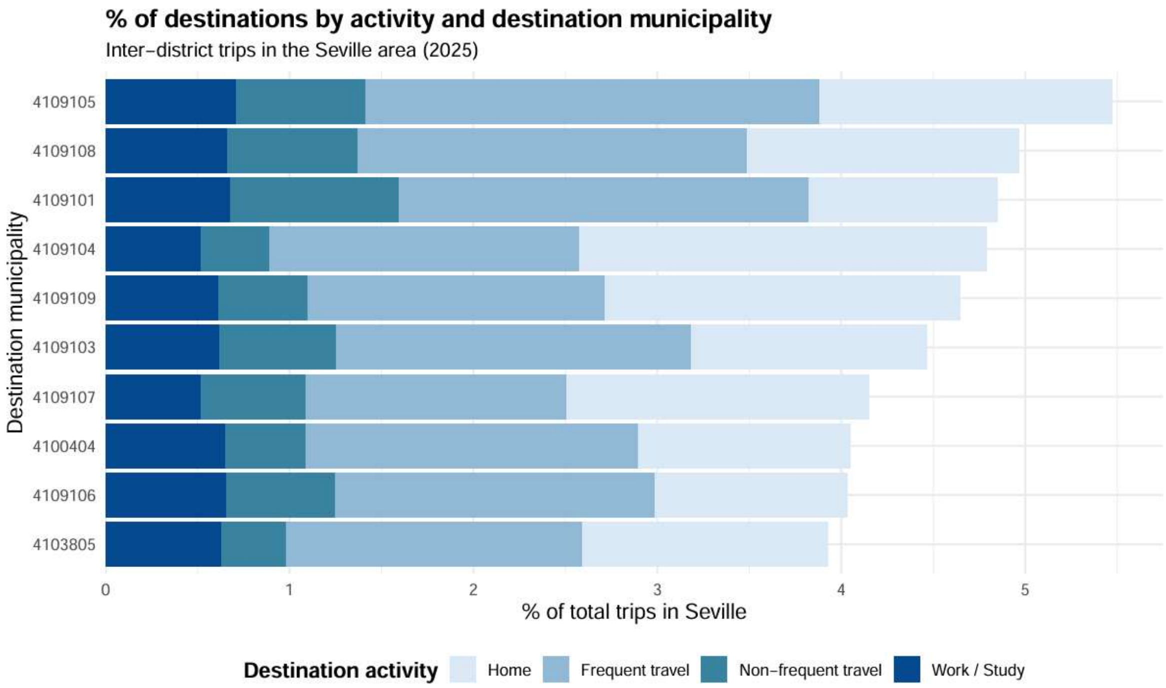

Figura 1: Porcentaje de destinos por actividad y municipio de llegada

Una observación clave es la presencia relativamente uniforme de los viajes por motivos de trabajo y estudio en todos los municipios analizados. Esta regularidad sugiere un patrón descentralizado de los destinos laborales y educativos, en el que múltiples zonas contribuyen de forma equilibrada a la estructura funcional de la ciudad, sin depender de un único centro dominante.

En cambio, los porcentajes de viajes frecuentes y no frecuentes muestran mayor variabilidad. Algunos distritos, como 4109103 y 4109104, registran una mayor proporción de viajes frecuentes, probablemente vinculados a servicios regulares como compras o atención médica. Otros, como 4109108 y 4109109, atraen más desplazamientos no frecuentes, lo que puede asociarse con destinos administrativos, culturales o institucionales visitados de forma ocasional.

La categoría de "hogar" también varía en su relevancia. Distritos como 4109105 y 4109101 presentan un porcentaje más alto de viajes cuyo destino es el hogar, lo que podría reflejar su carácter predominantemente residencial o su papel como punto final habitual en los trayectos de retorno. Por el contrario, los municipios más orientados a servicios o empleo muestran una presencia algo menor de esta categoría.

La composición interna de los viajes en cada municipio ofrece una visión valiosa sobre el papel funcional del área. Por ejemplo, dos municipios pueden atraer un volumen total de viajes similar, pero los propósitos de esos viajes pueden diferir significativamente, lo que indica perfiles urbanos distintos, niveles de provisión de servicios variados o diferentes grados de accesibilidad. Estas diferencias sugieren que la desigualdad espacial no se limita a la cantidad de desplazamientos, sino también a su orientación funcional.

Aunque este resumen destaca únicamente algunos resultados, representa solo una parte de un análisis más amplio y detallado desarrollado en el capítulo de resultados. La sección completa incluye múltiples figuras e indicadores complementarios destinados a capturar la estructura espacial de la accesibilidad y las desigualdades subyacentes en el área metropolitana de Sevilla.

DISTRIBUCIÓN ESPACIAL DE LOS TIEMPOS DE VIAJE EN SEVILLA

Como complemento a los análisis anteriores centrados en los propósitos del viaje y los tipos de trayecto, esta sección introduce una perspectiva espacial para evaluar cómo se distribuyen las disparidades temporales en la movilidad a lo largo del Área Urbana Funcional (AUF) de Sevilla. Comprender la geografía de los tiempos de viaje ofrece una visión valiosa sobre cómo varían las condiciones de accesibilidad entre distritos, revelando patrones que no siempre se reflejan en cifras agregadas.

La Figura 2 muestra el tiempo medio de viaje por distrito, con un claro gradiente visual que distingue las zonas centrales de las periféricas. Los distritos situados en el núcleo urbano de Sevilla aparecen en tonos más claros, lo que indica duraciones promedio de viaje más cortas. Estas áreas se benefician de una alta concentración de servicios, distancias relativamente reducidas entre destinos clave y una mayor cobertura del transporte público.

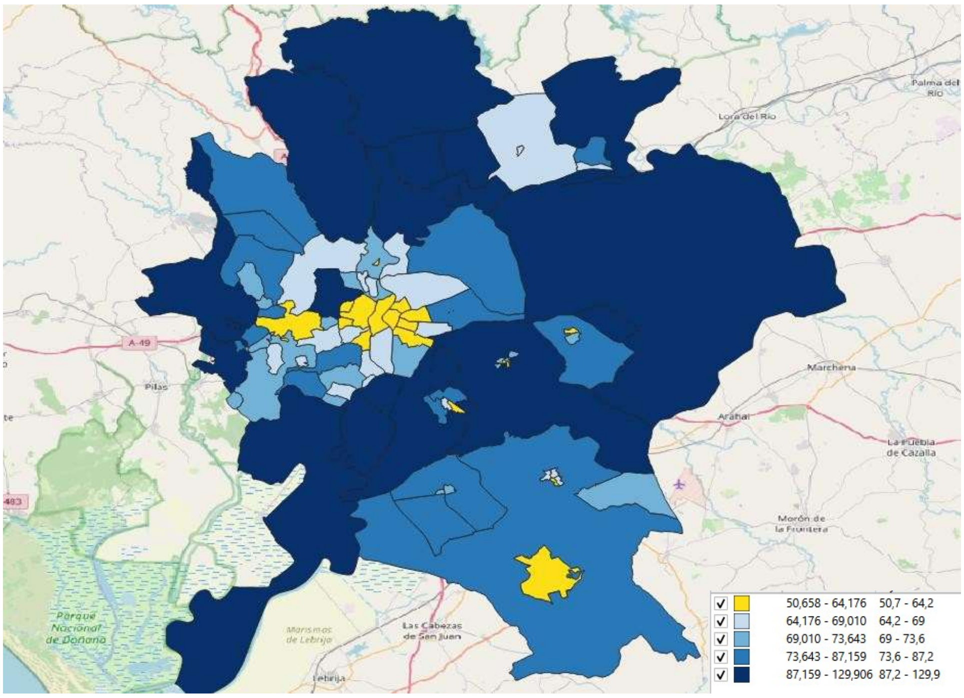

Figura 2: Tiempo medio de viaje en transporte público por distrito en el Área Urbana Funcional de Sevilla (2025)

En contraste, los municipios periféricos—especialmente aquellos situados en los extremos norte, noreste, sureste y suroeste del área metropolitana—se representan con tonos más oscuros, lo que refleja tiempos de viaje considerablemente más altos. Estos distritos suelen estar más alejados de los centros de empleo y servicios, y dependen en mayor medida de sistemas de transporte intermunicipal que, con frecuencia, operan con menor frecuencia o presentan una integración más débil. Las zonas más al sur del área metropolitana también registran duraciones más elevadas, probablemente debido a su aislamiento geográfico.

Esta distribución espacial es coherente con los patrones habituales de movilidad urbana, donde la centralidad se asocia a una mejor conectividad y menores tiempos de desplazamiento, mientras que la distancia al centro urbano implica una mayor carga temporal para acceder a las actividades cotidianas. Estos hallazgos refuerzan la importancia de considerar la equidad espacial en la planificación del transporte. Los distritos que enfrentan de forma persistente mayores tiempos de viaje pueden sufrir desventajas acumuladas, especialmente si estas barreras coinciden con menores niveles de renta o una oferta de servicios más limitada.

Aunque el análisis presentado aquí se centra en la Figura 2 como ejemplo representativo, constituye solo una parte del conjunto más amplio de patrones espaciales explorados en el capítulo de resultados, el cual incluye mapas adicionales, distribuciones estadísticas e indicadores comparativos.

COMPARACIÓN DE COSTES ENTRE MODOS DE TRANSPORTE EN SEVILLA

Además de las desigualdades temporales, resulta fundamental considerar la dimensión económica de la movilidad. Comprender cómo varían los costes según el modo de transporte aporta información valiosa sobre la carga financiera que soportan los usuarios y permite identificar desigualdades que no se reflejan únicamente en los indicadores de tiempo. Esta sección introduce la comparación entre los costes de desplazamiento en vehículo privado y en transporte público, teniendo en cuenta la distribución espacial y las características medias de los trayectos en el área metropolitana de Sevilla.

La Figura 3 muestra la distribución de los costes de viaje estimados por trayecto para ambos modos de transporte. Las diferencias entre ellos son inmediatamente evidentes. La distribución de costes del transporte público se concentra claramente en el extremo inferior del espectro, lo que indica una estructura tarifaria más uniforme y, en general, asequible. Su curva presenta un ascenso pronunciado y una ligera asimetría hacia la derecha, lo cual refleja sistemas tarifarios regulados mediante precios fijos o por zonas, característicos del transporte metropolitano.

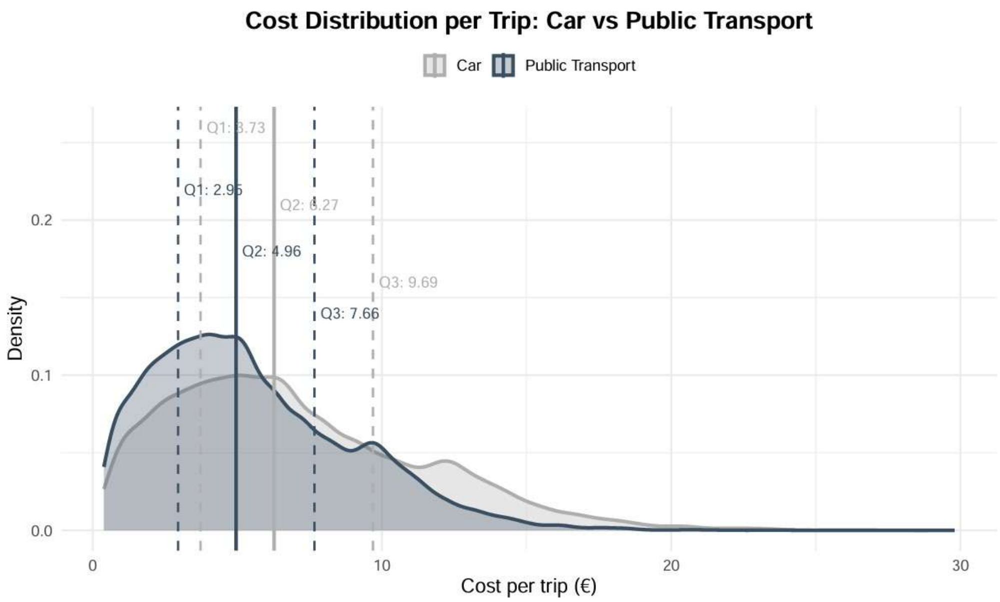

Figura 3: Distribución de los costes de viaje por trayecto según el modo (coche frente a transporte público) en la región de Sevilla

En cambio, la distribución de los desplazamientos en coche es más amplia y dispersa, con una cola derecha más pronunciada. Este patrón refleja una mayor variabilidad en los costes asociados al uso del vehículo privado, los cuales dependen de factores como la distancia, el consumo de combustible o los gastos de aparcamiento. En áreas de baja densidad o periféricas, donde los trayectos suelen ser más largos, los costes tienden a ser más heterogéneos y elevados.

La posición de los cuartiles refuerza este contraste. Los viajes en transporte público se concentran por debajo de los 5 €, con un primer cuartil (Q1) en 2,95 € y un tercer cuartil (Q3) en 7,66 €. Por el contrario, los desplazamientos en coche presentan un rango intercuartílico más amplio, que va desde los 3,73 € hasta los 9,69 €. Estas cifras subrayan la previsibilidad relativa del coste del transporte público frente a la volatilidad y mayor gasto medio del vehículo privado.

Este contraste revela una posible barrera económica para quienes viven en zonas dependientes del coche, donde la cobertura del transporte público es insuficiente o poco eficiente. En estos casos, el mayor coste del transporte privado puede representar una carga financiera desproporcionada, especialmente para los hogares con ingresos bajos o mayores necesidades de movilidad.

Aunque aquí se presenta únicamente el resumen relacionado con la Figura 3, este análisis de costes forma parte de un conjunto más amplio de indicadores desarrollados en el capítulo de resultados, que también incluye variaciones espaciales, relaciones entre costes modales y comparaciones integradas entre tiempo y coste para evaluar la equidad del sistema de transporte en Sevilla.

CLASIFICACIÓN FINAL DE LOS DISTRITOS SEGÚN SU NIVEL DE VULNERABILIDAD EN EL TRANSPORTE

La Figura 4 muestra la clasificación final de los distritos del área metropolitana de Sevilla según su nivel de vulnerabilidad en el transporte. Esta clasificación combina indicadores tanto de tiempo de viaje como de coste económico para los desplazamientos entre el hogar y el lugar de trabajo o estudio, asignando a cada distrito una de cinco categorías predefinidas (A–E). La metodología emplea umbrales estadísticos —concretamente el tercer cuartil (Q3)— para determinar si un distrito supera los límites aceptables en cualquiera de las dos dimensiones, asegurando así que la clasificación refleje desventajas relativas dentro del contexto metropolitano.

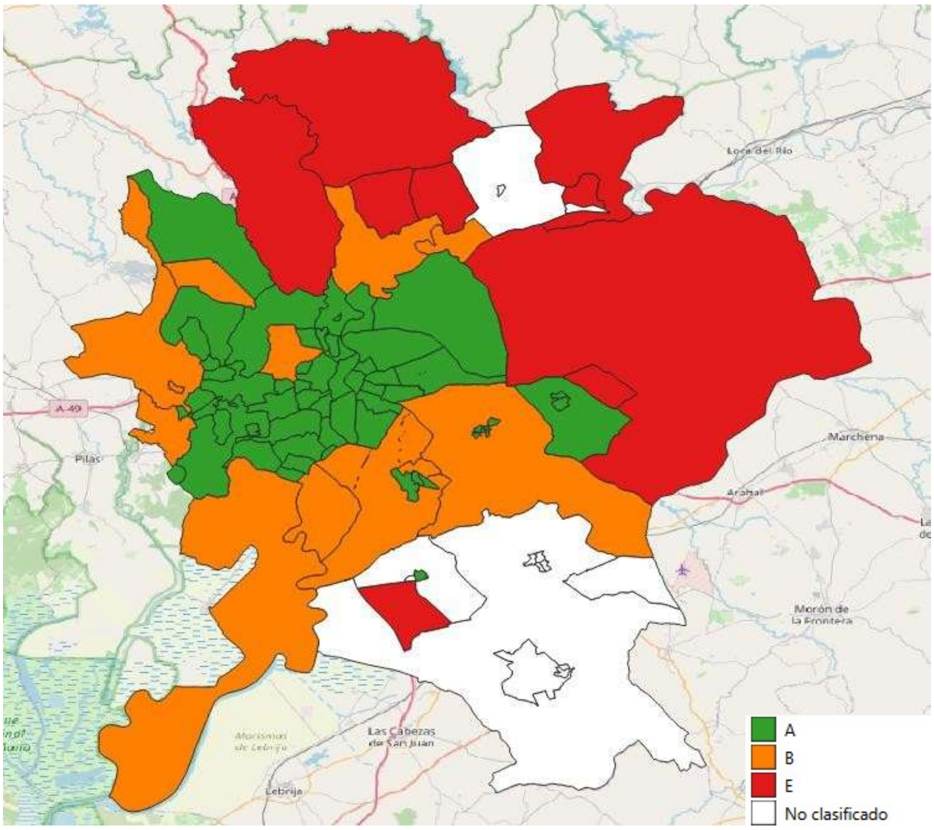

Figura 4: Clasificación final de los niveles de vulnerabilidad en el transporte en el área metropolitana de Sevilla.

Los resultados revelan un patrón espacial claro. Los distritos del Grupo A (color verde), situados principalmente en las zonas centrales y suroccidentales de Sevilla, presentan buenas condiciones de accesibilidad: tiempos de viaje cortos y bajos costes, especialmente mediante transporte público. Estas áreas están bien conectadas y cuentan con redes de transporte frecuentes e integradas.

Los distritos del Grupo B (color naranja), localizados en zonas más periféricas, permiten acceder en un tiempo razonable únicamente mediante vehículo privado, aunque sin que ello suponga una carga económica excesiva. Su dependencia del coche refleja la limitada cobertura del transporte público, lo que plantea interrogantes en términos de sostenibilidad ambiental y equidad en la movilidad.

El Grupo E (color rojo) incluye los distritos más vulnerables, ubicados mayoritariamente en los márgenes exteriores del área metropolitana. Estos territorios enfrentan tanto largos tiempos de viaje como altos costes, independientemente del modo de transporte utilizado, lo que puede limitar gravemente el acceso al empleo, a la educación y a servicios esenciales.

Esta clasificación final constituye una herramienta visual clara y útil para orientar las políticas públicas. Pone de relieve la necesidad de mejorar la cobertura y asequibilidad del transporte público, especialmente en los distritos periféricos donde las restricciones de movilidad son más acusadas.

5.- DISCUSIÓN

La discusión pone de manifiesto la existencia de desigualdades espaciales en la accesibilidad al transporte en el área metropolitana de Sevilla, determinadas por la combinación de los tiempos de viaje y los costes asociados. Los distritos periféricos enfrentan de forma sistemática mayores duraciones en los desplazamientos y una alta dependencia del vehículo privado, lo que incrementa la carga económica sobre poblaciones ya vulnerables. Aunque el transporte público representa una alternativa más asequible, sus limitaciones —como la baja frecuencia o las rutas indirectas— reducen su efectividad en muchas zonas.

El análisis también revela que los costes del transporte público son relativamente estables, mientras que los del vehículo privado presentan una mayor variabilidad, especialmente en áreas de baja densidad. Estos resultados subrayan la doble naturaleza de la desventaja en el transporte: las restricciones de tiempo y coste suelen solaparse, generando patrones estructurales de exclusión.

Desde una perspectiva política, el estudio ofrece recomendaciones útiles para diseñar intervenciones específicas, especialmente en los distritos con mayores déficits de accesibilidad. No obstante, también se reconocen ciertas limitaciones. Las suposiciones sobre el rendimiento promedio de los viajes y el uso de datos agregados a nivel distrital pueden ocultar variaciones internas y restricciones de movilidad individuales. Por ello, se propone que futuras investigaciones integren una mayor resolución espacial y variables sociodemográficas para profundizar en el análisis de la vulnerabilidad en el transporte.

En última instancia, el concepto de vulnerabilidad utilizado aquí es de carácter relativo, no absoluto: mide la desventaja en comparación con otros distritos. Esta perspectiva contribuye al desarrollo de estrategias de transporte más justas e inclusivas en el contexto urbano cambiante de Sevilla.

6.- CONCLUSIÓN

Este estudio ha analizado la accesibilidad al transporte en el área metropolitana de Sevilla, identificando importantes disparidades espaciales tanto en los tiempos de viaje como en los costes asociados. A través de la integración de datos GTFS de transporte público, matrices origen-destino y modelización geoespacial, la investigación pone de manifiesto cómo ciertos distritos—especialmente los periféricos—enfrentan desventajas sistémicas derivadas de trayectos largos, cobertura limitada del servicio y elevados costes de movilidad.

Los principales hallazgos confirman que la vulnerabilidad en el transporte en Sevilla es una cuestión multidimensional. En algunas zonas, los largos desplazamientos en coche suponen una carga económica; en otras, la ineficiencia del transporte público refleja la ausencia de alternativas viables. Las diferencias entre modos de transporte y tipos de trayecto—especialmente los relacionados con el trabajo y la educación—demuestran cómo el tiempo y el coste pueden actuar como verdaderas barreras al acceso a oportunidades y a la participación en la vida urbana.

Para operacionalizar estos patrones, el estudio desarrolló un sistema de clasificación que agrupa los distritos según su nivel de vulnerabilidad en materia de accesibilidad. Este marco ofrece una herramienta práctica para identificar áreas prioritarias de intervención política, especialmente aquellas en las que confluyen elevados tiempos de viaje y altos costes.

Aunque existen limitaciones metodológicas—como el uso de velocidades medias estimadas—el estudio presenta un enfoque escalable y replicable que puede aplicarse a la planificación basada en datos en otras ciudades. En última instancia, los resultados refuerzan la idea de que un transporte equitativo es clave para la justicia urbana, y que la planificación debe abordar no solo la infraestructura, sino también la asequibilidad, la integración y la equidad territorial.

7.- PRÓXIMOS PASOS

A partir de los resultados obtenidos, este estudio plantea diversas líneas de desarrollo futuro. Metodológicamente, el marco propuesto puede replicarse en otros contextos metropolitanos para identificar tanto factores comunes como específicos que determinan la vulnerabilidad en el transporte. Investigaciones futuras podrían incorporar variables adicionales como la frecuencia del servicio, su fiabilidad o datos en tiempo real, con el fin de captar patrones de accesibilidad más dinámicos y precisos.

A nivel institucional, los resultados ofrecen una herramienta práctica para las autoridades locales—en particular, el Ayuntamiento de Sevilla—con el fin de orientar intervenciones específicas en planificación, asignación de servicios o políticas tarifarias. Integrar estos hallazgos en procesos participativos podría además reforzar los resultados en términos de equidad.

Por último, este trabajo se alinea con los objetivos de política europea en materia de movilidad inclusiva y transición ecológica. Los indicadores de accesibilidad desarrollados pueden contribuir a estrategias a largo plazo basadas en datos para construir sistemas de transporte urbano más resilientes, equitativos y sostenibles.

ANALYSIS OF TRANSPORT ACCESIBILITY

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ABSTRACT

Keywords: accessibility, transport poverty, public transport

1.- PROJECT DESCRIPTION

This chapter introduces the foundations and context of the project, which aims to evaluate public transport accessibility in the metropolitan area of Seville. The main objective is to identify areas where residents face significant difficulties in reaching essential services such as employment, education, healthcare, or leisure. The study responds to the increasing importance of transport poverty as a multidimensional form of social exclusion, going beyond traditional economic affordability to include spatial and temporal barriers.

The work stands out for its trip-based analysis, considering various daily travel patterns such as commuting to work or school, frequent trips to places like gyms or supermarkets, and occasional or social outings. This perspective enables a more detailed understanding of inequalities in urban mobility.

The project integrates GTFS data, geospatial analysis, and R programming tools to calculate estimated travel times and accessibility indicators at the district level. Seville serves as a relevant case study due to its mixed urban structure and significant disparities in public transport coverage between central and peripheral areas.

The project also aligns with several Sustainable Development Goals (SDGs), particularly those addressing poverty, health, infrastructure, inequality, and climate action. Finally, the chapter discusses the context of transport poverty in Spain, highlighting its complexity and the different indicators used to quantify it, such as the percentage of income spent on transport and access to services. The analysis reflects how demographic, spatial, and economic factors intersect to shape mobility inequalities, especially in suburban and low-income areas.

2.- STATE OF THE ART

The academic debate on transport poverty reveals persistent gaps in how accessibility is defined and measured. While economic affordability has often been the central focus, many researchers argue that this perspective alone is insufficient. Accessibility involves not only cost, but also the spatial and temporal characteristics of transport systems, which can severely limit individuals' ability to participate in everyday life when poorly designed or distributed.

Various methodologies have attempted to address these limitations. Some studies rely on static indicators or financial proxies, while others incorporate more dynamic approaches such as time-dependent accessibility or activity space analysis. Although these methods offer valuable insights, they frequently overlook the physical structure and territorial layout of transport infrastructure, particularly in suburban or rural settings where public transport coverage is limited.

The role of innovation and technology also emerges as a critical factor in addressing transport inequalities. Real-time data, mobile applications, ride-sharing platforms, and the development of electric and autonomous vehicles offer new ways to improve both coverage and efficiency. Inclusive design principles, supported by policy tools like the European Social Climate Fund, further enhance the potential for accessible mobility solutions, especially for vulnerable groups.

Despite these advancements, there remains a need for studies that directly analyze public transport infrastructure in detail. Incorporating spatial and service-level dimensions into transport poverty assessments can provide a more accurate understanding of inequalities and inform policies that promote equitable and sustainable urban mobility.

3.- METHODOLOGY

The research applies a multi-stage methodological framework to assess transport accessibility across Seville's metropolitan area, integrating official mobility data, public transport network information, spatial indicators, and socioeconomic variables. The analysis follows five key phases: data collection, preprocessing and cleaning, spatial integration, travel time estimation, and the construction of accessibility and cost indicators.

Primary data sources include the origin-destination mobility matrix from the Ministry of Transport, Mobility and Urban Agenda (MITMA), which provides detailed trip flows between districts with variables such as trip purpose, distance, and demographic segmentation. Four GTFS feeds—covering buses, metro, tram, and commuter rail—were merged to reconstruct Seville's multimodal public transport system. In addition, geographic centroids were used to anchor trips spatially, and socioeconomic data on household and individual income were obtained from the Seville City Council's statistical office.

The study area encompasses the full metropolitan region of Seville, chosen for its diverse urban morphology and high-quality transport datasets. A cleaning and filtering process removed inconsistent or incomplete records and focused on inter-district trips to better reflect structural accessibility. All datasets were georeferenced and harmonized to allow spatial analysis and realistic multimodal routing.

Public transport travel times were estimated using GTFS-based routing simulations for a typical Monday morning at peak hour (6:00 AM). These simulations calculated the estimated total travel time, number of transfers, and the transport lines used between origin-destination pairs. When no feasible connection was available, the trip was excluded from subsequent analysis. Parallel processing was applied to accelerate route computations for high-volume travel flows.

To provide a more comprehensive view of accessibility, socioeconomic context was incorporated through district-level income indicators. Notable income disparities across districts were identified, with lower-income areas often experiencing longer travel times and less frequent services, reinforcing the importance of transport equity in urban planning.

The MITMA matrix was enriched with spatial coordinates and trip-level data on travel distance, duration, and cost per transport mode. Travel distances were adjusted using detour indices (1.3 for car, 1.5 for public transport) to account for non-linear routing. Estimated travel times were then calculated using average speeds—30 km/h for car and 25.77 km/h for public transport—based on official statistics.

Transport costs were calculated using per-kilometer rates: €0.35/km for private vehicles and €0.24/km for public transport, the latter derived from a weighted average of actual fare and distance data from Metro de Sevilla and RENFE Cercanías services. This enabled the construction of three comparative datasets: one for travel time, one for distance, and one for cost, disaggregated by trip type and mode.

By combining network efficiency, spatial distribution, and socioeconomic vulnerability, this methodological design enables a multidimensional assessment of accessibility and highlights the inequalities embedded within the urban transport system. The results serve as a basis for identifying disadvantaged districts and supporting data-driven planning aimed at promoting equitable mobility.

4.- RESULTS

TRAVEL TIME PATTERNS ACROSS SEVILLE

FUNCTIONAL PROFILES OF INTER-DISTRICT DESTINATIONS

Within the broader results section, this subsection focuses on the analysis of travel time patterns across the metropolitan area of Seville, with particular attention to the functional purpose of inter-district trips. The aim is to understand how different municipalities serve as destinations for distinct types of activities—such as work, education, daily errands, or occasional visits—thereby uncovering their roles within the urban mobility system. This disaggregated approach allows for a deeper interpretation of spatial dynamics that shape accessibility and help identify variations in demand and land use.

‘Figura 5’ presents the ten municipalities that receive the highest volume of inter-district trips, as identified through aggregated data from the full mobility matrix. Each bar breaks down the percentage of trips by four categories of destination activity: work/study, frequent travel, non-frequent travel, and home. This visualisation enables both quantitative and qualitative comparisons between municipalities based on the functional nature of the trips they attract.

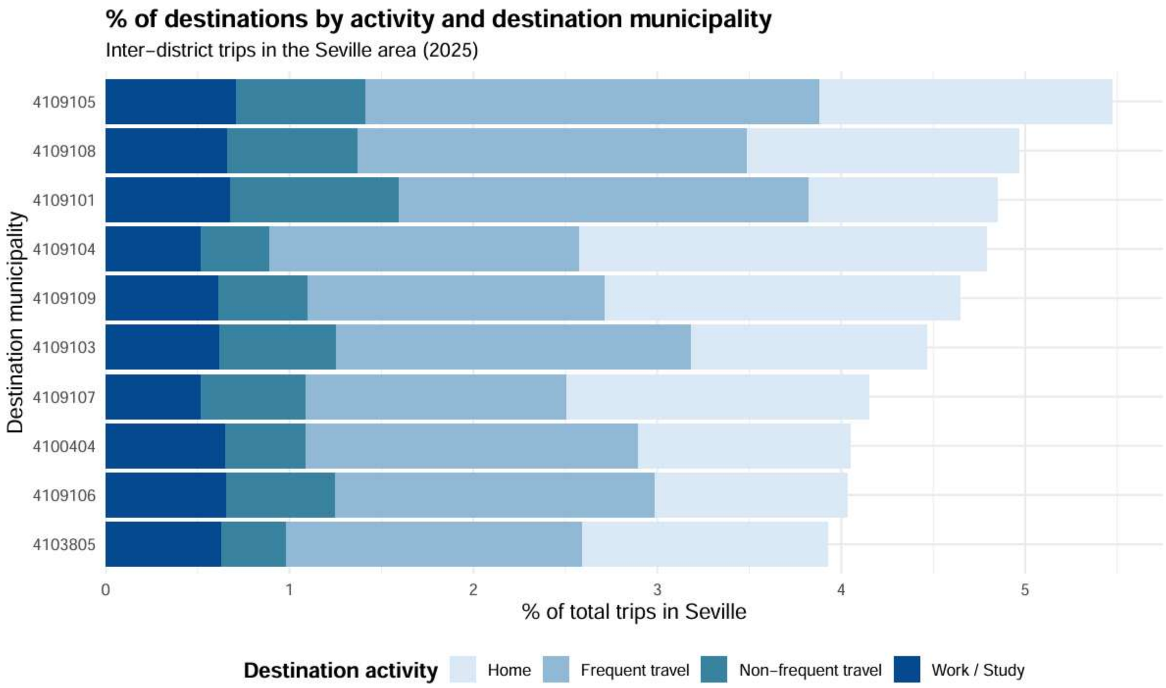

Figura 5: Percentage of destinations by activity and destination municipality

One key observation is the relatively uniform presence of work and study-related trips across all ten municipalities. This consistency suggests a decentralised pattern of employment and education destinations, where multiple areas contribute equally to the city's functional structure rather than relying on a single dominant centre.

In contrast, the proportions of frequent and non-frequent trips vary more noticeably. Some districts, such as 4109103 and 4109104, show higher shares of frequent trips, likely linked to regular services like shopping or healthcare. Others, including 4109108 and 4109109, attract more non-frequent travel, which may indicate destinations related to administrative or cultural activities visited less regularly.

The 'home' category also varies in significance. Districts such as 4109105 and 4109101 register a higher percentage of home-bound trips, possibly reflecting their residential nature or their function as common endpoints in return journeys. Conversely, service-oriented or employment-focused municipalities show a slightly lower presence of this category.

The internal composition of trips within each municipality provides valuable insight into the area's functional role. For example, while two municipalities may attract a similar overall number of trips, the purposes of those trips can differ markedly—indicating different urban profiles, levels of service provision, or degrees of accessibility. These contrasts suggest that spatial inequality is not only a matter of quantity but also of functional orientation.

Although the current summary highlights only some findings, it represents a small part of a broader and more detailed analysis presented in the results chapter. The full section includes multiple figures and complementary indicators aimed at capturing the spatial structure of accessibility and the underlying inequalities across the Seville metropolitan area.

SPATIAL DISTRIBUTION OS TRAVEL TIMES IN SEVILLE

Complementing the previous analyses based on travel purposes and trip types, this section introduces a spatial lens to evaluate how temporal disparities in mobility are distributed across the Functional Urban Area (FUA) of Seville. Understanding the geography of travel times provides valuable insight into how accessibility conditions differ from one district to another, revealing patterns that may not be captured by aggregate figures alone.

‘Figura 6’ displays the average travel time per district, with a clear visual gradient that distinguishes central zones from peripheral ones. Districts located in the urban core of Seville appear in lighter tones, indicating shorter average travel durations. These areas benefit from a high concentration of services, relatively short distances between key destinations, and denser public transport coverage.

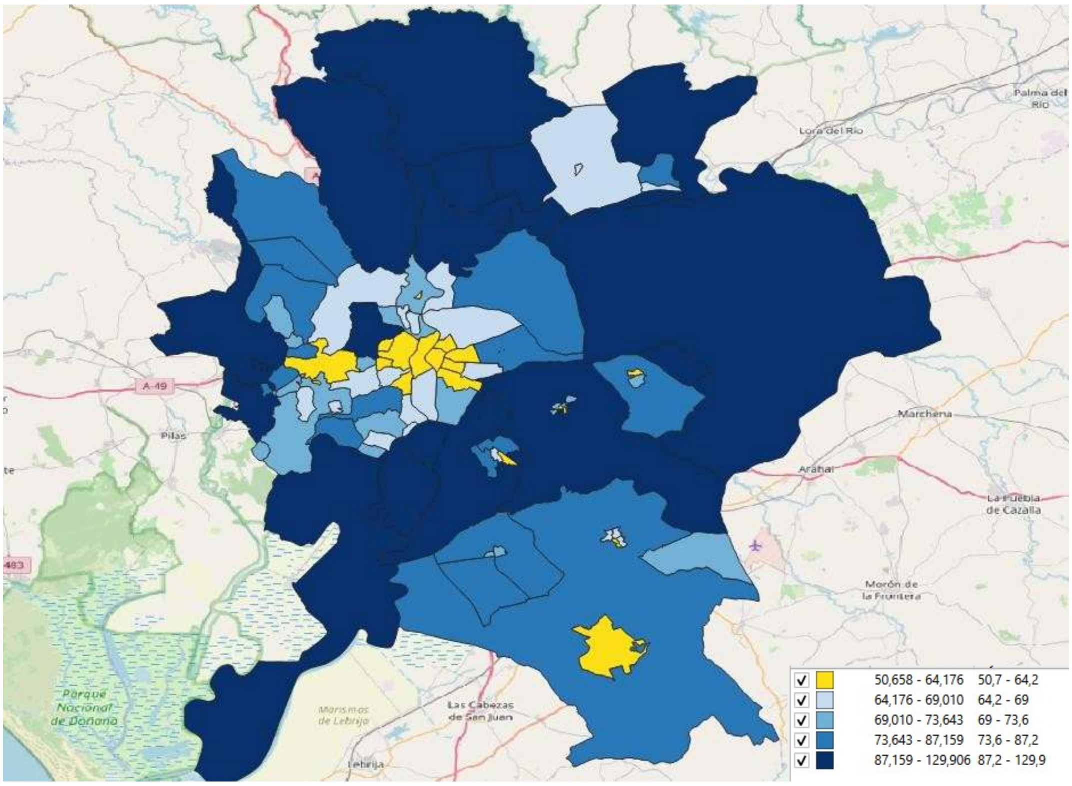

Figura 6: Average public transport travel time per district in the Seville Functional Urban Area (2025)

In contrast, the peripheral municipalities—particularly those on the metropolitan edges to the north, northeast, southeast, and southwest—are shaded in darker tones, reflecting significantly higher travel times. These districts tend to be farther from employment and service centers and are often more dependent on inter-municipal transport systems, which may operate with lower frequency or weaker integration. The southernmost districts also exhibit longer durations, likely due to their geographic isolation.

This spatial distribution is consistent with typical urban mobility patterns, where centrality is associated with better connectivity and shorter travel times, while distance from the urban core implies greater time burdens for accessing everyday activities. These findings reinforce the importance of spatial equity in transport planning. Districts persistently facing longer travel times may experience compounding disadvantages, especially if these barriers intersect with lower income levels or reduced service availability.

Although the analysis presented here is focused on 'Figura 6' as a representative example, it reflects only a small portion of the broader set of spatial patterns explored in the full results chapter, which includes additional maps, statistical distributions, and comparative indicators.

TRAVEL COST PATTERNS ACROSS SEVILLE

COST COMPARISON BETWEEN TRANSPORT MODES IN SEVILLE

In addition to temporal disparities, it is essential to consider the economic dimension of mobility. Understanding how costs vary across transport modes offers valuable insight into the financial burden experienced by users and helps identify inequalities that may not be captured through time-based indicators alone. This section introduces the comparison between private vehicle and public transport travel costs, taking into account spatial distribution and average trip characteristics across the metropolitan area of Seville.

'Figura 7' illustrates the distribution of estimated travel costs per trip for both private cars and public transport. The differences between the two modes are immediately apparent. The cost distribution for public transport is highly concentrated toward the lower end of the spectrum, indicating a more uniform and generally affordable price structure. Its curve shows a steep rise and a moderate rightward skew, reflecting typical fare capping or zone-based pricing commonly found in metropolitan transit systems.

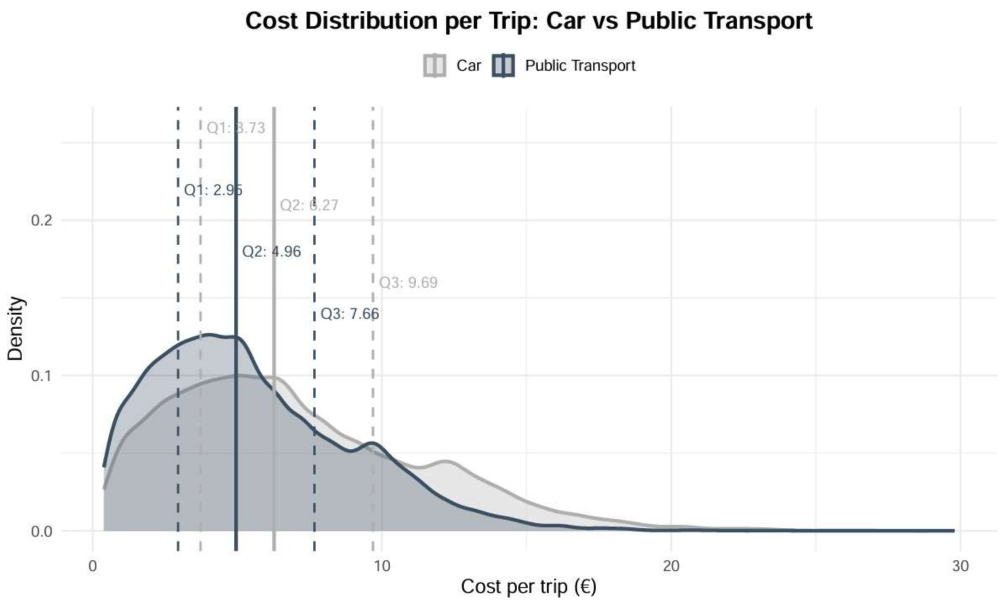

Figura 7: Distribution of travel costs per trip by mode (car vs public transport) across the Seville region.

By contrast, the distribution for car trips is broader and more dispersed, with a heavier right tail. This pattern reflects greater variability in car-related expenses, which depend on a combination of factors such as distance, fuel consumption, and parking. Car trips, especially in low-density or peripheral areas, often cover longer distances, resulting in more heterogeneous and generally higher costs.

The position of the quartiles reinforces this contrast. Public transport trips cluster below the €5 mark, with Q1 at €2.95 and Q3 at €7.66, while car trips exhibit a wider interquartile range, extending from €3.73 to €9.69. These figures underscore the relatively predictable cost structure of public transport, versus the volatility and higher average expense associated with private vehicle use.

Importantly, this discrepancy highlights a potential barrier for individuals in car-dependent areas, where public transport coverage is insufficient or inefficient. In such cases, the higher cost of car travel may place a disproportionate financial burden on households, particularly those with lower incomes or greater mobility needs.

Although the focus here is on the summary presented in ‘Figura 7’, this cost analysis is part of a broader set of indicators developed in the results chapter, which also includes spatial variations, modal cost ratios, and combined time-cost comparisons to assess overall transport equity across Seville.

FINAL CLASSIFICATION OF DISTRICTS BY TRANSPORT VULNERAVILITY LEVEL

'Figura 8' presents the final classification of districts in the metropolitan area of Seville according to their level of transport vulnerability. This classification combines both travel time and cost indicators for home-to-work/study trips, assigning each district to one of five predefined categories (A–E). The methodology applies statistical thresholds—specifically, the third quartile (Q3)—to determine whether a district exceeds acceptable limits in either dimension, ensuring that the classification reflects relative disadvantage within the metropolitan context.

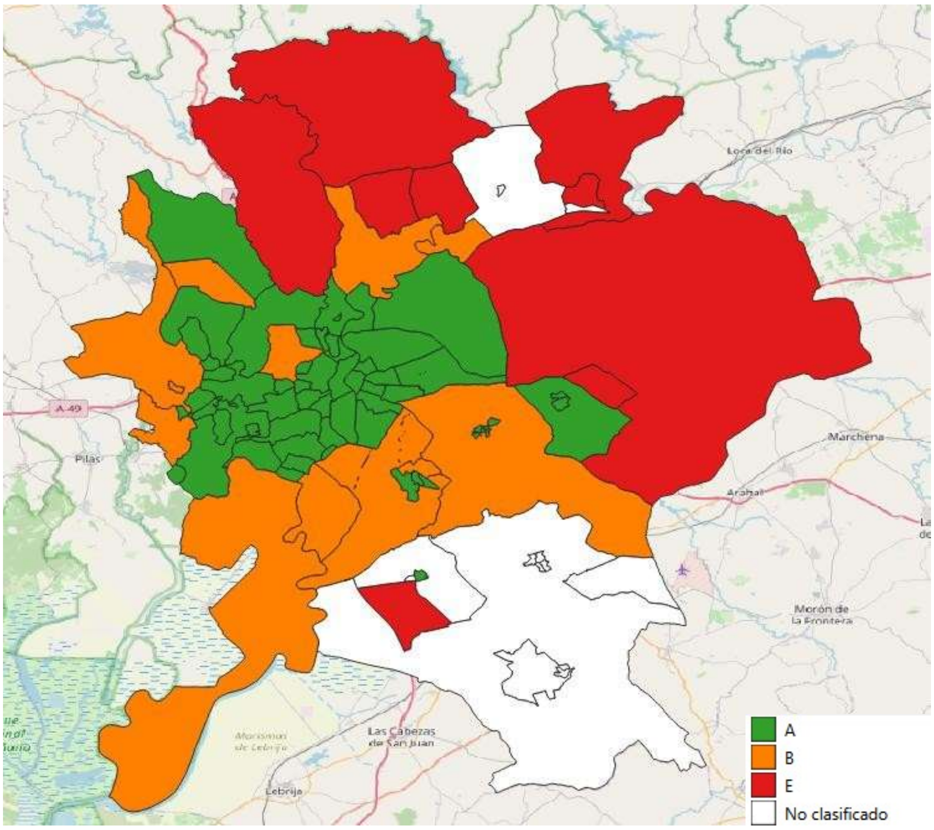

Figura 8: Final classification of transport vulnerability levels across the metropolitan area of Seville.

The results show a clear spatial pattern. Districts in Group A (green), located mainly in the central and southwestern parts of Seville, enjoy good accessibility conditions: short travel times and low costs, primarily using public transport. These areas are well served by frequent and integrated transit networks.

Group B districts (orange), found in more peripheral zones, offer timely access only via private vehicle, though without a significant financial burden. Their reliance on car use reflects limited public transport availability, raising concerns about environmental impact and transport equity.

Group E (red) includes the most vulnerable districts, predominantly on the outer edges of the metropolitan area. These territories face long travel times and high costs regardless of the mode of transport, which can severely limit access to employment, education, and essential services.

This final classification provides a clear and actionable visual tool for identifying where policy efforts should focus. It highlights the need to improve public transport coverage and affordability, particularly in those outer districts where mobility constraints are most severe.

5.- DISCUSSION

The discussion highlights the existence of spatial inequalities in transport accessibility across Seville's metropolitan area, shaped by the combined effects of travel time and cost. Peripheral districts consistently face longer travel durations and higher dependence on private vehicles, which increases the financial burden on already vulnerable populations. While public transport offers a more affordable option, its limitations—such as low frequency and indirect routes—diminish its effectiveness in many areas.

The analysis also reveals that public transport costs are relatively stable, whereas private vehicle costs vary more widely, particularly in low-density zones. These findings underscore the dual nature of transport disadvantage: time and cost constraints often overlap, generating structural patterns of exclusion.

From a policy perspective, the study offers practical insights for designing targeted interventions, especially in districts with the most severe accessibility gaps. However, limitations remain. Assumptions on average travel performance and aggregated district-level data may mask internal variability and individual mobility constraints. The study recommends future research incorporating higher spatial resolution and socio-demographic variables to deepen the understanding of transport vulnerability.

Ultimately, the concept of vulnerability used here is relative, not absolute—measuring disadvantage in comparison to other districts. This perspective supports the development of fairer, more inclusive transport strategies in Seville's evolving urban context.

6.- CONCLUSION

This study has examined transport accessibility in Seville's metropolitan area, uncovering significant spatial disparities in both travel time and cost. By integrating GTFS public transport data, OD matrices, and geospatial modelling, the research highlights how certain districts—particularly peripheral ones—face systemic disadvantages due to long travel durations, limited service coverage, and high mobility costs.

Key findings reveal that transport vulnerability in Seville is multidimensional. In some areas, long car commutes signal economic burden; in others, inefficient public transport reflects a lack of viable alternatives. The differences between modes and trip types—especially for work and education—demonstrate how time and cost function as real barriers to opportunity and participation in urban life.

To operationalise these patterns, the study developed a classification system that groups districts by their levels of accessibility-related vulnerability. This framework offers a practical tool for identifying priority areas for policy intervention, particularly where both time and cost burdens converge.

While methodological limitations exist—such as assumptions on average travel speeds—the study presents a scalable and replicable approach that can support data-driven planning in other cities. Ultimately, the findings reinforce the notion that equitable transport is central to urban justice, and that planning must address not only infrastructure, but also affordability, integration, and territorial equity.

7.- FUTURE STEPS

Building on its findings, this study outlines several pathways for future development. Methodologically, the proposed framework can be replicated in other metropolitan contexts to identify shared and context-specific drivers of transport vulnerability. Future research could also integrate variables such as service frequency, reliability, and real-time data to capture dynamic accessibility patterns more accurately.

At the institutional level, the results offer a practical tool for local authorities—particularly the Seville City Council—to inform targeted interventions in planning, service allocation, and fare policies. Incorporating these insights into participatory processes could further enhance equity outcomes.

Finally, this work aligns with broader European policy goals related to inclusive mobility and green transition planning. The accessibility indicators developed here can contribute to long-term, data-driven strategies for building more resilient, equitable, and sustainable urban transport systems.

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CHAPTER 1. PROJECT DESCRIPTION

1.1 PROJECT OBJECTIVE AND MOTIVATION

The objective of this thesis is to assess public transport accessibility in the metropolitan area of Seville, identifying areas where residents experience significant disadvantages when trying to reach essential services such as employment, education, healthcare, or leisure. The project responds to the growing relevance of transport poverty as a social issue and aims to go beyond traditional analyses focused solely on economic affordability.

What distinguishes this work is its detailed examination of accessibility through the lens of different types of daily trips. These include travel from home to workplaces or ed ucational centers, frequent destinations such as shops or gyms, and occasional or social activities. This trip-based approach provides a more nuanced understanding of transport inequality within the urban fabric.

The project is also motivated by the lack of applied, data-driven studies that integrate GTFS transport data, geospatial analysis, and R programming tools to evaluate mobility conditions at a district level. By building accessibility indicators and calculating estimated travel times across modes and areas, the study offers a replicable methodology that can support future planning and policy development.

Ultimately, this work seeks to contribute to a broader discussion on transport equity, helping identify which neighborhoods and travel patterns are most affected by poor accessibility and offering insights to guide more inclusive and effective transport interventions.

1.2 ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

This project is intricately aligned with several Sustainable Development Goals (SDGs) established by the United Nations. This alignment underscores the project's broader impact on fostering sustainable, inclusive, and equitable development by addressing the critical issue of transport poverty and improving accessibility for all.

1. SDG 1: No Poverty

○ **Contribution:** By addressing transport poverty and enhancing accessibility to essential services, the project contributes to reducing poverty. Improved transport options enable better access to employment, education, and healthcare, which are crucial for poverty alleviation.

2. **SDG 3: Good Health and Well-being**

○ **Contribution:** Enhancing transportation accessibility ensures that individuals, especially those in vulnerable groups, can reach healthcare facilities more easily. This contributes to better health outcomes and overall well-being by reducing barriers to accessing medical care.

3. SDG 9: Industry, Innovation, and Infrastructure

○ **Contribution:** The project emphasizes the role of technological innovations and smart mobility solutions in improving transport infrastructure. By advocating for inclusive and sustainable transport systems, the project supports the development of resilient infrastructure and promotes inclusive industrialization.

4. SDG 10: Reduced Inequality

○ **Contribution:** By identifying and addressing the needs of vulnerable populations affected by transport poverty, the project aims to reduce inequalities in access to transportation. Ensuring equitable access to transport services helps bridge social and economic disparities.

5. SDG 11: Sustainable Cities and Communities

- **Contribution:** The project supports the creation of sustainable urban mobility plans that prioritize safe, inclusive, and affordable public transport. This aligns with the goal of making cities and human settlements inclusive, safe, resilient, and sustainable.

6. SDG 13: Climate Action

- **Contribution:** Promoting the use of electric and autonomous vehicles, along with other green transport options, contributes to reducing greenhouse gas emissions. This aligns with efforts to combat climate change and its impacts by fostering low-carbon transport solutions.

Through these contributions, the project not only addresses immediate transport issues but also advances broader global efforts towards a sustainable, inclusive, and equitable future.

1.3 DESCRIPTION OF SEVILLE

Seville is the fourth-largest city in Spain and the capital of the Andalusia region. As of 2021, the city itself had a population of approximately 684,000 inhabitants, while its wider metropolitan area exceeds 1.5 million people. The city presents a diverse urban structure, combining a compact historic center with expanding suburban districts. Seville's public transport system includes urban and metropolitan buses, a single metro line, a tram network, and regional commuter rail services. However, disparities in frequency, coverage, and connectivity are evident between central and peripheral areas, often limiting access to key services for residents in outlying neighborhoods. These contrasts make Seville a particularly suitable case study for analyzing spatial inequalities in transport accessibility and for understanding how urban form and infrastructure shape everyday mobility.

1.4 CONTEXT

The fight against climate change and the path toward carbon neutrality by 2050, as outlined in the Paris Agreement, place the transport sector at the center of Europe's energy transition. In the European Union, transport is responsible for over 25% of greenhouse gas emissions. While progress has been made in energy poverty recognition, transport poverty remains a lesser-known but equally urgent dimension of social vulnerability, particularly in the context of rapid decarbonisation.

Transport poverty refers to the inability or difficulty experienced by individuals and households in accessing or affording the transport systems necessary for full participation in social and economic life. This includes not only financial limitations, but also spatial, temporal, and physical barriers. In Spain, transport is the third-highest household expense, after housing and food, accounting for more than 10% of family budgets. Recent studies estimate that between 1.3 and 1.8 million people in Spain live in households affected by severe transport vulnerability, particularly in suburban, rural, and low-income urban areas.

The European Parliament has stressed the importance of defining and measuring transport poverty, recognizing that the shift toward greener mobility—while essential—can disproportionately affect vulnerable populations. Measures such as low-emission zones, fuel taxes, or infrastructure investment often fail to account for existing inequalities, especially among those who rely heavily on private vehicles due to the lack of accessible public transport.

Moreover, the problem is exacerbated by demographic and territorial disparities. Households with limited income, those living far from service hubs, and families whose members work irregular hours or are self-employed often face long travel times and few mobility options.

Transport poverty intersects with other dimensions of social exclusion, including employment, education, health access, and digital connectivity.

Spain's national and regional frameworks—such as the Long-Term Decarbonisation Strategy and the Integrated National Energy and Climate Plan—have begun to acknowledge these challenges. However, addressing transport poverty requires more granular, city-level analyses that reveal how mobility barriers manifest in specific territories.

In this context, the city of Seville presents a particularly relevant case. With a diverse urban structure and uneven public transport distribution, many districts face accessibility challenges that limit opportunities for social and economic inclusion. This project aims to contribute to that discussion by identifying spatial patterns of transport disadvantage and proposing evidence-based insights to support more inclusive urban planning.

1.5 CONCEPTUAL FRAMEWORK

Transport poverty is gaining visibility in European discussions on sustainability, social inclusion, and mobility equity. However, it remains a complex and multidimensional phenomenon, requiring coordination across policy levels and robust frameworks for analysis. The European Parliament, Council, and Commission have adopted a shared definition, stating that transport poverty refers to:

"The inability or difficulty of individuals and households to cope with the costs associated with public or private transport systems, or their lack of access or limited access to the means necessary to carry out their daily travel to essential services and activities."

This concept includes not only affordability issues but also broader structural and geographic limitations, such as the lack of nearby transport options, long travel times, and poor transport system connectivity.

Multiple indicators have been proposed internationally to assess transport poverty. Some focus on economic burden, such as:

- **The 10% rule**, where households are considered transport-poor if they spend over 10% of their income on transport.
- **The 2M indicator**, which defines poverty when transport costs are twice the national median.
- **The Low Income High Cost (LIHC)** method, adapted from energy poverty metrics, where households are considered vulnerable if they fall below a certain income threshold after deducting housing and transport costs.

Other models highlight spatial or accessibility dimensions. For instance, the Sustrans approach (UK) considers three combined factors: high transport costs, distance from the nearest public transport stop, and lack of nearby essential services. Meanwhile, researchers like Mattioli et al. emphasize how mobility needs and transport systems interact with household structure, income, and location.

In Spain, recent studies suggest that between 1.3 and 1.8 million people live in households suffering from severe transport vulnerability. These include families spending over 10% of their income on transport and those living in areas with poor service coverage. Socioeconomic factors compound the issue: households in rural or peripheral urban areas, with low income or with self-employed members, are more likely to face transport-related hardship.

In addition to affordability and access, time is emerging as a critical component of analysis. Travel time can significantly affect quality of life and limit access to employment, education, or healthcare. Spatial analyses using observed travel patterns, such as those conducted by the Instituto de Investigación Tecnológica (IIT) or BC3, explore how different profiles of vulnerability can be identified in both urban and metropolitan contexts. Indicators linked to travel time, fuel costs, income level, and distance to workplaces or basic services are now commonly used to evaluate accessibility gaps.

This multidimensional approach shows that transport poverty is not only an economic issue but also one of equity, planning, and territorial justice. It is essential to adopt this broader understanding to design public policies that truly address structural barriers and ensure that the energy and mobility transition leaves no one behind.

1.6 THE SITUATION IN SPAIN

Quantifying transport poverty and vulnerability in Spain presents a significant challenge due to the complexity of the phenomenon and the variety of available measurement approaches. Different methodologies and indicators yield varying estimates, reflecting both economic and accessibility-related aspects of transport disadvantage.

According to the Basque Centre for Climate Change (BC3), household vulnerability to transport costs can be assessed using several key indicators: the 10% rule, the 2M (double the national median), and two multidimensional measures: LIHC (Low Income, High Costs) and VTU (Transport Vulnerability Unit).

- The 10% rule defines a household as vulnerable if it spends more than 10% of its income on transport. Based on this, more than 2.5 million households in Spain were classified as vulnerable in 2021, equivalent to 6.68 million people.

- The 2M metric identifies households that spend a proportion of their income on transport that is twice the national median. This captures a broader group—approximately 4.76 million people in 2021—although it tends to include many who are not necessarily transport-poor in practice.

- The LIHC indicator focuses on households that fall below 60% of the median income after covering housing and transport costs. It identified around 1.45 million people as severely transport-vulnerable in 2021.
- The VTU index, more restrictive, incorporates not just financial hardship but also poor access to public transport. It reported 1.05 million people in situations of severe transport vulnerability.

The data also shows clear temporal trends. From 2006 to 2014, there was a significant increase in transport vulnerability, largely attributed to rising energy prices, falling incomes, and the aftermath of the 2008 economic crisis. Vulnerability peaked around 2012, particularly under the 2M metric. A moderate decline was observed from 2014 to 2018, and a sharp drop occurred in 2020, largely driven by the COVID-19 pandemic and the resulting reduction in mobility and fuel consumption. For example, the proportion of households using transport services dropped from 69.4% in 2019 to 55.8% in 2020.

Household fuel spending is a central concern. According to Sanz Fernández (2023), about 21% of Spanish households spend more than twice the national median on fuel, representing a substantial burden, especially for low-income groups. The territorial distribution of this burden is uneven: rural and peripheral regions, where public transport is limited and private vehicles are essential, are disproportionately affected. In contrast, urbanized areas with stronger transport networks, such as Madrid, the Basque Country, and Catalonia, generally report lower vulnerability.

The analysis also reveals structural patterns. Households with "forced mobility"—where residents must travel long distances for work—face high time and fuel costs, often unrelated to income levels. These dynamics underscore the need to consider transport poverty as a multidimensional issue, integrating economic, spatial, and temporal factors.

A spatial typology of vulnerability developed by Sanz (2023) classifies municipalities into three rings based on their proximity to Madrid. The innermost ring, despite high transport use, shows moderate vulnerability. The second ring shows increased risk due to the presence of car-dependent commuting patterns. The outermost ring, composed of smaller, more isolated towns with poor accessibility, displays the highest levels of transport vulnerability across all indicators. These municipalities often rely on a single transport mode, have limited service options, and their populations report making transport-related decisions based on cost rather than need, revealing deep economic constraints.

In conclusion, Spain's national context illustrates that transport poverty is not a marginal issue, but a widespread and complex problem influenced by income, geography, energy prices, and public policy. Any strategy to address it must consider these overlapping dimensions to prevent deepening inequalities—particularly in the face of future transitions in mobility and energy.

CHAPTER 2. STATE OF THE ART

The concept of transport poverty can be broadly understood as the condition in which individuals or households are unable to access adequate transport options to meet essential needs such as employment, education, and social inclusion. Several academic papers have been reviewed in order to assess transport poverty, but there remains a significant gap in how accessibility is defined and measured.

The work of Lucas, Mattioli, Verlinghieri, and Guzman (2016) identifies accessibility poverty as the inability to reach essential services or activities within reasonable time or cost, emphasizing its relevance as a key dimension of transport poverty. However, much of the existing research focuses heavily on affordability, which is important, but not key when tackling this huge problem.

Studies like Mattioli (2017) highlight how forced car ownership arises when individuals are compelled to own vehicles due to inadequate public transport, thus focusing on the affordability side of transport poverty. Similarly, the Social Exclusion Unit (2003) report underscores how inadequate transport access can lead to broader social exclusion. In contrast, Gomide, Leite and Rebelo (2005) and Benevenuto and Caulfield (2020) propose spatial accessibility indices, taking into account factors such as distance to public transport and service frequency. These studies provide more quantitative methods to assess accessibility but still rely on proxies or static data that may not fully capture real-time service availability or adequacy.

The Vulnerability Index for Petrol Expense Rises (VIPER), introduced by Dodson and Sipe (2007), further emphasizes the financial burden of transport in suburban areas but lacks an in-depth exploration of public transport infrastructure. Meanwhile, Tao et al. (2020) propose an activity space approach, which evaluates the range of locations individuals can access within a given time frame.

A more recent study by Allen and Farber (2019) brings this discussion into a national context by examining transport poverty in Canada. The authors analyze access to employment in eight major cities and highlight that nearly one million low-income Canadians live in areas with low transit accessibility. Despite improvements in urban public transport, a significant portion of the low-income population in suburban areas remains vulnerable to transport poverty due to the lack of adequate transit options. Their findings also recommend targeting transit investments in underserved areas and exploring ride-sharing solutions for low-density suburbs, thereby addressing both spatial and socioeconomic inequalities.

The gap identified in the literature, particularly in works like those of Alonso-Epelde, García-Muros and González- Eguino (2023), lies in the use of simple proxies for accessibility, such as public transport expenditure. While these proxies offer a practical approach, they do not sufficiently consider the actual layout of transport services. This lack of comprehensive data limits the ability to assess true accessibility, especially in rural or suburban areas where public transport is often sparse.

Tao, He, Kwan and Luo (2020) investigate how income levels affect mobility by analyzing activity space in Hong Kong, which examines the range of locations people can access within a given timeframe. Their findings highlight how lower-income individuals often face reduced mobility, though they focus on temporal rather than other key dimensions of accessibility. This indicates a gap in understanding how the geographical layout of transport services affects accessibility for different income groups.

Cebollada (2006) focuses on the relationship between territory and daily mobility to understand social exclusion processes. This research emphasizes how territorial factors shape individuals' ability to move freely and access essential services. While this study contributes to understanding territorial inequality, it lacks a detailed analysis of how specific transport infrastructure contributes to accessibility challenges, leaving a gap that this research can address.

Another critical gap is highlighted by Litman (2021), who examines transport affordability and its impact on individuals' access to services. Although Litman addresses affordability extensively and proposes strategies for improvement, the study primarily focuses on the economic aspect and does not delve deeply into how transport options impacts accessibility.

Fransen, Neutensm Farber, De Maeyer, Deruyter and Witlox (2015) take a different approach by analyzing public transport gaps using time-dependent accessibility levels. Their research uses advanced models to assess how public transport services can create barriers to accessibility based on the timing and availability of services. However, while time-dependent models are valuable, this study does not focus on the physical distribution of transport infrastructure, which is essential for understanding the access to transport services.

The European Commission's sustainable and smart mobility strategy emphasizes the importance of safe, inclusive, and affordable public transport as the core of sustainable urban mobility planning. Technological advancements in smart mobility can significantly alleviate transport poverty by improving the efficiency and accessibility of transport services. For instance, real-time data analytics and IoT (Internet of Things) can optimize public transport routes and schedules, ensuring adequate frequency and coverage, particularly in underserved areas (European Commission, 2020).

In addition to all these approaches, technological innovations such as digital platforms and mobile apps are crucial for improving transport accessibility by offering real-time information on public transport schedules and routes. Additionally, ride-sharing and carpooling apps provide flexible and cost-effective transport solutions, particularly benefiting low-income individuals and those in remote areas. The shift to electric vehicles offers environmental and cost benefits through reduced fuel consumption, though their higher acquisition costs pose challenges, potentially mitigated by subsidies.

Autonomous vehicles hold the potential to enhance accessibility, especially for people with disabilities, by offering independent mobility options, though their affordability depends on their integration into transport systems. Inclusive transport design, such as low-floor buses and accessible train carriages, and universal design principles in infrastructure, can remove barriers for individuals with disabilities. Furthermore, the European Commission's Social Climate Fund supports vulnerable households by reducing transport costs through investments in greener transport and income support.

These solutions are key to enhancing the accessibility, affordability, and inclusivity of transport services, especially for disadvantaged groups. By adopting these innovations, policymakers can create a more equitable and sustainable transport system. Furthermore, there is a critical need for research that incorporates specific details and analysis of public transport infrastructure using new dimensions, offering a thorough understanding of how the system impacts accessibility and transport equity.

CHAPTER 3. METHODOLOGY

This section describes the methodology followed to evaluate transport accessibility in the metropolitan area of Seville, combining official mobility data, public transport network information, and socioeconomic indicators. The approach consisted of five stages: data collection, preprocessing and cleaning, integration of geographic and transport network data, estimation of travel times and distances, and the construction of accessibility indicators.

3.1 DATA SOURCES

The analysis was based on several open-access datasets from official institutions. The most important were:

- **Mobility Data**: the Ministry of Transport, Mobility and Urban Agenda (MITMA) provides a highly detailed origin-destination mobility matrix that describes flows of individuals between districts in Spain. The dataset, downloadable from its online portal, includes fields such as origin and destination codes, purpose of travel (e.g., commuting, leisure), estimated travel distance bands (e.g., 10–15 km), number of trips (viajes), and total kilometers traveled (viajes_km). Additional demographic information, such as age, gender, income, and residency, is included when available.

- **Public Transport Network Data (GTFS)**: four General Transit Feed Specification (GTFS) feeds were collected to model Seville's multimodal public transport system:
  - **TUSSAM**: Urban bus lines and tram.
  - **Metro de Sevilla**: Metro line 1.
  - **Consorcio Metropolitano**: Regional intercity buses.

- **RENFE Cercanías**: Commuter rail lines serving the metropolitan area.

These datasets include information on routes, stops, schedules, transfers, and vehicle frequencies, essential for calculating real-world travel times by public transport.

- **Centroid coordinates:** a separate file provided the geographical coordinates (latitude and longitude) of each district centroid, used to associate mobility flows with spatial locations and to identify the nearest public transport stops for each origin and destination pair.

- **Socioeconomic data**: data on net average income per person and per household by district were provided by the Statistical Service of the Seville City Council, derived from experimental estimates of the National Statistics Institute (INE).

3.2 AREA OF STUDY

The study focuses on the metropolitan area of Seville, a highly relevant case due to its demographic size, spatial heterogeneity, and multimodal transport infrastructure. The city consists of a compact historical center surrounded by peripheral neighborhoods and municipalities, where access to transport and public services varies significantly.

Seville offers complete and up-to-date GTFS data for all modes, and MITMA's mobility matrix provides full coverage of travel flows within and between its districts. This made it possible to analyze not only the physical distance of trips, but also the accessibility and efficiency of the public transport system under real network conditions.

3.3 DATA PREPROCESSING AND CLEANING

The MITMA mobility matrix was filtered to retain only inter-district trips within the metropolitan area. Trips where origin and destination codes were identical (intra-district trips) were excluded. The dataset was merged with the centroid coordinates to associate each district with a geographic location.

For each origin-destination pair, the number of trips and total kilometers were aggregated. These values were used to prioritize the most relevant travel flows and to calculate average trip distances. Data cleaning also involved:

- Verifying the consistency of district codes,
- Ensuring all locations were correctly georeferenced,
- Removing or flagging incomplete or inconsistent records (e.g., with missing coordinates or demographic data).

The four GTFS datasets were then merged into a single feed to allow seamless routing across the different modes and operators. This ensured that calculated travel times could include realistic multimodal transfers.

3.4 TRAVEL TIME ESTIMATION USING GTFS

For each origin-destination pair, a representative centroid-to-centroid route was calculated using GTFS data. The stop nearest to each origin and destination was identified using geographic proximity.

Using the GTFS feed and a routing function (implemented in R), estimated public transport travel times were calculated for a typical weekday (Monday) at 6:00 AM, simulating morning peak conditions. Routes could include transfers between modes, and total travel time was extracted from the start to the final arrival at destination.

If no feasible route was found (e.g., due to disconnected zones or lack of coverage), the pair was excluded from the accessibility indicators. Each successfully computed route included:

- Total estimated travel time,

- Number of transfers,
- Routes taken.

To accelerate computation, parallel processing was used for the most frequent OD pairs (by trip volume).

3.5 SOCIOECONOMIC CONTEXT AND SPATIAL INEQUALITY

To enrich the accessibility analysis, income data at the district level were integrated. The net average income per household and per person were obtained from the Seville City Council's Statistical Service, based on data from the National Statistics Institute (INE).

Net income per person is calculated using consumption units, dividing total net household income by the number of members, weighted according to their household role (adult, dependent, etc.), following an OECD-modified equivalence scale.

In 2020:

- The citywide average income was €12,490 per person and €32,289 per household.
- Los Remedios was the district with the highest average household income (€47,306), followed by Nervión (€44,946) and Casco Antiguo (€38,251).
- On the lower end, Cerro-Amate had the lowest average income (€22,145 per household), with Macarena and Norte also below the city average.

These differences reveal clear spatial disparities. Wealthier districts tend to be better served by high-frequency public transport services, while lower-income districts, especially those on the periphery, often face longer journeys or poorer connectivity. This underlines the relevance of transport accessibility as a key element of urban equity (Ayuntamiento de Sevilla, 2022).

3.6 STRUCTURE OF THE MOBILITY MATRIX

The MITMA dataset contains a wide set of variables, including:

- fecha: data collection date,
- periodo: time period (e.g., AM, PM),
- origen, destino: district codes,
- distancia: travel distance band,
- actividad_origen, actividad_destino: activity types (e.g., home, work/study),
- viajes: number of trips,
- viajes_km: total kilometers traveled.

Each row represents aggregated flows between two districts under specific conditions. For this study, data was aggregated by origin-destination pair, regardless of time period, to focus on structural accessibility rather than short-term fluctuations. The dataset was enriched with:

- Geographic coordinates of centroids,
- Estimated travel time by public transport (GTFS),
- Estimated car travel time (based on distance and average speed),
- Estimated travel cost per mode (using €/km assumptions).

This unified structure enabled the calculation of multiple accessibility indicators, segmented by purpose of travel and income level.

3.7 ESTIMATING TRAVEL TIME AND COST BY MODE

In addition to analyzing public transport accessibility using GTFS-based routing, the study also estimated average travel time and cost by mode (car and public transport) for each origin-destination pair and trip type. This enabled a more comprehensive comparison between the mobility options available across Seville's metropolitan area.

To perform this analysis, a radial (straight-line) distance between each origin and destination was first calculated by dividing the total kilometers traveled (viajes_km) by the number of trips (viajes) for each pair. However, since real-world routes are not perfectly straight, these distances were corrected using a Detour Index.

The Detour Index is a multiplier used to approximate the actual length of a trip compared to its direct, straight-line distance. It reflects the reality that travel paths—whether by road or public transport—tend to be longer due to network layouts, street configurations, or route planning constraints.

In this study:

- A Detour Index of 1.3 was applied for car travel, accounting for reasonably direct road routes (Rodrigue, 2023).
- A higher Detour Index of 1.5 was applied for public transport, recognizing the more circuitous nature of transit networks, including transfers and longer routing (Rodrigue, 2023).

These adjusted distances were then used to estimate travel time in minutes, using the following average speeds:

- **30 km/h for private cars**, a commonly accepted benchmark for urban driving conditions. This value reflects the average speed under typical traffic, signalization, and congestion levels in European cities, particularly in medium-sized urban environments like

Seville. It aligns with estimates used in transportation studies and public mobility reports, where speeds between 25 and 35 km/h are frequently used to simulate private vehicle travel in city settings (Movotiv, 2023). The selection of 30 km/h offers a balanced reference point, avoiding the extremes of peak-hour congestion or free-flow traffic.

- **25.77 km/h for public transport**, calculated as the arithmetic mean of the daily average commercial speeds of all transit modes operating in Seville, including urban buses (12.8 km/h), interurban buses (16.7 km/h), metropolitan buses (29.8 km/h), metro (29.3 km/h), tram/light rail (8.6 km/h), and commuter rail (57.4 km/h). These figures are derived from official data published by the Spanish Ministry of Transport (*Ministerio de Transportes, Movilidad y Agenda Urbana*, 2022, Table 20).

$$Average\ speed = \frac{12.8 + 16.7 + 29.8 + 29.3 + 8.6 + 57.4}{6} = 25.77\,\frac{km}{h}$$

Equation 1: Average commercial speed of public transport modes in Seville

In parallel, the trip cost was calculated using fixed cost-per-kilometer estimates:

- **€0.35/km for car trips**, incorporating fuel, maintenance, insurance, and depreciation *(Ministerio de Transportes, Movilidad y Agenda Urbana, 2024, p. 164).*

- **€0.24/km for public transport**, based on average fare structures in the region. To estimate the cost per kilometer of public transport use, an empirical approach was adopted using official fare and distance data from Seville. The objective was to obtain a representative value that reflects average expenditure per kilometer for typical users, particularly those traveling within urban and metropolitan zones.

Two fare-distance combinations were selected based on 2022 data published by the Spanish Ministry of Transport:

- For Metro de Sevilla, the average trip distance was 4.6 kilometers, and the standard single fare within the minimum fare zone was €1.50 *(Ministerio de Transportes, Movilidad y Agenda Urbana, 2022, Tables 7 and 40).*

- For RENFE Cercanías commuter trains, the average trip distance was 23.6 kilometers, and the maximum zone fare was €3.65 *(Ministerio de Transportes, Movilidad y Agenda Urbana, 2022, Tables 7 and 40).*

These two values were used to estimate the per-kilometer cost for each mode:

$$Metro: \frac{1.50€}{4.6\ km} = 0.326\,\frac{€}{km}$$

Equation 2: Metro de Sevilla – Cost per kilometer

$$Cercanías: \frac{3.65€}{23.6\ km} = 0.155\,\frac{€}{km}$$

Equation 3: RENFE Cercanías – Cost per kilometer

$$Average\ cost\ public\ transport: \frac{0.326 + 0.155}{2} = 0.24\,\frac{€}{km}$$

Equation 4: Average public transport cost per kilometer

Taking the arithmetic mean of these two estimates resulted in an average cost of €0.24/km, which was used as the standard reference value for public transport costs in this study.

This method captures both shorter, inner-city trips and longer-distance suburban journeys, providing a balanced approximation suitable for comparing transport costs across different districts. The result also aligns with expectations, as it is slightly lower than the €0.35/km estimated for private vehicle travel—reflecting the typically lower financial cost of using public transport.

This resulted in three comparative datasets:

- A time comparison table, showing estimated duration by mode for each trip type.
- A distance table, showing adjusted distances for both car and public transport.
- A cost table, comparing total monetary cost per trip.

This methodological step allowed the study to assess not only accessibility in terms of time, but also in economic terms, identifying which districts may be disproportionately affected by longer travel distances and higher transport costs.

CHAPTER 4. RESULTS

4.1 TRAVEL TIME PATTERNS ACROSS THE FUNCTIONAL URBAN AREA (FUA) OF SEVILLE

A total of 14 distinct types of trips were identified within the Functional Urban Area (FUA), based on combinations of origin and destination activity types. These include trips from home to work/study, frequent, or non-frequent destinations, as well as flows starting at other activity locations. When aggregated by destination type, the average travel time per trip reveals modest variations that are nevertheless informative. The longest trips are those ending at work/study locations, averaging 50.5 minutes, followed closely by those to non-frequent destinations (50.2 minutes). Trips to home and frequent destinations are slightly shorter, at 48.9 and 47.6 minutes respectively.

This distribution is both logical and revealing. Trips to frequent destinations likely involve more centralized or familiar routes, which may benefit from routine behavior and better accessibility, contributing to slightly shorter travel times. In contrast, non-frequent trips—potentially linked to leisure, errands, or other irregular activities—may be more spatially dispersed and less optimized by public transport, explaining their nearly equivalent duration.

Interestingly, the average duration of return trips to home is not the longest, as was observed in the previous version of this analysis. This suggests that return trips by public transport may be increasingly efficient, possibly due to improved service frequency during evening hours or a shift in travel behavior that prioritizes more direct paths home. While the differences across destination types are relatively narrow, they reflect meaningful distinctions in how urban activities are spatially organized and how accessible they are by public transport.

Unless otherwise specified, all travel times discussed in this section refer to journeys made using public transport. This methodological focus ensures consistency across comparisons and reflects the objective of assessing accessibility through the lens of collective mobility.

Moreover, these findings speak to the territorial structure of Seville. As a polycentric urban area with decentralized residential development and varied functional centers, mobility patterns are shaped not just by distance, but by network design, frequency of service, and the timing of trips. Figure 1 summarizes these dynamics, offering a snapshot of how the purpose of a trip influences its temporal cost in the broader context of Seville's metropolitan mobility landscape.

This temporal distribution across destination types is visually summarized in Figure 1, which shows the average travel time per trip for each destination category within the FUA of Seville.

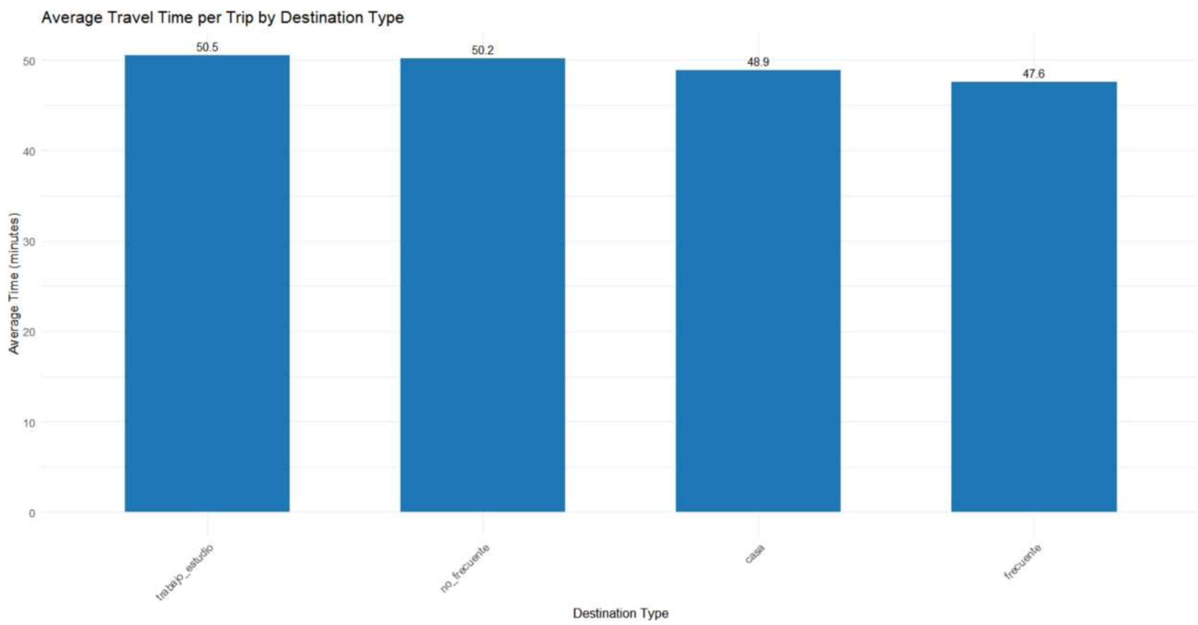


Figure 1: Average travel time per trip by destination type in public transport

Figure 2 presents a boxplot distribution of travel times for trips originating at home, segmented by destination type. Across all three categories—frequent, non-frequent, and work/study destinations—the distributions show a high degree of similarity in both central tendency and spread. Median travel times fall within a narrow band between approximately 67.5 and 75 minutes, as shown in the accompanying color scale, indicating that the majority of home-origin trips have comparable durations regardless of their purpose.

The presence of numerous outliers above the 150-minute mark, particularly in the work/study and frequent categories, suggests that a subset of trips may involve peripheral destinations or extended commute times. However, the interquartile ranges remain relatively compact, reinforcing the earlier finding that Seville's transport network provides consistent temporal accessibility across most daily journeys.

This visualization further supports the interpretation that, within the Functional Urban Area of Seville, home-based trips tend to follow similar spatial and temporal patterns regardless of whether they are directed toward habitual activities, irregular tasks, or work-related obligations. The compactness of the boxes and the alignment of the medians reflect a structurally balanced system, with travel time variations largely explained by specific spatial outliers rather than systemic inefficiencies.

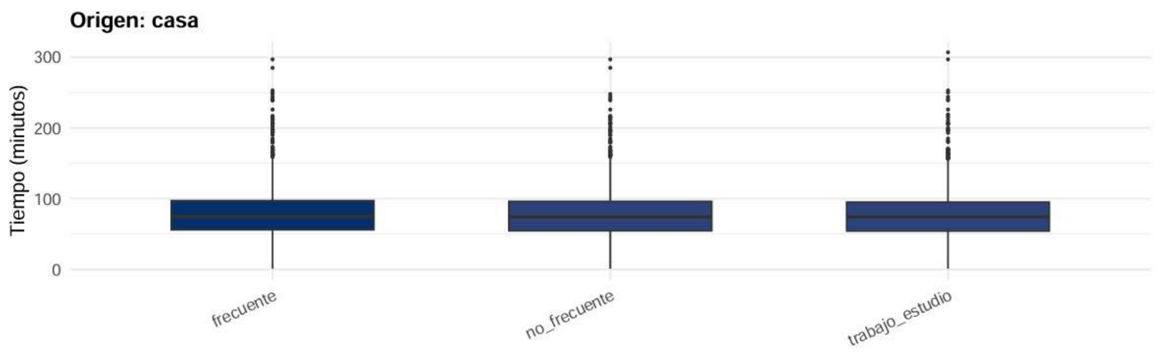


Figure 2: Travel time distribution for home-origin trips by destination type in public transport

Figure 3 displays the distribution of travel times for trips originating at frequent destinations, such as schools, shops, or recurring service points. The overall pattern is similar to that observed in home-origin trips: median travel times are closely aligned across all destination types, generally ranging between 65 and 75 minutes. However, trips returning home tend to show slightly higher central values and a more compact interquartile range, which may indicate more direct or familiar return routes despite occasional longer durations.

The presence of a considerable number of outliers—particularly for work/study and home-bound trips—suggests variability in spatial distribution or scheduling among a subset of users. Nevertheless, the consistency in the box widths reinforces the idea of temporal uniformity in Seville's mobility system, even when movements begin from outside the residential base.

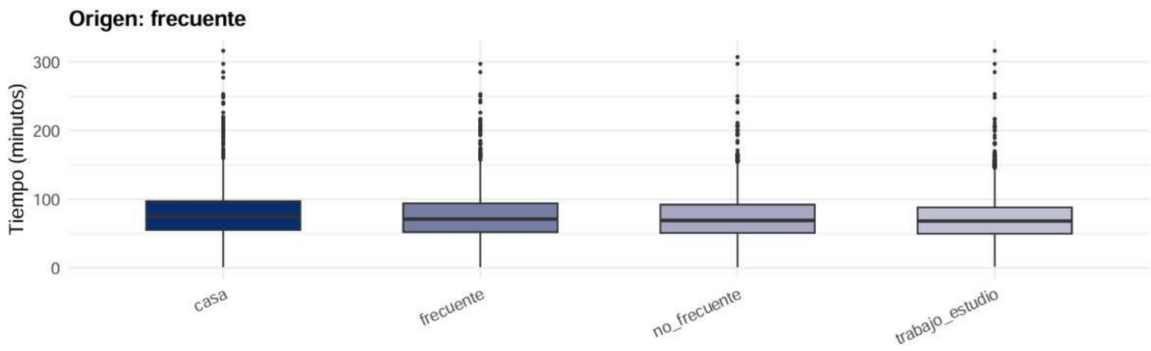


Figure 3: Travel time distribution for trips originating at frequent destinations

Figure 4 illustrates the distribution of travel times for trips that begin at non-frequent destinations, which may include occasional leisure, administrative, or irregular activity points. As with previous cases, the median travel times across all destination types remain consistent, with values typically concentrated between 65 and 75 minutes. Notably, return trips to home again register slightly higher central values, reinforcing the pattern observed in other origin categories.

The dispersion of data remains relatively stable, and while outliers are present—especially in trips toward work/study or frequent destinations—the interquartile ranges are compact and comparable across categories. This suggests that, even for irregular origins, Seville's transport network offers a generally uniform travel experience in terms of duration. The similarity of distribution patterns further underscores the robustness of the system regardless of where trips originate.

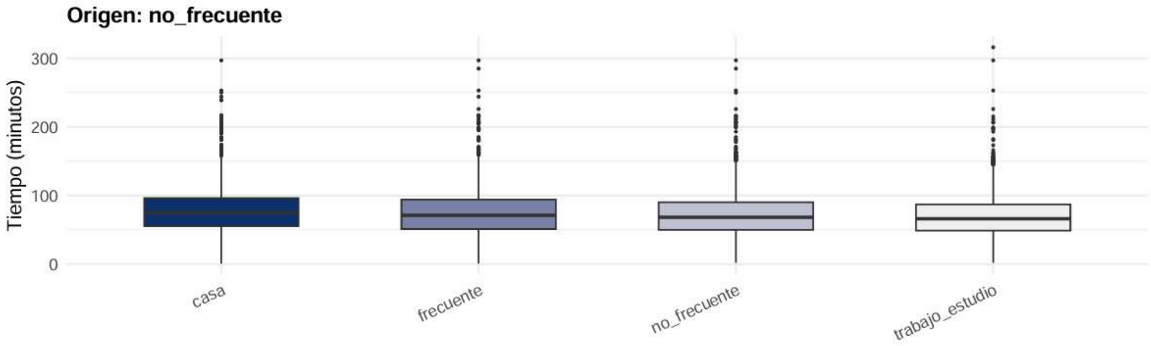


Figure 4: Travel time distribution for trips originating at non-frequent destinations

Trips originating from work or study locations exhibit consistent travel time patterns across all destination types. Median values remain within the familiar range of 65 to 75 minutes, with home-bound trips showing slightly higher central tendencies. This aligns with expected commuting dynamics, where return journeys may span longer distances or coincide with peak-hour congestion.

As illustrated in Figure 5, the variability in travel times is relatively contained, and the number of extreme outliers is lower than in other origin categories. This may be attributed to the structured and repetitive nature of commutes from educational or occupational centers. The distribution reinforces the notion that Seville's public transport infrastructure maintains a uniform level of service regardless of trip direction or purpose.

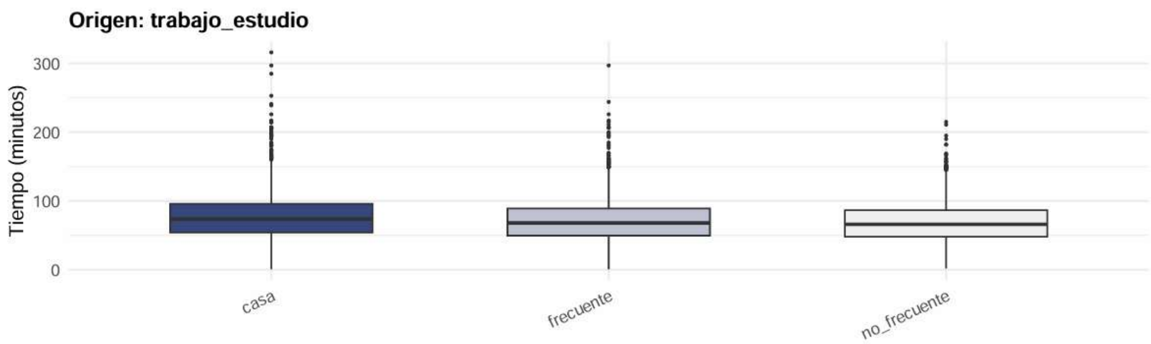


Figure 5: Travel time distribution for trips originating at work/study locations

Taken together, the four boxplots reflecting travel time distributions by origin and destination type reveal a remarkably stable and homogeneous pattern across the Functional Urban Area of Seville. Regardless of the point of origin—be it home, a frequent activity hub, a non-frequent location, or a workplace/school—the median travel times fall within a narrow range between approximately 67.5 and 75 minutes. This consistency points to a transport system that, while not necessarily rapid, provides temporal equity across most mobility flows.

The slightly longer durations observed in return trips to the home are especially notable across all origin categories. This pattern may reflect the dispersion of residential areas on the metropolitan periphery, the timing of trips (often aligning with afternoon peaks), and possible reductions in service frequency later in the day. Conversely, trips toward non-frequent destinations exhibit the shortest travel times, likely due to their more localized nature and less dependence on fixed schedules or central nodes.

Overall, the boxplots confirm that Seville's public transport infrastructure, despite potential inefficiencies or spatial imbalances, sustains a consistent level of temporal accessibility. The moderate interquartile ranges and presence of occasional outliers highlight some variability—expected in any urban mobility system—but do not detract from the overall regularity of travel durations. These results support the idea that most users experience similar time costs for their trips, regardless of their specific purpose or origin-destination pairing.

Building upon the previously examined temporal patterns, Figure 6 shifts the analytical lens toward the functional and spatial characteristics of inter-district travel within the Functional Urban Area (FUA) of Seville. The chart illustrates the percentage distribution of trips by activity type across the ten municipalities with the highest total number of inter-district trips. These municipalities were identified through aggregation of the full dataset, ranking destinations by total trip volume and selecting the top ten. This approach ensures that the analysis focuses on areas that structurally shape the majority of mobility flows, enabling comparisons grounded in both functional relevance and statistical significance.

At a first glance, the ten municipalities present comparable overall magnitudes, with total percentages that occupy relatively similar space along the horizontal axis. However, more detailed inspection reveals differences not only in the scale of trip attraction but also in how trip purposes are functionally distributed within each area. In this regard, the share of work and study trips—depicted in the darkest tone—stands out for its visual consistency across nearly all municipalities. While slight variations are present, most districts maintain this segment within a narrow range, suggesting a highly even spatial distribution of employment and educational destinations. This pattern points toward a decentralized configuration in which no single municipality monopolizes these functions, and instead, several areas offer comparable levels of attraction for work and study purposes.

In contrast, the proportions of trips categorized as frequent or non-frequent show more pronounced variability. Some municipalities, such as 4109103 and 4109104, display a noticeably larger segment for frequent trips, which may indicate their association with regular, repeated activities like medical appointments, shopping, or personal care services. These municipalities might serve as routine service centers embedded in the daily practices of nearby populations. Others, such as 4109108 or 4109109, register a greater share of non-frequent trips, possibly reflecting the presence of more specialized or irregular destinations—administrative offices, cultural or religious sites, and less regularly accessed institutions.

The 'Home' category, represented by the lightest tone, maintains a visible presence across all municipalities, but it lacks uniformity. In districts like 4109105 or 4109101, the proportion of home-bound trips is comparatively higher, which could relate to their residential character or their location within typical return itineraries. In contrast, municipalities with more pronounced service or employment functions tend to exhibit slightly lower values in this category, which is consistent with the role of home destinations as endpoints rather than primary attractors of activity.

The balance—or imbalance—of these categories within each municipality provides insight into their functional roles within the metropolitan system. For example, 4109103 combines a relatively high volume of trips with a strong presence of both frequent and home-related destinations, suggesting a dual role as both residential zone and everyday activity hub. Meanwhile, 4109108, despite a similar total trip share, shows a different configuration, with more weight on non-frequent and work/study trips, implying a profile closer to that of a specialized destination rather than a mixed-use environment.

These differences do not solely reflect land-use patterns; they also hint at differences in accessibility, urban morphology, and even socioeconomic structures within the municipalities. Districts with a broader distribution across activity types may provide more integrated and flexible mobility options, while those with more concentrated patterns could signal stronger specialization or segmentation in their urban fabric.

Lastly, it is worth noting that although the visual range of variation across municipalities is moderate, the internal composition of each bar reveals significant distinctions in functional orientation. This granularity highlights the value of analyzing mobility not only through aggregate indicators but also through the lens of purpose-specific flows, which better capture the complexity of how urban areas are used on a daily basis.

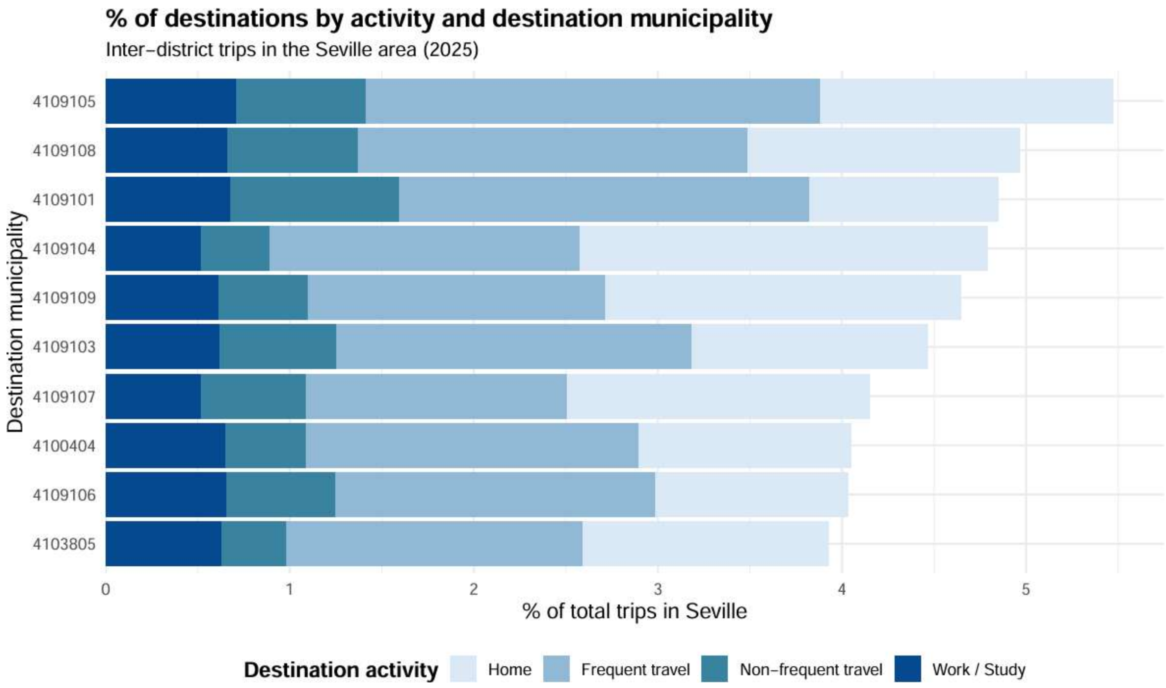


Figure 6: Distribution of destination activity types by municipality in the Seville metropolitan area.

Building on the previous analyses of travel durations by trip type and destination activity, it is also essential to examine how these temporal disparities manifest spatially across the Functional Urban Area (FUA) of Seville. The map shown in Figure 7 offers a comprehensive view of the average travel times per district, allowing for a territorial perspective on mobility conditions and potential inequalities within the metropolitan fabric.

The visualization reveals a clear spatial gradient in travel times. Central areas of Seville—particularly those located within the city's urban core—are shaded in lighter tones, reflecting the shortest average travel durations (between approximately 50 and 64 minutes). This outcome is expected, as these districts benefit from higher densities of services, shorter intra-city distances, and more extensive transport infrastructure coverage.

In contrast, peripheral zones—especially those situated in the northern, northeastern, southeastern, and southwestern edges of the FUA—exhibit significantly longer travel times, as indicated by progressively darker blue shades. These areas typically lie farther from employment and service hubs and may suffer from less frequent or less integrated transport connections. The southern outskirts of the metropolitan area, for instance, also display elevated average travel times, possibly due to their geographic remoteness and greater dependence on inter-municipal transit.

Such spatial patterns align with established urban mobility trends, where proximity to the center correlates with better transport accessibility. Peripheral districts, on the other hand, face higher time costs to access daily activities, potentially exacerbating existing socioeconomic inequalities. This reinforces the relevance of considering spatial equity in transport planning, especially for districts consistently associated with longer travel durations.

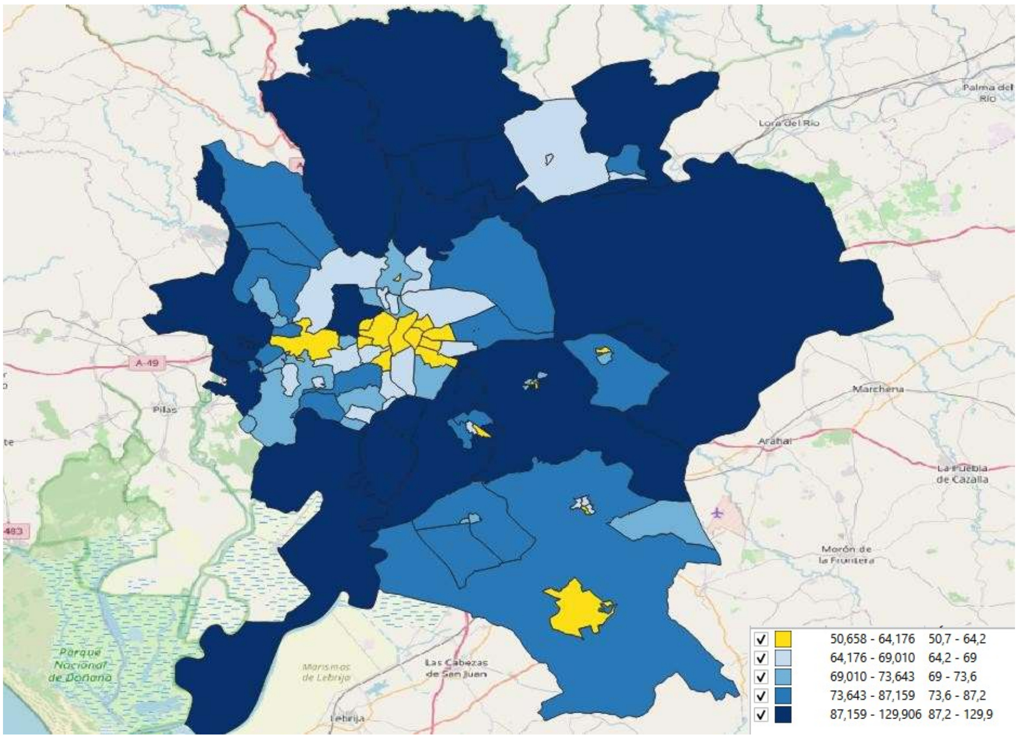


Figure 7: Average public transport travel time per district in the Seville Functional Urban Area (2025)

Compared to the general travel time map (Figure 7), the spatial distribution of travel times for trips from home to frequent destinations reveals both expected patterns and subtle differences (Figure 8). As in the previous map, peripheral districts—particularly in the north, northeast, and northwest of the Functional Urban Area (FUA)—continue to experience the longest average travel times, with several municipalities shaded in the darkest blue category (91.2–136.9 minutes). However, this map highlights some regional nuances that are specifically associated with commuting or recurring travel routines.

Notably, while the central districts maintain their position as the areas with the shortest average travel times—especially those colored in yellow and light blue—it is interesting to observe that some southeastern municipalities, which previously displayed moderate values, now fall into darker categories. This suggests that for residents in these areas, access to frequent destinations—such as supermarkets, childcare, or recurring errands—is significantly more time-consuming. This may reflect infrastructural limitations, limited connectivity, or dependency on slower transport modes.

Conversely, southwestern municipalities display a slightly improved situation in this travel category, with several areas shifting toward lighter shades. This indicates relatively shorter travel times for repeated activities, which may suggest better spatial planning or a concentration of frequent destinations within reachable proximity.

These spatial variations underscore the relevance of differentiating trip types when evaluating accessibility. Travel times are not only shaped by distance but also by the nature and distribution of destination types, which in this case appear to vary more unevenly across the metropolitan area.

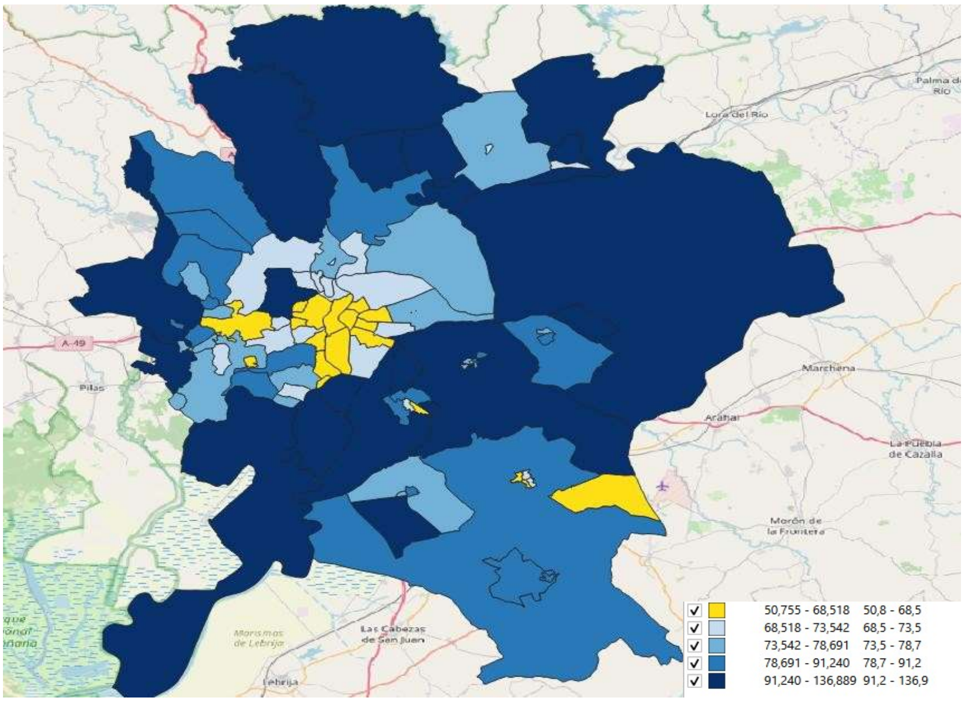


Figure 8: Average public transport travel time for trips from home to frequent destinations in the Seville Functional Urban Area (2025)

Compared to previous travel patterns, the spatial distribution of average travel times from home to non-frequent destinations (Figure 9) reveals both similarities and unique deviations. As with other trip types, the central areas of Seville remain characterized by shorter average travel durations, reflected in the presence of lighter colors on the map. This suggests a concentration of non-frequent destinations that are more accessible from central neighborhoods.

However, one notable difference in this map is the greater presence of lighter shades (indicating better accessibility) extending into the western and southern intermediate zones, particularly when compared to the previous map representing frequent destinations. This may reflect the nature of non-frequent travel—often associated with leisure, sporadic errands, or irregular visits—which can be satisfied by a broader range of destinations beyond the core metropolitan center. In contrast, more structured destinations such as work or routine activities tend to cluster in more centralized or better-connected locations.

Longer travel times continue to dominate in peripheral zones, particularly in the northeast and eastern outskirts of the metropolitan area. These darker regions suggest that residents in these neighborhoods may face significant challenges in reaching non-frequent destinations efficiently, whether due to lower public transport coverage or fewer local amenities that meet non-routine needs.

Interestingly, certain southern municipalities that previously exhibited mid -range travel times now show lower durations in this case. This could indicate a stronger internal provision of diverse destinations in these zones, allowing residents to access non-frequent locations without extensive commuting.

Overall, the results indicate that while centrality continues to be a major determinant of travel efficiency, the nature of the destination also plays a role in shaping accessibility patterns. The flexibility of non-frequent destinations appears to allow for a slightly more balanced distribution of travel times across some intermediate zones, while still exposing accessibility gaps in more remote areas.

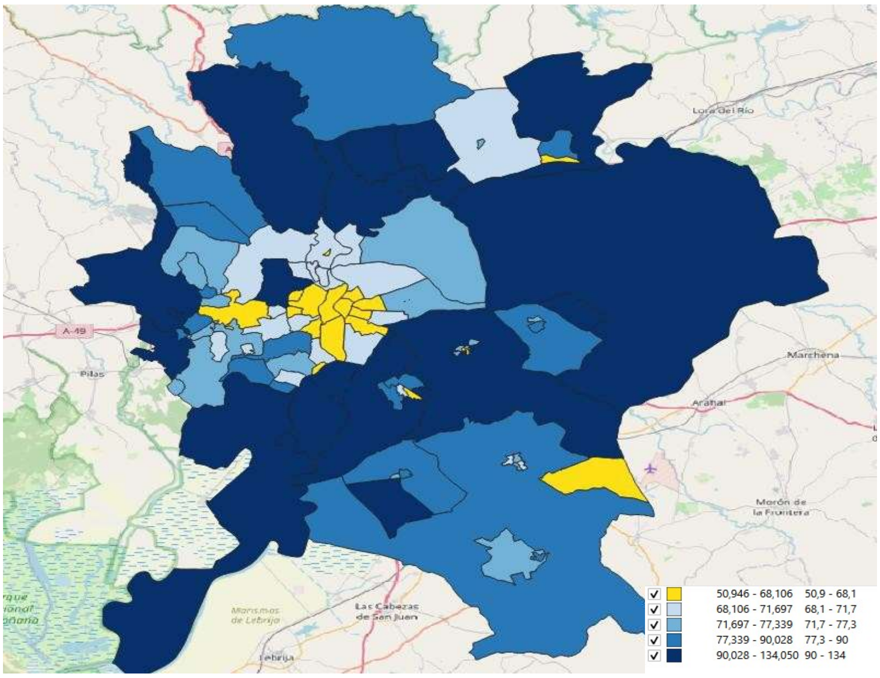


Figure 9: Average public transport travel times from home to non-frequent destinations.

The spatial distribution of average travel times from home to work or study locations (Figure 10) reflects some of the most structured mobility patterns in the metropolitan area. As expected, central districts again display the shortest average durations, indicative of greater concentration of employment and educational opportunities in the urban core. The map also reinforces the pattern observed in previous maps, where the periphery—especially in the northeast and eastern outskirts—consistently experiences the longest travel times.

Compared to trips toward frequent or non-frequent destinations, journeys with a work or study purpose seem to involve slightly longer durations overall. This may reflect the fact that such trips are often more constrained by time schedules and therefore less flexible in route choice, amplifying the effects of poor connectivity in less central areas. In addition, workplaces and educational institutions are typically concentrated in fewer, more centralized zones, requiring longer commutes from peripheral neighborhoods.

Interestingly, the southern and southwestern areas show somewhat better accessibility in this case, as reflected in mid-range travel times. This could be explained by the presence of specific work or educational hubs in these zones, or by better transport links facilitating these movements.

In contrast, some outer districts in the northeast and parts of the southeast show persistent challenges, as evidenced by the darker tones. These areas likely suffer from both distance-related and infrastructural barriers, making access to job or study opportunities particularly time-consuming for residents.

Overall, the map confirms that travel for essential purposes such as employment and education presents the most pronounced disparities in terms of travel time, underscoring the importance of improving direct and efficient transport connections between outer municipalities and the urban center.

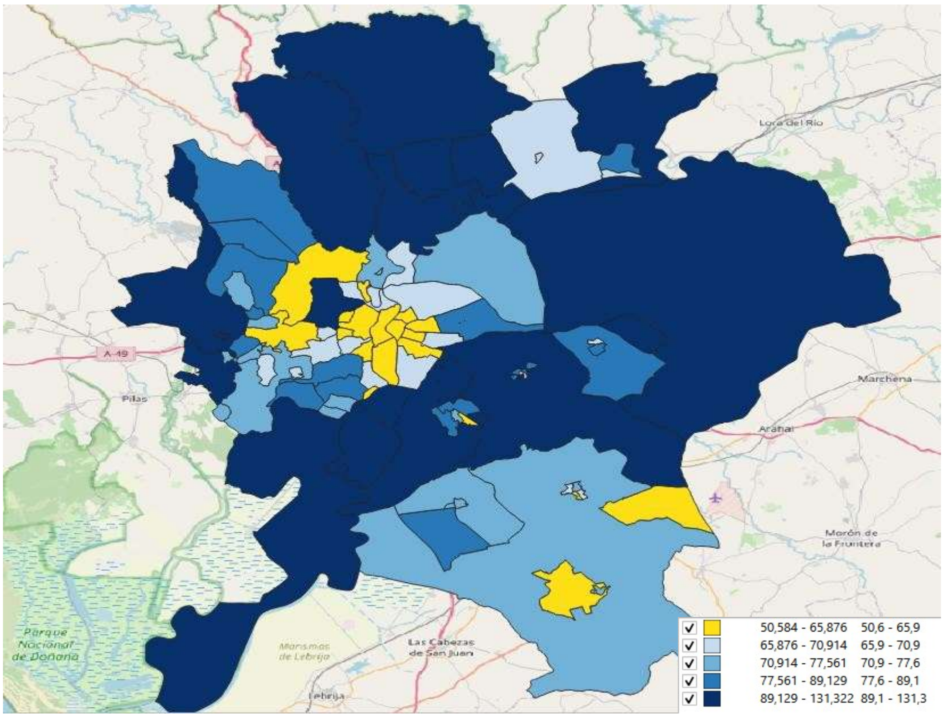


Figure 10: Average public transport travel times from home to work/study locations.

Although the individual temporal patterns of each district reveal some local variability, a broader analysis of the ten districts with the highest overall travel times (as shown in Figure 11) uncovers a number of significant and coherent trends. These districts are not randomly distributed throughout the urban fabric, but rather share structural and spatial characteristics that help explain their mobility challenges.

In general terms, all ten districts exhibit consistently high travel durations across the three primary categories of movement—toward frequent, non-frequent, and work/study destinations. This consistency reinforces the notion that the underlying limitations are not tied to a specific type of activity, but rather reflect systemic issues that affect accessibility across multiple aspects of daily life. Most of these districts likely fall within peripheral or semi-peripheral zones of the Functional Urban Area (FUA), where distance to key central hubs, fragmented urban design, or insufficient public transport coverage amplify travel time regardless of purpose.

The comparative ratios between commuting and leisure travel (home → work/study divided by home → non-frequent) provide further insight into the functional character of these areas. Several districts display ratios significantly greater than 1, suggesting that commuting trips require considerably more time than leisure-oriented movements. This is a particularly revealing pattern, as it implies that these zones may serve predominantly as residential enclaves with weak proximity to employment clusters. In such cases, trips for work or study may require longer distances and more complex transit chains—either due to geographic remoteness or poor integration with the metropolitan transport network.

On the other hand, a few districts present ratios closer to or even below 1. These cases could reflect either better integration with employment centers or, conversely, a situation in which leisure destinations are located far from the district of origin. Lower ratios do not necessarily imply better conditions—they may instead indicate a lack of diverse opportunities nearby, forcing residents to travel longer distances for basic amenities or recreational activities.

Importantly, when comparing this figure with the spatial distribution shown in the previous choropleth maps—particularly the global travel time map and the thematic maps by destination type—there is a clear spatial alignment. The darker shaded zones in the northeast, far east, and some southern peripheries correlate strongly with the districts highlighted in this matrix. This overlap validates the selection of these ten districts for focused analysis, and suggests that the factors driving long travel times are not isolated anomalies but rather part of a larger spatial pattern.

From a policy and planning perspective, this subset of districts should be treated as critical intervention areas. They appear to be caught in a dual disadvantage: long travel times and significant asymmetries between essential and non-essential mobility. Whether due to insufficient transit services, low density development, or socio-spatial segregation, the mobility burdens faced by these residents are likely to affect both quality of life and equity in access to opportunities.

In sum, the combination of absolute travel times and functional mobility ratios provides a powerful lens through which to identify urban areas most in need of accessibility improvements. These districts not only exhibit the greatest cumulative delays but also the most unbalanced mobility profiles, which should inform the prioritization of infrastructural and service-based interventions.

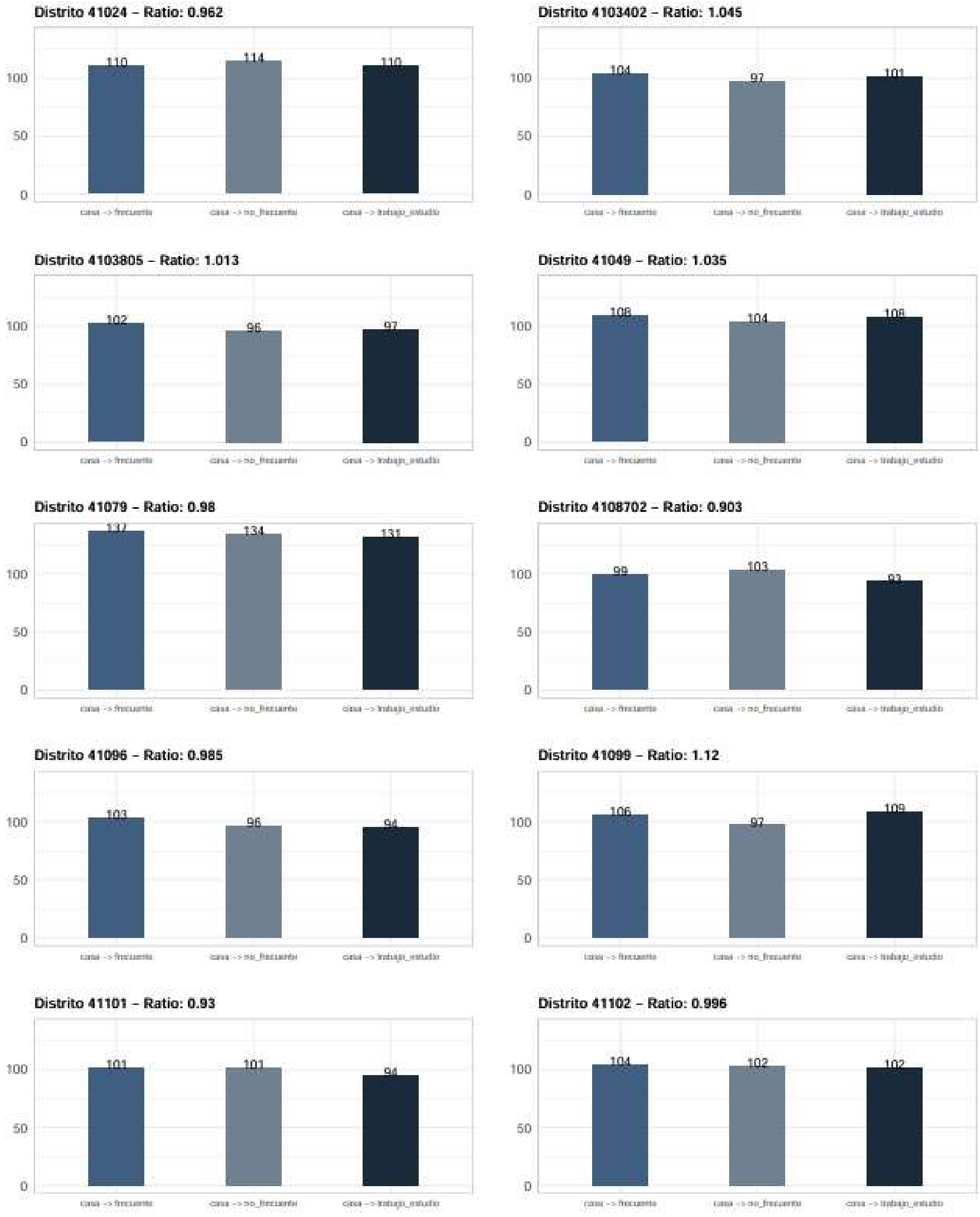


Figure 11: Average travel time and commuting ratio in the ten most mobility-challenged districts of Seville

To complement the previous matrix and further consolidate the observed patterns, Figure 12 displays the calculated ratios between average travel times from home to work/study and home to non-frequent destinations for the ten districts with the highest overall travel durations. This metric offers a compact comparison of how much longer, on average, it takes residents in these areas to reach essential destinations (typically tied to employment or education) relative to non-essential or leisure-related locations.

Most of the ratios cluster around the value of 1, suggesting that in many of these districts, travel times to both categories are relatively similar—highlighting a uniform challenge in accessing various urban functions. However, a few cases stand out. District 41099, for instance, exhibits the highest ratio, indicating that accessing work or educational opportunities from this area is substantially more time-consuming than reaching non-frequent destinations. This could reflect a lack of direct transit routes to major employment hubs or a peripheral residential profile with limited integration into the regional labor geography. On the other end, districts such as 4108702 or 41101 fall below 1, which might indicate stronger connectivity to employment centers or, conversely, poorer accessibility to dispersed non-frequent destinations.

Overall, this ratio-based synthesis reinforces previous insights: the districts with the longest average travel times are not just distant in physical terms but also exhibit nuanced disparities depending on the purpose of travel. It further underlines the spatial segregation of urban functions and the critical role that transport accessibility plays in shaping everyday mobility across the metropolitan area of Sevilla.

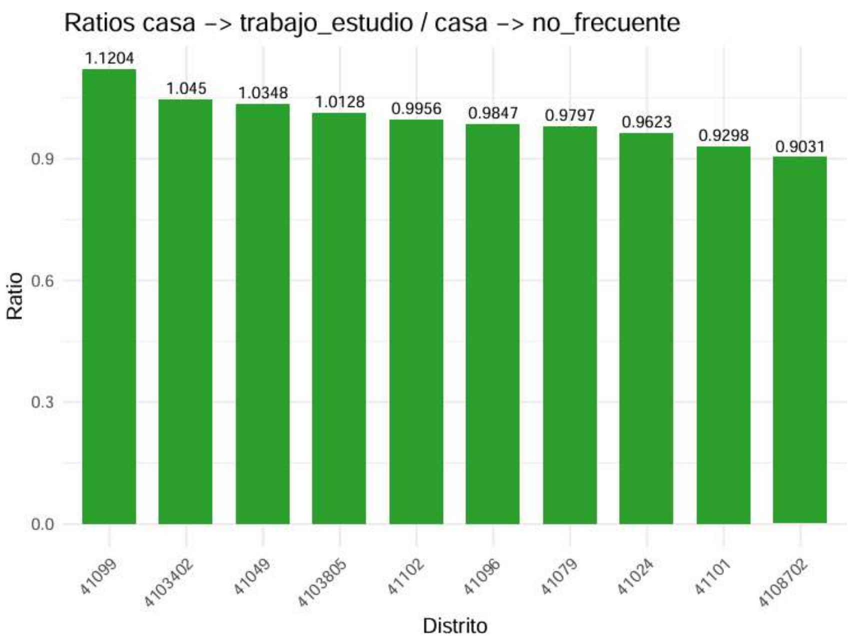


Figure 12: Ratio of travel time: home to work/study vs. home to non-frequent destinations.

The distribution of the ratio between average travel times from home to work or study destinations and from home to non-frequent destinations provides key insights into the structure and orientation of urban mobility across the metropolitan area. As observed in Figure 13, a slight majority—56% of districts—show a ratio below 1, meaning residents typically reach work or study locations faster than non-frequent destinations. This pattern is consistent with transport networks that historically prioritize access to essential activities like employment and education.

However, the remaining 44% of districts present a ratio greater than or equal to 1, which suggests that in a considerable portion of the urban area, reaching workplaces or educational institutions takes longer than accessing destinations typically associated with leisure or irregular activities. This outcome is particularly notable considering that a city like Sevilla generally offers strong transit coverage in central areas, and one might expect more efficient connections to structured activities compared to non-essential ones.

Several urban and transport-related factors could contribute to this. In some peripheral neighborhoods, access to employment centers may be hindered by a lack of direct or high-frequency connections, requiring longer, multi-modal routes. Alternatively, some of these zones may be relatively better connected to commercial centers or entertainment districts—especially those accessible by private vehicle or outer-ring public transport—than to institutional or job-related destinations. It may also reflect the spatial distribution of educational and work facilities, which are often centralized, requiring longer commutes from decentralized residential areas.

The presence of a substantial proportion of districts with a ratio above 1 suggests that, beyond individual trip characteristics, there may be broader structural mismatches between the location of essential services and the availability or efficiency of transport options. This metric offers an additional layer of interpretation when evaluating accessibility across different trip purposes and may help contextualize previous observations related to travel time inequalities in the metropolitan area.

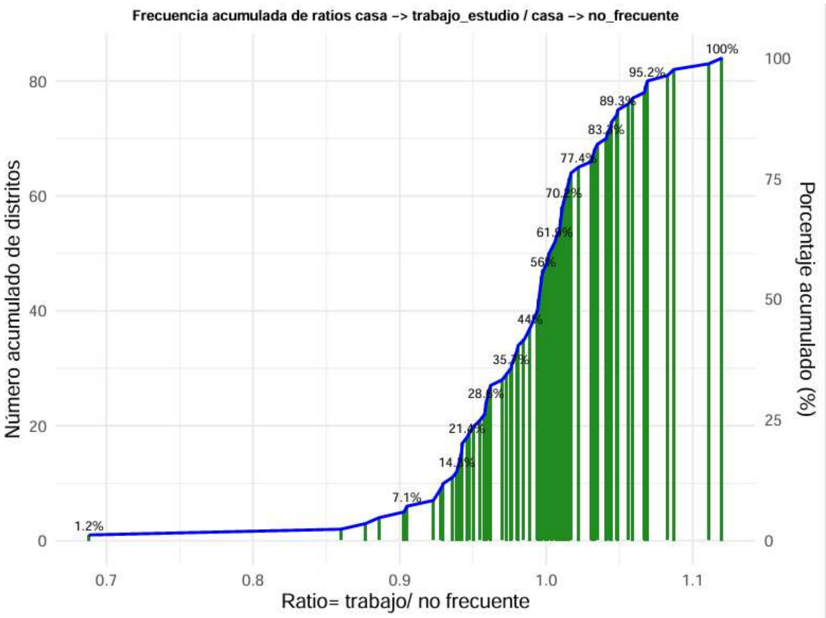


Figure 13: Cumulative distribution of travel time ratios (home → work/study divided by home → non-frequent).

Figure 14 illustrates the distribution of average travel time ratios between public transport and private car for each origin district within the Seville metropolitan area. These ratios were computed by dividing the mean estimated public transport travel time—based on simulated itineraries across the GTFS network—by a derived average car travel time, calculated from the total kilometers traveled per district and a fixed driving speed of 36.7 km/h, consistent with urban mobility benchmarks for Seville.

In this updated version of the graph, the ratios span a considerably wider range than in earlier iterations, from 2.31 in the best-performing district to a striking 11.61 in the worst. These figures confirm that no district in the metropolitan area achieves parity between public transport and private vehicle travel time. Instead, the data reveal significant disparities in accessibility efficiency, with some districts requiring over 11 times more time by public transport than by car—an alarming indicator of spatial transport inequity.

The shape of the distribution conveys important spatial and structural dynamics. The leftmost portion of the chart features a steep drop from the highest values, indicating a small group of origin districts that are clear outliers in terms of transit disadvantage. These areas likely correspond to highly peripheral zones with weak transit service coverage, long access times, or indirect route structures that inflate public transport durations disproportionately. The drop between the first few bars is particularly sharp, suggesting that transit accessibility deteriorates dramatically for a small subset of districts before stabilizing across the remainder of the metropolitan area.

As one moves rightward along the graph, the curve becomes progressively smoother, with ratio values gradually decreasing. This smoother midsection of the chart, spanning ratios roughly between 8 and 4, likely corresponds to more moderately connected districts where public transport, while clearly less efficient than private car travel, remains within a tolerable range. These districts might benefit from partial integration into the city's transit backbone or shorter trip distances that limit inefficiency even when service frequency is suboptimal.

In the rightmost segment of the graph—where the lowest ratios are found—the trend flattens significantly, showing that the best-performing districts cluster tightly within a narrow band of ratios from 3.7 to 2.3. These values, though still favoring private cars, point to districts with relatively robust public transport infrastructure or high population density, which tends to support more frequent and direct services. It is telling, however, that even in the most transit-efficient zones, public transport still takes more than twice as long as driving, underscoring the systemic car-orientation of Seville's mobility structure.

This updated distribution highlights an enduring and multidimensional transport gap within the urban fabric. The most disadvantaged districts are not merely outliers in quantitative terms, but symptoms of deeper geographic and infrastructural marginalization. Conversely, the flatter lower end of the curve reflects a partial success story of urban integration, where transit services align more closely with residents' mobility needs—yet still fall short of achieving true modal competitiveness. The chart thus reinforces the need for spatially differentiated planning strategies that target the most critical accessibility deficits without neglecting the structural biases embedded in the metropolitan transport network.

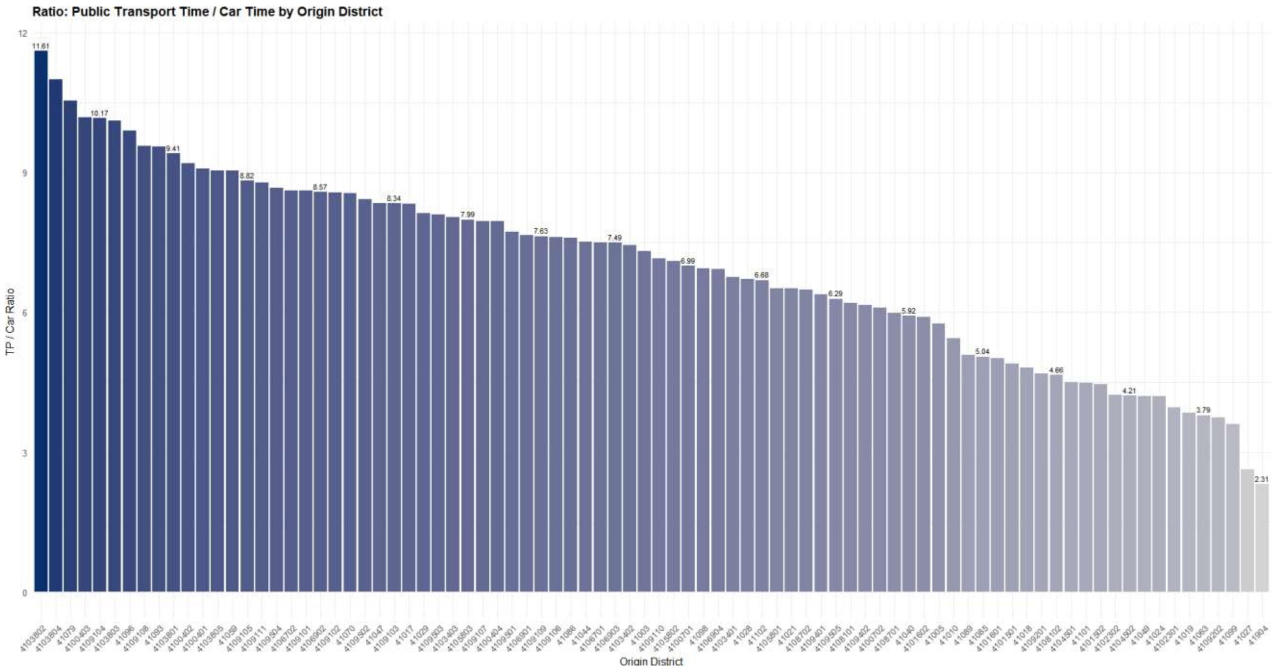


Figure 14: Ratio of travel time by public transport versus car by district of origin in the Seville metropolitan area

Figure 15 offers a territorial visualization of the public transport to car travel time ratios across origin districts in the Seville metropolitan area. The color gradient ranges from yellow (lowest ratios) to dark blue (highest ratios), representing increasing disparity between public transport and private car travel times. This spatial lens complements the distributional insight provided in Figure 14 by anchoring those disparities within the urban geography.

The northern and northeastern districts of the metropolitan region are predominantly colored in yellow and pale blue, indicating that their public transport travel times are relatively close to those by car, with ratios ranging between approximately 2.3 and 4.9. This suggests a certain degree of temporal parity between modes, which may reflect better infrastructure coverage, shorter travel distances to central destinations, or more efficient transit services in these areas. Their relative proximity to employment and service hubs—along with stronger connectivity to primary transport corridors—could be contributing to this more balanced modal performance. In practical terms, these districts may offer a more competitive and viable alternative to car use, potentially supporting more sustainable commuting patterns.

In contrast, the southern and southwestern districts are overwhelmingly shaded in darker blue tones, reflecting ratios above 7.6, and in some cases, exceeding 11. This implies that public transport in these areas can take up to eleven times longer than private car travel for the same journeys. These striking disparities likely stem from longer distances, lower service frequencies, or fragmented transport networks that fail to offer direct or f requent connections. Many of these districts lie at the edge of the functional urban area, and their spatial remoteness from main transit corridors further compounds the problem. The implication is a structural disadvantage in accessibility, which can contribute to mobility-related exclusion, limit employment opportunities, and deepen territorial inequalities.

The central and inner-ring districts present a more diverse picture, with a mix of light to medium blue shades. These zones appear to occupy an intermediate position in terms of accessibility. While public transport is still slower than car travel, the differences are less extreme than in the periphery. This variation could reflect local differences in transit integration, urban density, or availability of multimodal connections. Some central districts may benefit from overlapping transit services (e.g., bus, metro, commuter rail), while others—despite their location—may remain poorly served due to physical barriers or legacy planning limitations.

Finally, the eastern and southeastern zones show a range of conditions, with some districts falling into the mid-range of the color scale and others showing higher ratios. This heterogeneity indicates that spatial location alone does not determine transport eff iciency; rather, the design and quality of the network, as well as the urban morphology and land use mix, play a crucial role in shaping travel time outcomes.

Figure 15 not only reveals the spatial distribution of modal travel time disparities but also underscores their functional consequences. Districts where the ratio is lower (yellow and light blue) may foster more equitable and sustainable mobility behaviors, while those in darker shades face substantial challenges that reinforce car dependency. The map thus provides a critical input for spatially targeted transport planning, helping to identify where investments in transit infrastructure or service redesign are most urgently needed to improve accessibility and reduce structural disadvantages.

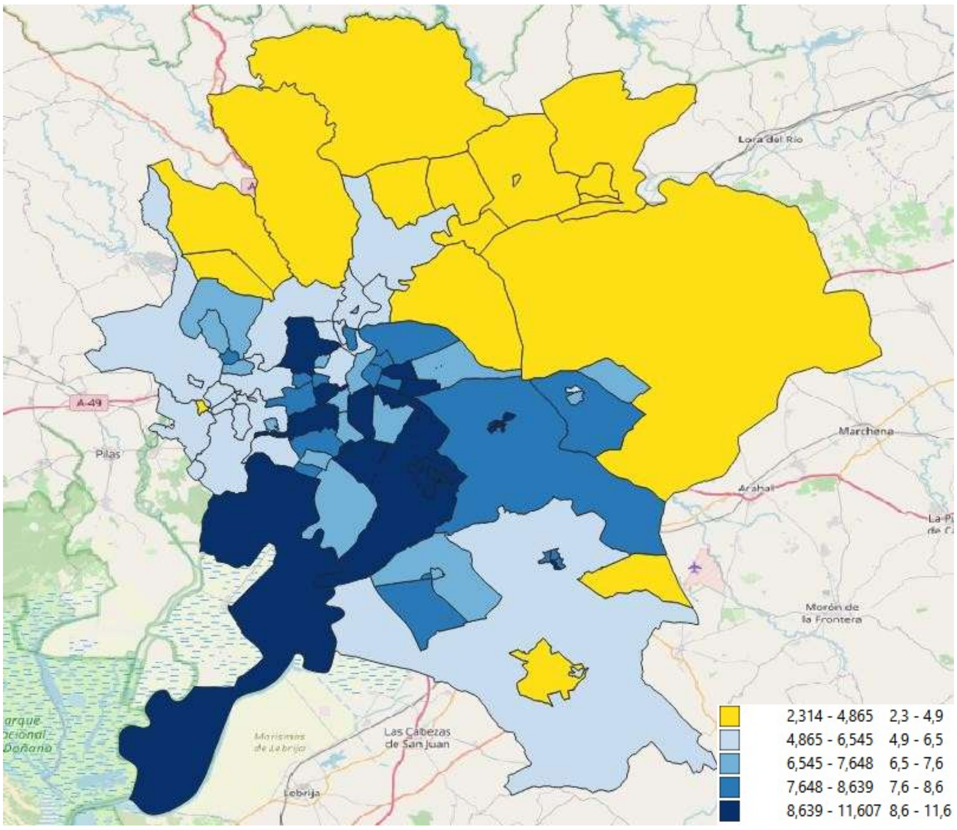


Figure 15: Spatial distribution of public transport vs. car travel time ratios by origin district in the Seville metropolitan area

Figure 16 presents the distribution of average travel times across 14 types of origin-destination combinations in the metropolitan area of Seville. Each graph corresponds to a distinct type of trip — for example, from home to work/study or from one non-residential activity to another — and illustrates the variability in travel duration using density plots marked with their first quartile (Q1), median (Q2), and third quartile (Q3). These visualizations provide a clearer sense of how travel time differs not just by district, but by the functional purpose of the trip itself.

One of the most immediate patterns is that home-based trips, such as *"home → work/study"* or *"home → non-frequent"*, tend to have higher medians and broader spreads than trips that start from other types of locations. This makes intuitive sense: residential areas — particularly those in the outer rings of the city — are often farther from main centers of employment, education, or leisure. The variability in travel times here likely reflects both the greater distances involved and the uneven quality of public transport connections in peripheral zones.

When comparing distributions, some travel types, like *"frequent → frequent"* or *"non-frequent → frequent"*, have more compact and symmetrical shapes. These suggest routine, shorter trips — possibly occurring within well-connected, central areas — where public transport is relatively frequent and direct. On the other hand, certain categories like *"work/study → non-frequent"* or *"non-frequent → work/study"* show wider or skewed distributions, sometimes even with secondary peaks. These could indicate more complex or less predictable journeys, perhaps combining long-distance commuting with occasional or discretionary trips.

Skewness varies substantially. Several curves — particularly for trips originating at home — lean to the right, meaning most trips cluster around a central value, but a significant minority take much longer. This is especially evident in *"home → work/study"*, which reflects not just distance but rigid schedules and potential transfers. In contrast, return trips like *"work/study → home"* or *"frequent → home"* often show more balanced or slightly compressed distributions, hinting at more flexibility or more consistent travel patterns on the way back.

There are also interesting asymmetries between outbound and return trips for the same pairings. For instance, the trip from *"home → frequent"* is noticeably more condensed than *"frequent → home"*, suggesting that people tend to leave home toward frequent destinations in a more synchronized way (perhaps during a standard morning peak), while returns may be more spread throughout the day. The same pattern is observed — though to a lesser extent — for work or study trips.

Not all distributions follow the same general shape. Some, like *"work/study → frequent"*, show a fairly narrow, almost bell-shaped pattern, implying a degree of consistency in travel time. Others, like *"non-frequent → work/study"*, are flatter and more spread out, possibly pointing to more varied origins and transport options. The fact that these differences align with the functional nature of the trip suggests that mobility is not only a matter of geography, but of social routine, infrastructure, and temporal constraint.

These variations help reveal the complexity of travel in a city like Seville, where different parts of the population move in different ways depending on where they live, what they do, and when they travel. The structure of the transport system, the location of key activity centers, and the spatial layout of the metropolitan area all shape these patterns — and do so in clearly distinct ways depending on the type of journey.

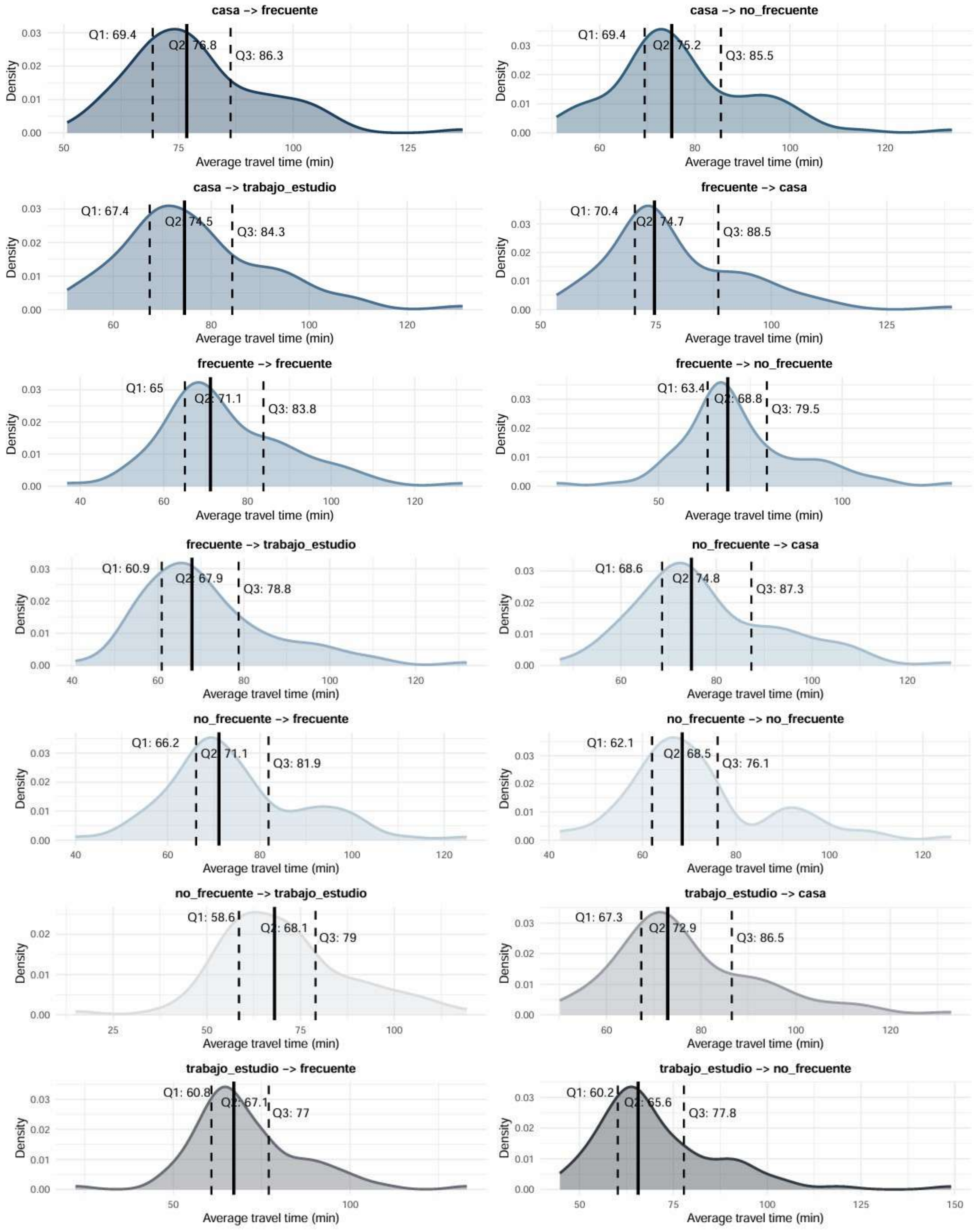


Figure 16: Travel time distributions by type of trip across the city of Seville.

4.2 TRAVEL COST PATTERNS ACROSS THE FUNCTIONAL URBAN AREA (FUA) OF SEVILLE

4.2.1 COST DISPARITIES BY TRANSPORT MODE ACROSS SEVILLE'S METROPOLITAN AREA

Figure 17 illustrates the distribution of estimated travel costs per trip for both private car and public transport modes across the entire study area. As expected, public transport trips tend to be significantly less expensive, with their distribution concentrated toward the lower end of the cost spectrum. The curve for public transport is visibly skewed to the right, resembling a log-normal distribution, which is consistent with a pricing structure that is relatively uniform and capped, especially under flat-fare or zone-based systems typical of metropolitan areas.

In contrast, the cost distribution for private car trips is broader and exhibits a longer right tail. This reflects greater variability in car-related expenses, which are directly influenced by travel distance, fuel consumption, and parking costs, among other factors. Car trips often cover longer and more dispersed routes, particularly in low-density or peri-urban areas, leading to significantly higher and more heterogeneous cost estimates.

The positions of the quartiles further emphasize these differences. While the interquartile range for public transport is narrower and concentrated below the median car cost, the car distribution spans a wider cost range, suggesting more pronounced economic variability depending on origin and destination. This disparity also highlights the unequal financial burden of commuting for car users, especially in peripheral zones with limited or inefficient public transport alternatives.

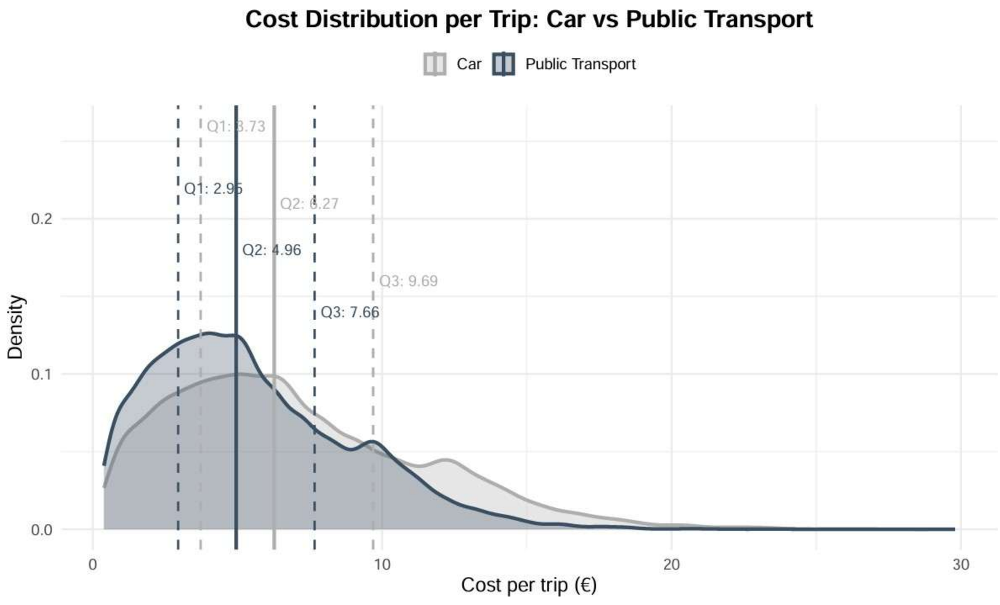


Figure 17: Distribution of travel costs per trip by mode (car vs public transport) across the Seville region.

4.2.2 COST VULNERABILITY IN HIGH-DISPARITY DISTRICTS

To explore more patterns of economic vulnerability linked to mobility in the Seville metropolitan area, a specific cost-based metric was developed. This approach focuses on identifying those districts where the difference between the cost of travelling by private car and the cost of using public transport is the greatest. This absolute difference—calculated as the average car travel cost minus the average public transport cost for each district—was used as a proxy for identifying areas where the burden of mobility is structurally higher.

The rationale behind this metric is rooted in the way transport costs scale with distance for each mode. In the case of public transport, fare structures tend to increase only modestly with distance or number of connections, particularly in integrated systems with flat or zonal pricing. As a result, a trip involving one bus or three buses may have relatively similar financial costs. By contrast, private car usage incurs costs that grow more significantly with travel distance—mainly due to fuel consumption, wear and tear, and opportunity costs associated with time and congestion.

Therefore, when the cost of a car trip significantly exceeds the equivalent trip by public transport, it suggests that residents in that district are making longer journeys on average—possibly for work, education, or essential services located far from their homes. Crucially, if these long-distance trips are made predominantly by car, either due to lack of viable alternatives or other constraints, it implies a heightened exposure to transport-related economic stress.

Districts with the highest cost differentials were thus interpreted as being more vulnerable from a transport perspective. Not because they necessarily lack access to public transport, but because their residents appear to depend on longer, more expensive car trips to meet their basic mobility needs. This situation points to a structural disadvantage: longer journeys often mean greater time investment, higher cumulative costs, and fewer modal options, all of which are characteristic dimensions of transport poverty.

Based on this approach, the four districts with the highest car-versus-public transport cost gaps were selected for further analysis. Their respective cost distributions are presented in the following figures, offering a detailed view of how travel costs are distributed by mode in areas most exposed to mobility-related economic vulnerability.

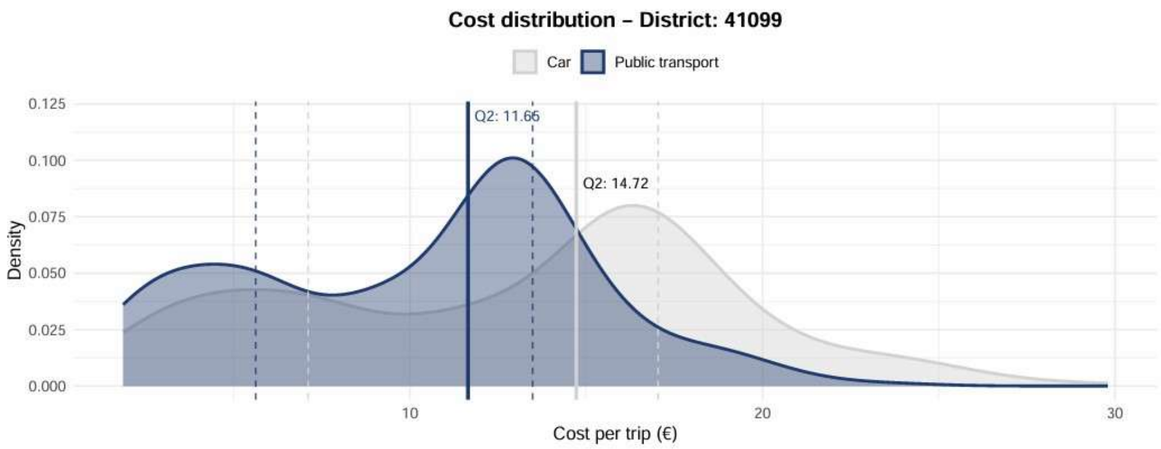


Figure 18: Cost distribution by transport mode – District 41099

Figure 18 presents the cost distribution of both public transport and private car trips for District 41099, which exhibits the highest cost differential between the two modes. The figure shows a clear pattern: the median cost of car travel (14.72 €) significantly exceeds that of public transport (11.66 €), resulting in a difference of over 3 € per trip. When considered over the course of a working month or year, this gap can translate into a substantial financial burden for residents who rely on private vehicles.

The distribution of public transport costs appears more compact and centered around a single mode, reflecting relatively stable pricing policies that are often unaffected by the number of transfers or moderate increases in distance. In contrast, the cost distribution for car travel is noticeably more dispersed, with a wider spread and a flatter density curve. This variability is consistent with the nature of car use, where costs increase sharply with distance due to fuel consumption, maintenance, and time-related expenses.

This pattern suggests that trips originating from this district tend to cover longer distances, a factor that amplifies the cost disparity between transport modes. While public transport absorbs these longer distances with minimal cost increases, car travel becomes significantly more expensive. This reinforces the idea that residents of such districts may be structurally dependent on longer commutes to reach employment, education, or essential services, often in areas that are not easily accessible by public transport.

Figure 18 therefore highlights a clear asymmetry in transport affordability, where the reliance on private vehicles leads to disproportionately higher costs. This makes District 41099 a relevant case in the identification of transport-cost-related vulnerability.

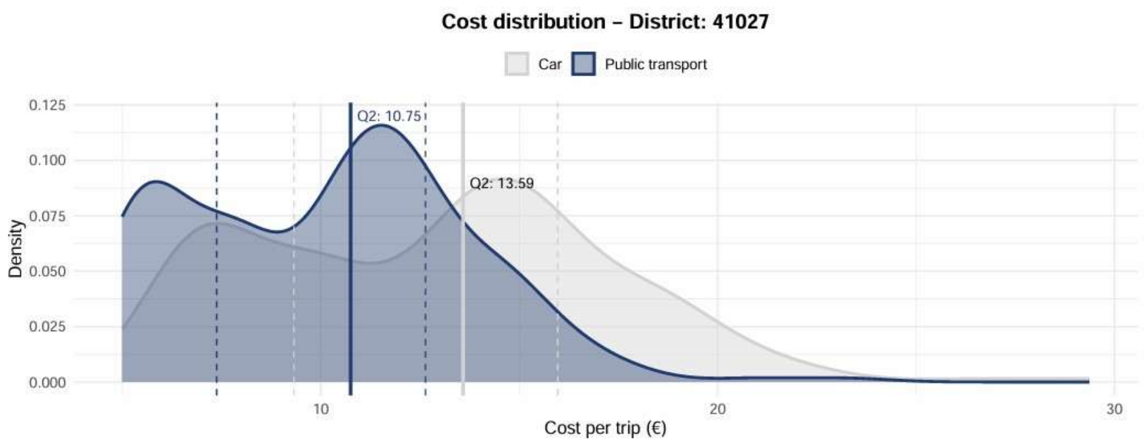


Figure 19: Cost distribution by transport mode – District 41027

Figure 19 shows the cost distribution for District 41027, which ranks among the districts with the greatest disparity in average cost per trip between private car and public transport. The data reveal a median cost of 13.59 € for car travel compared to just 10.75 € for public transport, reinforcing the same structural gap observed in other vulnerable districts.

Once again, the public transport cost distribution is narrower, more symmetrical, and concentrated within a lower range. This reflects a uniform pricing mechanism that remains relatively stable even across varying distances. The car cost distribution, by contrast, is wider and slightly skewed, indicating substantial variability across users. This wider dispersion suggests that residents often travel longer routes by car, or face inconsistent travel patterns that translate into higher operating costs.

The contrast between the two distributions indicates that for a district like 41027, the economic penalty of relying on a private vehicle is significant. The structure of commuting from this area likely involves journeys to peripheral or dispersed destinations, which public transport accommodates at a relatively stable cost, while the car becomes an increasingly expensive alternative. This contributes to a disproportionate economic burden for households that depend on private transport, particularly those for whom public alternatives may be less convenient or comprehensive.

Figure 19 thus reinforces the relationship between distance, mode choice, and financial vulnerability, suggesting that spatial isolation or functional disconnection from key destinations may underlie the higher transport costs incurred by car users in this district.

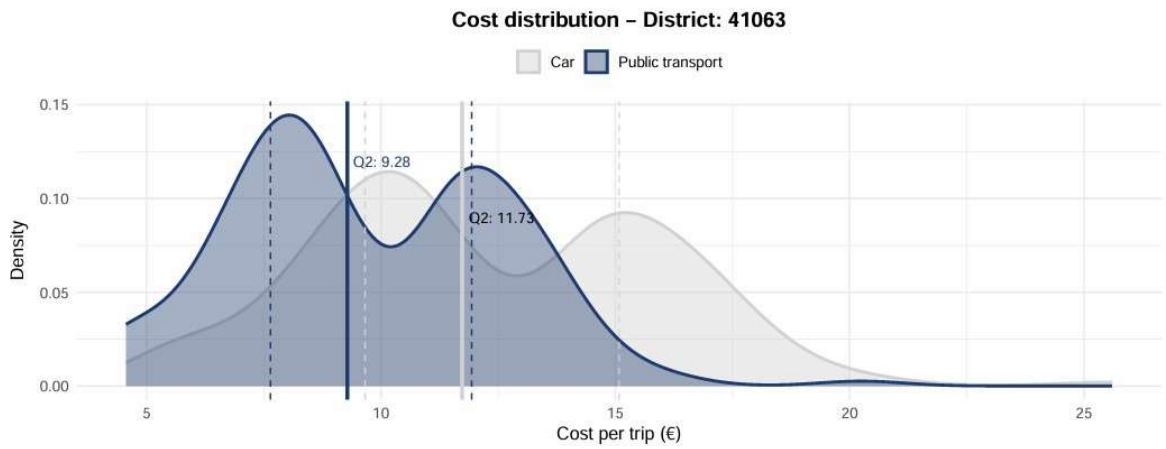


Figure 20: Cost distribution by transport mode – District 41063

Figure 20 presents the cost profiles for District 41063, where the median trip cost by car (11.73 €) once again exceeds that of public transport (9.28 €), marking a clear divergence between both mobility options. Although the absolute difference may appear moderate compared to other districts, its presence is reinforced by the broader and more skewed distribution of car travel costs.

The public transport distribution in this district is more compact, peaking sharply and tapering quickly, suggesting consistency in pricing and likely reflecting the presence of flat or zone-based fares. In contrast, the car cost distribution shows a bimodal structure, which may be indicative of two dominant commuting patterns: shorter, more local trips and longer, higher-cost journeys. This duality reinforces the idea that private car use exposes residents to wider cost variability, depending on destination and route characteristics.

The rightward spread of the car cost curve reflects increased exposure to fuel, distance-based expenses, and possibly tolls or parking costs—factors which public transport largely buffers against. The observed cost gap underlines the financial strain that reliance on private vehicles may entail, particularly when travel patterns are shaped by long distances or poor public transport connectivity.

In summary, District 41063 illustrates a scenario where even modest differences in median cost, when accompanied by pronounced variability in private transport expenditure, may signify underlying transport disadvantage and highlight the uneven economic burden between mobility alternatives.

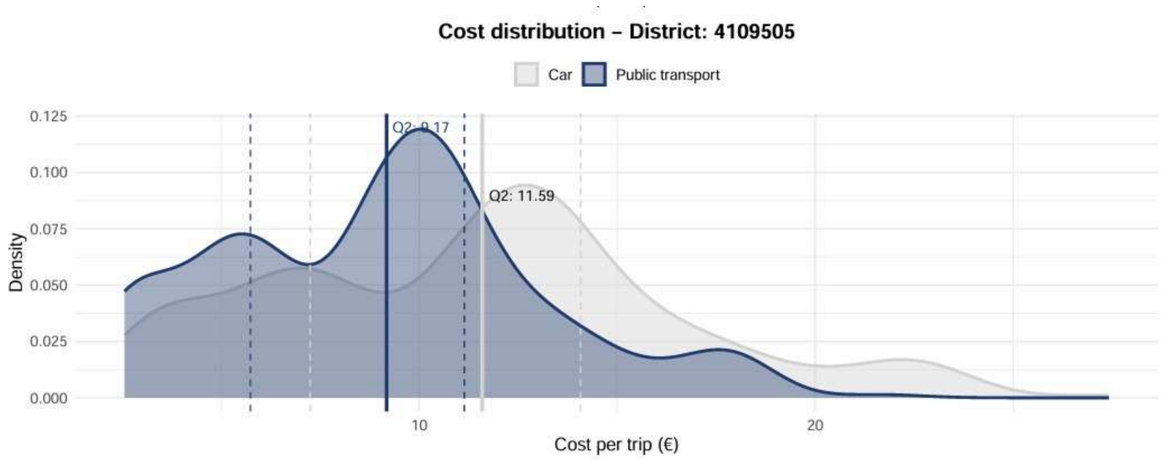


Figure 21: Cost distribution by transport mode – District 4109505

The cost distribution for District 4109505 reveals a particularly compelling dynamic between transport modes. The public transport distribution is sharply peaked and notably skewed toward the lower end of the cost spectrum, with a median cost (Q2) of €9.17. This tight cluster of values suggests a high level of fare consistency and affordability across trip types within the district. The profile evokes a reimagined model of mobility accessibility — especially for residents relying on public options to navigate the urban labyrinth.

Conversely, the distribution for private car use, while still anchored at a relatively low median cost of €11.59, exhibits broader dispersion and multiple subtle peaks. These local maxima likely correspond to distinct usage patterns or varied destination typologies—each a thread in the intricate tapestry of urban commutes. The overlapping nature of the two density curves suggests that, in this district, public transport offers a particularly competitive cost structure, potentially narrowing the financial deterrent often associated with alternative travel modes.

When observing the four districts with the largest disparities between car and public transport travel costs, several important differences and patterns emerge, both in statistical terms and in the shape of their respective distributions.

All four districts — 41099 (Figure 18), 41027 (Figure 19), 41063 (Figure 20), and 4109505 (Figure 21) — exhibit the same overarching trend: a higher median cost for car travel compared to public transport. However, the magnitude and form of this gap vary significantly. District 41099 presents one of the most marked cost separations, with a visibly wider spacing between medians and a flatter, more diffuse car distribution, suggesting a high dispersion in travel behaviors and distances. The public transport distribution, by contrast, remains relatively concentrated, reflecting consistency in fare levels.

District 41027, while showing a similarly structured pattern, is notable for its compressed cost ranges and more concentrated distributions for both modes. This may suggest more geographically bounded commuting patterns, with fewer extremes in terms of either cost or distance.

District 41063 stands out for its bimodal car cost distribution — a rare occurrence — which may reflect the coexistence of two predominant commuting logics: one more localized and another extending to more distant destinations. This internal diversity reinforces the notion of a spatially heterogeneous district, where the car is used for purposes of varying length and intensity.

Lastly, District 4109505 displays a clear peak in the public transport curve and a relatively smooth but right-skewed distribution for the car, suggesting that while most users benefit from stable PT pricing, a substantial portion of car users are exposed to disproportionately higher costs. The lower Q2 for public transport in this district also places it among those with the strongest price advantage for PT users.

In sum, the analysis of these four districts reinforces the central thesis that the economic burden of mobility is not evenly distributed. The differences in shape and spread — from flat tails to bimodal structures — reflect both geographic and infrastructural conditions that modulate accessibility. Districts with a wide gap between car and public transport costs, particularly when paired with significant car cost dispersion, can be seen as structurally more vulnerable in terms of transport equity, especially where reliance on private vehicles becomes a necessity due to connectivity deficits or spatial segregation.

4.3 FINAL CLASSIFICATION OF TRANSPORT VULNERABILITY LEVELS

This section brings together the complete analytical process developed throughout the study and applies it to a definitive classification of districts in the metropolitan area of Seville according to their level of transport vulnerability. After the prior disaggregation and assessment of travel times, monetary costs, and accessibility through both public transport and private vehicles, it becomes essential to synthesize all these variables into a categorical system that allows for clear interpretation, comparison, and spatial visualization. The ultimate goal is to identify and localize those territories where the existing transport system fails to guarantee access to essential urban opportunities in a fair and equitable manner.

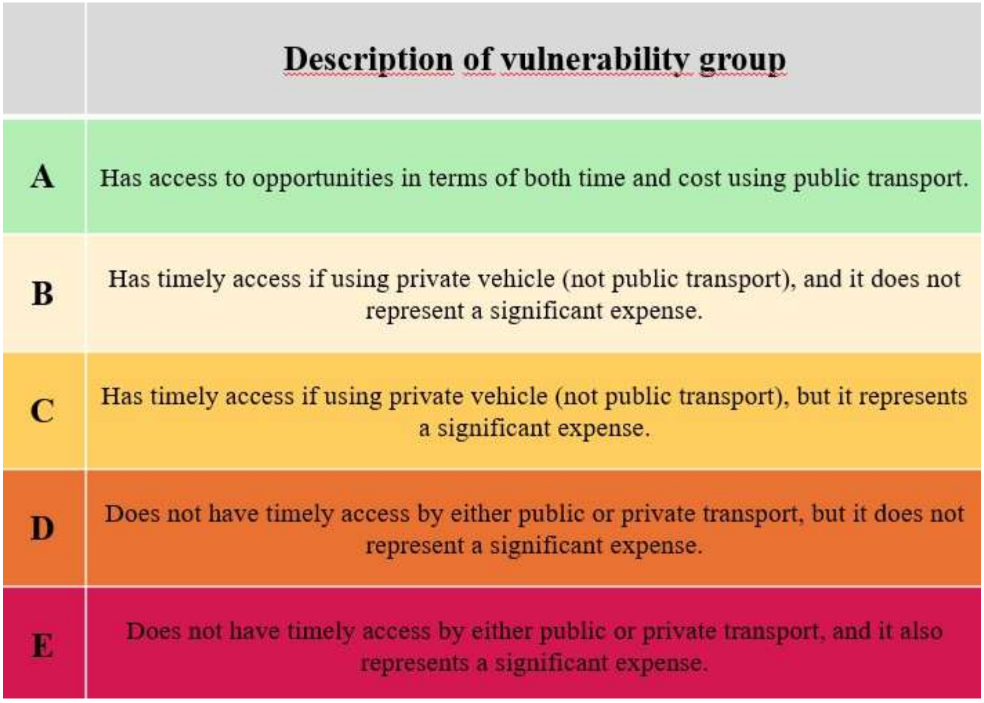
The classification proposed in this section divides all districts into five groups—A, B, C, D, and E—based on their combined performance in travel time and cost of mobility, and depending on whether acceptable access can be achieved via public transport or only by private vehicle. This five-level structure is not arbitrary: it reflects a conceptual typology widely used in the literature on transport disadvantage, which seeks to distinguish between those who can access opportunities efficiently (group A), those who depend on a private car (groups B and C), and those for whom access is difficult or costly by any means (groups D and E). In this way, the classification captures not only the severity of access limitations but also the modal dependence and the economic burden associated with each context.

From a methodological point of view, the classification uses a statistical criterion based on the third quartile (Q3) of the distribution of average travel times and costs across all districts. A district is considered to experience excessive travel time or cost if its average value is greater than or equal to Q3. This approach ensures that vulnerability is defined in relative and comparative terms, identifying as vulnerable those districts that lie within the top 25% worst-off areas in terms of time or cost. The choice of Q3 as a threshold—rather than more restrictive options such as the interquartile range (IQR) or twice the median—reflects the need to capture meaningful inequality without excluding moderately disadvantaged territories that still face clear barriers to access. This threshold strikes a balance between analytical rigor and practical relevance, offering a robust yet interpretable classification scheme.

Furthermore, it is important to emphasize that this classification is based exclusively on trips from home to work or educational destinations. The focus on this specific type of trip is deliberate and justified. Work and study-related trips are the most frequent, regular, and time-critical journeys in people's daily routines. They are also the trips with the least flexibility in terms of schedule or destination, meaning that limitations in transport for these movements can have a disproportionate impact on social and economic inclusion. In contrast, other trips—such as those made for leisure, shopping, or sporadic purposes—may involve longer travel times or higher costs, but their non-essential nature and lower frequency mean that they do not generate the same kind of systemic disadvantage. By restricting the analysis to work and study commutes, the classification ensures a focus on structural, recurring patterns of accessibility, rather than exceptional or marginal cases.

In summary, this section presents a final territorial segmentation of Seville's metropolitan area based on a multidimensional approach to transport poverty. By integrating both temporal and economic barriers, and by differentiating between public and private transport, the classification provides a nuanced, evidence-based framework for identifying spatial inequalities in access to opportunities. The resulting categorization into groups A through E will serve as the basis for later discussion, mapping, and policy recommendations.

Figure 22 presents the final classification of all districts into the five vulnerability groups (A to E), based on their combined performance in terms of travel time and cost. Each group is defined by a specific combination of accessibility conditions, distinguishing whether access is possible via public transport or private vehicle, and whether such access represents a significant economic burden. The criteria used for this classification are summarised in the figure itself.



	Description of vulnerability group
A	Has access to opportunities in terms of both time and cost using public transport.
B	Has timely access if using private vehicle (not public transport), and it does not represent a significant expense.
C	Has timely access if using private vehicle (not public transport), but it represents a significant expense.
D	Does not have timely access by either public or private transport, but it does not represent a significant expense.
E	Does not have timely access by either public or private transport, and it also represents a significant expense.

Figure 22: Classification of districts into transport vulnerability groups (A–E) based on travel time and cost criteria.

To operationalize the final classification of districts into transport vulnerability groups, a specific R script was developed. The code is structured into six main steps: filtering only those trips related to home-to-work/study journeys; calculating average travel times and costs for each district by mode of transport; merging these summaries into a single dataset; computing the 75th percentile (Q3) for each variable to establish vulnerability thresholds; and finally, assigning each district to one of the five predefined vulnerability groups (A–E) based on a combination of travel time and cost indicators. This classification logic is implemented using conditional rules in dplyr::case_when(). The resulting classification is then exported as a CSV file, ready to be imported and visualized in GIS environments such as QGIS.

Figure 23 shows the final classification map of districts in the province of Seville based on their level of transport vulnerability. This representation, developed using QGIS, displays the spatial distribution of each vulnerability group (A, B, E) resulting from the classification algorithm applied in R.

From a spatial perspective, it is immediately apparent that the districts falling within Group A, marked in green, are primarily concentrated in the central urban area of Seville, as well as in some adjacent western and southwestern municipalities. These districts benefit from an extensive and well-connected public transport network, characterized by frequent service, higher density of stops, and relatively short distances between residential areas and employment or educational centers. Consequently, residents in these zones enjoy good accessibility both in terms of travel time and cost, particularly when using public transport.

Group B districts, shaded in orange, are more commonly found in intermediate peripheral areas, particularly towards the west and south of the metropolitan region. These territories do not offer efficient or affordable access via public transport, but they do allow reasonable travel times and costs when using private vehicles. This suggests a dependence on the car, potentially driven by insufficient public transport coverage, longer walking distances to transit nodes, or limited service hours. While these districts do not experience excessive economic burdens, their accessibility is clearly linked to private mobility, raising concerns in terms of environmental sustainability, congestion, and transport equity.

In contrast, Group E, shown in red, predominantly appears in the northern and eastern outskirts of the metropolitan area, far from the core. These districts are the most vulnerable from a transport perspective, as they suffer from both long travel times and high costs, regardless of the transport mode used. The causes may include long distances to central activity hubs, lack of efficient transport infrastructure, low service frequency, and dispersed land use. The implications are significant: these residents are not only limited in their daily mobility options but may also face real barriers to accessing employment or education, which can further perpetuate social and spatial inequality.

This spatial pattern reveals a classic example of urban transport polarization, where central zones are privileged in terms of infrastructure and connectivity, while peripheral areas accumulate multiple layers of vulnerability. The use of the Q3 threshold as a benchmark ensures that vulnerability is understood relative to the distribution within the metropolitan context, rather than based on an arbitrary fixed value, thus offering a context-sensitive and robust criterion. The map provides a crucial visual output for decision-makers, allowing targeted policy interventions to address inequalities in transport accessibility across Seville's metropolitan territory.

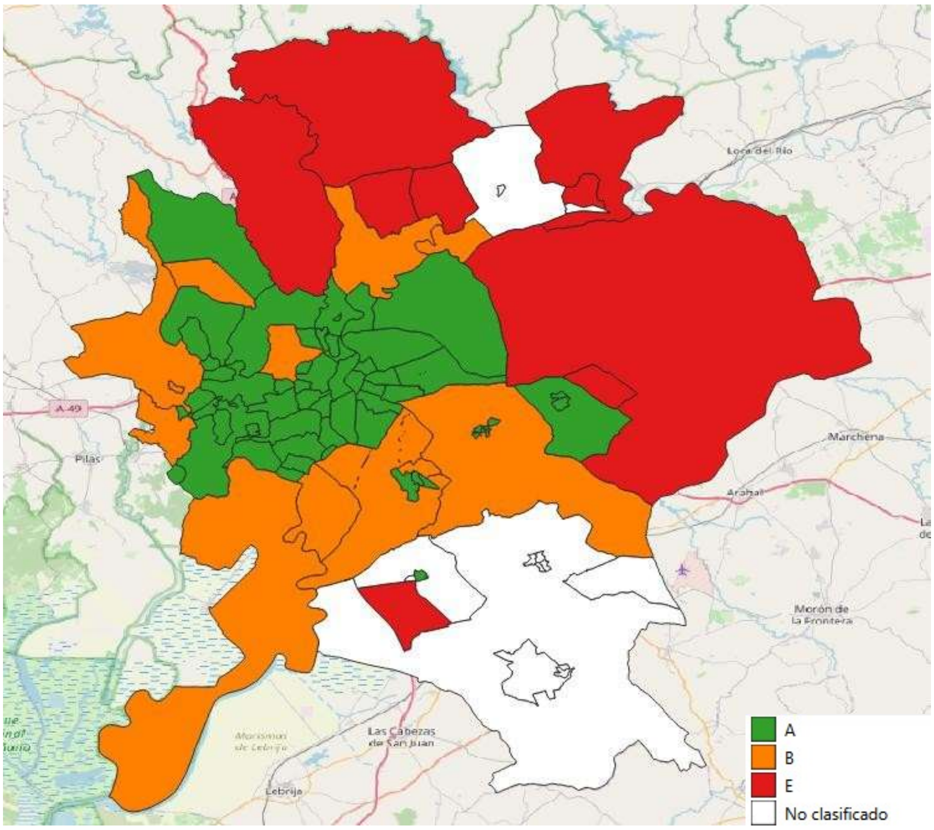


Figure 23: Final classification of transport vulnerability levels across the metropolitan area of Seville.

This spatial pattern reveals a classic example of urban transport polarization, where central zones are privileged in terms of infrastructure and connectivity, while peripheral areas accumulate multiple layers of vulnerability. The use of the Q3 threshold as a benchmark ensures that vulnerability is understood relative to the distribution within the metropolitan context, rather than based on an arbitrary fixed value, thus offering a context-sensitive and robust criterion. The map provides a crucial visual output for decision-makers, allowing targeted policy interventions to address inequalities in transport accessibility across Seville's metropolitan territory.

However, as further visualised in Figure 15 (see Figure 15), which represents the ratio of average public transport time to car travel time per district, some patterns may initially appear contradictory. The districts in the northern part of the metropolitan area—characterised by lighter yellow tones—exhibit some of the lowest ratios in Seville. On the surface, this could be interpreted as an indication of better public transport performance in those areas. Nevertheless, such a conclusion would overlook a critical nuance: low ratios can result not from short travel times by public transport, but from similarly long times across both modes. In other words, a ratio closer to one may simply reflect that neither transport option is efficient.

This interpretation gains clarity when compared with the final classification of vulnerability groups shown in Figure 23 (see Figure 23). Many of the same northern districts identified in Figure 15 with low public transport-to-car ratios are also classified within group E—the most vulnerable category—which indicates that their average travel times by both public transport and car exceed the Q3 threshold. This dual vulnerability suggests that these districts are not simply underserved by one mode, but structurally disconnected in a broader sense. The lack of efficient alternatives forces residents to endure long commutes regardless of the chosen mode, reinforcing their isolation and limiting access to opportunities.

Ultimately, the combination of low ratios and high absolute travel times illustrates the importance of analysing both relative and absolute metrics when assessing accessibility.

Districts with the lowest ratios—such as values around 2.30—yet classified as transport-poor under the Q3-based framework, exemplify how spatial disadvantage can manifest through compounded inefficiencies. These findings highlight the need for integrated mobility planning that addresses structural disconnection rather than isolated improvements to single transport modes.

Finally, it is also important to acknowledge several methodological limitations inherent to this classification approach. First, the use of relative thresholds based on the upper quartile (Q3) ensures that a fixed proportion of districts—approximately the top 25% worst-off—are always classified as vulnerable, regardless of whether their absolute performance has improved or deteriorated over time. This relative framing may mask broader improvements or declines in the transport system as a whole. Second, the methodology treats time and cost as uniform burdens across districts, without explicitly incorporating socio-economic factors such as household income or car ownership rates; thus, a high mobility cost is assumed to have the same weight in affluent and low-income areas, potentially underestimating the compounded disadvantage faced by poorer districts. Third, the exclusive focus on home-to-work and home-to-study trips, while analytically justified, omits other essential mobility needs—such as healthcare, childcare, or food access—which may also contribute significantly to patterns of transport poverty and social exclusion. These limitations should be considered when interpreting the results and formulating policy recommendations, as they highlight important dimensions that fall outside the scope of the current analysis.

CHAPTER 5. DISCUSSION

5.1 INTERPRETING ACCESSIBILITY INEQUALITIES ACROSS SEVILLE'S URBAN SPACE

The spatial analysis conducted in this study reveals pronounced inequalities in accessibility across Seville's metropolitan area. These disparities are not limited to one dimension, but rather emerge from the combined effect of travel time and travel cost—two variables that shape how residents interact with the transport system and, by extension, with the city itself.

Travel time, as analysed throughout the study, reflects more than mere d uration. In districts located farther from the urban core or served by less efficient networks, the time required to reach frequent or essential destinations is often significantly higher. This is especially evident in trips to work or education, where longer durations may constrain employment opportunities, increase fatigue, and reduce time available for personal, family, or educational activities. Time, therefore, functions as a hidden cost that disproportionately affects residents with fewer modal alternatives.

At the same time, the differences in travel cost between public transport and private vehicles offer further insight into the structural vulnerabilities faced by certain districts. While public transport costs remain relatively stable due to fare regulation, car-related expenses vary widely, particularly as a function of distance and trip frequency. The analysis showed that in districts with limited transit connectivity, car dependency often becomes a necessity rather than a choice. The resulting cost burden can be considerable, particularly for households already under economic strain.

By identifying the districts with the largest gap between average car and public transport costs, the analysis highlights areas where long-distance mobility is a daily reality. This gap is not merely a financial metric—it signals deeper spatial inequalities. In these districts, residents are more likely to commute to destinations located far from their place of residence, a pattern that reflects both the location of employment centres and the spatial organisation of housing and services. While public transport offers a more affordable alternative, its practicality diminishes when journeys involve multiple transfers, infrequent schedules, or long waiting times. The wider the cost gap, the more it points to a lack of effective alternatives, reinforcing transport dependence and spatial exclusion.

Moreover, differences in the shape of cost and time distributions between districts offer additional insights. Public transport cost distributions tend to be more compressed, reflecting regulated fares and consistent pricing schemes. In contrast, car cost distributions are more dispersed, with longer tails or secondary peaks, especially in peripheral areas. This suggests not only a diversity of trip distances but also greater variability and unpredictability in travel behaviour, often tied to decentralised land use patterns.

Taken together, the dual analysis of time and cost paints a comprehensive picture of transport accessibility in Seville. Vulnerability arises at the intersection of both dimensions: when travel takes too long, becomes too expensive, or offers no viable alternatives. These patterns are not random but spatially structured, revealing how geography, urban form, and transport provision jointly produce conditions of disadvantage. Addressing them requires more than expanding infrastructure—it calls for a coordinated approach that considers the lived realities of those who face the longest journeys, the highest costs, and the fewest choices.

5.2 IMPLICATIONS, CONSTRAINTS AND REFLECTIONS ON THE FINDINGS

Beyond the quantitative results obtained, the analysis conducted in this study opens the door to several critical reflections concerning both the practical implications and the methodological boundaries of the approach.

Firstly, the findings offer tangible insight into where accessibility deficits are concentrated, and thus provide a valuable starting point for local policy design. Identifying districts with disproportionate time or cost burdens enables a more targeted allocation of resources—whether by reinforcing public transport services, improving network connectivity, or adjusting fare structures in areas of pronounced vulnerability. This perspective moves beyond generalised infrastructure planning and encourages place-based interventions tailored to the lived mobility patterns of each urban area.

Nevertheless, it is important to acknowledge the methodological constraints that inevitably shape the results. While the use of GTFS data and a synthetic travel demand matrix allows for robust estimations of travel times, it assumes average performance across the transport network and does not fully capture variability due to service delays, congestion, or temporal inconsistencies. Similarly, cost estimates—particularly for private vehicle use—rely on average parameters such as distance, fuel efficiency, and detour factors, which may vary significantly depending on household characteristics and travel behaviour.

Another limitation stems from the spatial resolution of the analysis. District-level aggregation provides a clear overview but may mask important intra-district disparities, especially in heterogeneous urban contexts where accessibility conditions can differ markedly within short distances. Future studies might consider integrating more granular spatial units, such as census tracts or mobility cells, to enhance spatial precision.

It is also worth considering that accessibility is not only a function of transport supply, but of individual capacities, schedules, and socio-economic conditions. Factors such as age, income, gender, or household composition influence travel decisions and constraints in ways that are not directly observable through trip matrices or GTFS data alone. In this sense, the approach adopted in this study offers a solid foundation for identifying structural patterns of accessibility, but it should ideally be complemented by qualitative or participatory approaches to fully grasp the complexity of transport-related vulnerability.

Finally, the notion of vulnerability applied here is inherently relational. It does not imply that some districts are absolutely "poor" in transport, but rather that they are relatively disadvantaged compared to others in terms of time, cost, or modal choice. This distinction is essential when designing equitable transport policies that seek not only efficiency, but also fairness across the urban territory.

CHAPTER 6. CONCLUSION

This research has explored transport accessibility across the metropolitan area of Seville, with the aim of identifying structural inequalities that shape the mobility experiences of its residents. Drawing from a combination of geospatial modelling, GTFS transit data, origin-destination matrices, and comparative cost analysis, the study has produced an integrated understanding of how accessibility—both in terms of time and cost—is distributed across urban space.

The main findings confirm that accessibility in Seville is not uniform, and that marked disparities persist between districts, particularly when considering the time it takes to reach frequent destinations and the financial cost associated with doing so. Public transport networks, while offering affordable options through regulated fares, often fall short in peripheral or poorly connected areas. In these districts, long travel times and limited service frequencies constrain the real usability of the system, forcing many residents to rely on private vehicles. This car dependency introduces a parallel cost burden that disproportionately affects those who live far from major employment, education, or service hubs.

By modelling both travel time and cost, the study has demonstrated that transport poverty in Seville cannot be captured through a single variable. In some areas, the cost of driving long distances every day becomes a marker of vulnerability; in others, long travel times on public transport reflect the absence of viable alternatives. Particularly striking are the districts where the difference between car and public transport costs is highest—a pattern that points not only to economic strain but also to spatial isolation and a potential lack of modal flexibility. These findings support the idea that accessibility should be approached as a multidimensional concept, involving affordability, efficiency, and choice.

Moreover, the analysis of trip types reveals that not all journeys are affected equally. Commutes for work and education exhibit longer durations and higher stress levels than non-frequent trips, which may reflect the rigidity of schedules and the necessity of punctuality in daily life. The ratios between trip types, especially when disaggregated by district, provide further insight into how transport performance intersects with social needs, highlighting areas where time or cost represent tangible barriers to participation in urban life.

To operationalise these findings, the study introduced a final classification system dividing all districts into five vulnerability groups—A through E—based on whether they exceeded the third quartile (Q3) in time and cost variables, for both public transport and private vehicles. This classification was limited to work and education-related trips, in line with their greater relevance for understanding structural transport disadvantage. The results show that districts in central and well-connected areas tend to fall into Group A, indicating efficient and affordable access by public transport. In contrast, peripheral areas—particularly in the northeast and southwest—are overrepresented in Group E, reflecting dual vulnerability in both time and cost across all modes. Intermediate groups reveal further nuance, highlighting zones where private transport mitigates time disadvantages at the expense of increased cost. These spatial patterns confirm and reinforce previous analyses, while providing a clear framework for prioritising interventions.

From a methodological perspective, the research illustrates the potential of combining open transport data with spatial modelling to produce actionable insights into transport equity. Despite certain limitations—such as the assumption of average speeds or the absence of real-time variability—the approach offers a scalable, transparent framework for evaluating accessibility in other cities and metropolitan areas. It also opens avenues for incorporating additional layers of analysis, including demographic profiles, land use diversity, or behavioural data, to further enrich the understanding of mobility disadvantage.

Ultimately, the findings underscore that transport planning cannot be decoupled from questions of social justice. Ensuring equitable access to opportunities requires more than expanding infrastructure—it calls for rethinking the organisation of the city, the integration of different transport modes, and the financial barriers that shape individual choices. This study contributes to that effort by identifying the spaces where intervention is most needed and by proposing a replicable methodology to support evidence-based policy decisions. As Seville continues to grow and transform, placing accessibility at the core of urban and transport planning will be key to fostering inclusive, sustainable, and resilient mobility systems.

CHAPTER 7. FUTURE STEPS

The present thesis provides a robust foundation for understanding transport accessibility and the factors that contribute to transport poverty in the metropolitan area of Seville. However, its findings open a number of avenues for further development, both in terms of academic research and practical application.

One immediate line of future work involves the spatial extension and comparative application of the methodology to other metropolitan contexts. Replicating the analysis in regions with differing urban forms, socioeconomic profiles, or transport infrastructures could reveal patterns that are not only locally specific but also structurally embedded. This would allow for more generalized conclusions about the determinants of transport vulnerability and the effectiveness of policy responses.

From a methodological perspective, the work could be expanded by integrating additional variables—such as the frequency, reliability, or perceived quality of public transport services—that influence both perceived and actual accessibility. Moreover, incorporating real-time or user-generated data could enrich the temporal dimension of accessibility measurement, allowing for dynamic monitoring rather than static assessments. The use of emerging data sources such as mobile phone location data or transport app APIs presents a particularly promising opportunity.

Another critical step is the engagement with institutional actors. Sharing these findings with public authorities, particularly at the local level, could support the design of more targeted and equitable mobility interventions. In this regard, potential collaboration with the Ayuntamiento de Sevilla would be especially relevant. The city council could benefit from the accessibility indicators and spatial visualisations generated through this analysis to inform infrastructure planning, prioritise service improvements, or refine fare policies in districts identified as vulnerable. Additionally, embedding these tools within participatory planning processes could ensure that both technical data and local knowledge are reflected in transport decisions.

Beyond the local context, there is an opportunity to align this research with broader policy agendas. As highlighted in the European Commission's mobility and social equity strategies, transport accessibility is increasingly recognized as essential to inclusive urban development. The indicators and frameworks developed in this thesis could contribute to national or European-level assessments of transport equity, particularly within the context of green transition funding, resilience planning, and the implementation of Sustainable Urban Mobility Plans (SUMPs).

In the longer term, the approach outlined in this study has the potential to become part of a broader urban intelligence framework that supports resilient and socially inclusive mobility systems. By embedding accessibility metrics into ongoing monitoring tools and planning cycles, cities like Seville can move towards data-informed governance models that are responsive to structural inequalities rather than reactive to short-term demands. Ultimately, by institutionalising the measurement of transport equity, this type of work can help shape a future where mobility is not a barrier, but a bridge to opportunity.

CHAPTER 8. ANNEXES

Tabla 7 - Distancia media estimada de los viajes (km). Año 2022.

	Autobús urbano	Otros autobuses urbanos	Autobús metropolitano	Metro	Tranvía/ Metro ligero	Cercanías RENFE	FF.CC. autonómicos y de vía estrecha
Madrid	2,8	13,3		6,3	5,0	17,2	n.d.
Barcelona	3,0	4,1	14,1	5,0	2,7	20,8	17,3
Valencia	0,1	-	0,1	0,2	0,6	32,5	n.d.
Sevilla	3,4	-	15,7	4,6	1,0	23,6	-
Bizkaia	n.d.	n.d.	n.d.	n.d.	n.d.	9,5	1,1
Málaga	5,6	n.d.	10,4	5,4	-	16,8	-
Asturias	13,4	3356,4	-	-	-	18,8	18,0
Mallorca	3,2	-	-	n.d.	-	-	-
Zaragoza	7,4	-	n.d.	-	431,0	10	-
Bahía de Cádiz	n.d.	n.d.	24,1	-	-	24,2	8,4
Gipuzkoa	n.d.	n.d.	n.d.	n.d.	n.d.	18,9	n.d.
Alicante	n.d.	-	31,5	10,7	11,4	-	-
A Coruña	3,6	-	n.d.	-	-	n.d.	-
Valladolid	0,2	n.d.	n.d.	-	-	-	-
C. de Pamplona[1]		4,1		-	-	-	-
C. de Gibraltar	3,8	n.d.	17,6	-	-	-	-
León	7,1	-	n.d.	-	-	-	n.d.

Table 1: Estimated average travel distance by mode (km), 2022 (original source: Table 7)

Tabla 20 - Velocidad comercial media diaria (km/h). Año 2022.

	Autobús urbano	Otros autobuses urbanos	Autobús metropolitano	Metro	Tranvía/ Metro ligero	Cercanías Renfe	FF.CC. autonómicos y de vía estrecha
Madrid	12,9	n.d.	31 2[1]	27,0	22,5[1]	49,38	-
Barcelona	12,1	12,1	29,6	27,3	17,8	47,9	41,2
Valencia	12,1	n.d.	31,2	32,8	18,0	57,6	-
Sevilla	12,8	16,7	29,8	29,3	8,6	57,4	-
Bizkaia	n.d.	n.d.	n.d.	n.d.	n.d.	43,0	34,9
Málaga	14	n.d.	36,0	23,7	n.d.	42,3	n.d.
Asturias	15,7	14,2	n.d.	-	-	51,2	40,5
Mallorca	14,5	n.d.	n.d.	41,1	-	-	57,2
Bahía de Cádiz	n.d.	n.d.	36,6	-	-	65,4	-
Zaragoza	15,0	-	33,0	-	19,0	44,3	-
Gipuzkoa[1]	17,2	n.d.	n.d.	n.d.	n.d.	50	n.d.
C. de Tarragona	16,4	14,7	33,3	n.d.	n.d.	-	-
Granada[2]	11,9	n.d.	22,0	-	19,7	-	-
Alicante[3]	12,0	n.d.	15,4	31,4	29,4	-	n.d.
A Coruña	14,2	-	n.d.	-	n.d.	-	n.d.
Valladolid	15,6	n.d.	n.d.	-	-	-	n.d.
Lleida[4]	12,7	-	33,3	-	n.d.	-	50,0
C. de Pamplona[5]		12,7		-	-	-	-
C. de Gibraltar	n.d.	n.d.	35,0	-	-	-	-
León	13,1	-	n.d.	-	-	-	43,7
Cáceres	16,2	-	-	-	-	-	-

Table 2: Average commercial speed by transport mode (km/h), 2022 (original source: Table 20)

Tabla 40 – Tarifas de los títulos de transporte (en euros). Año 2022.

	Corona Mínima					Corona Máxima				
	Billete sencillo	Billete múltiple	Abono mensual	Abono estudiante	Abono jubilado	Billete sencillo	Billete múltiple	Abono mensual	Abono estudiante	Abono jubilado
Madrid[1]	1,5	12,2	27,3	10	1,6	5,1	37,4	41	10	1,6
Barcelona[2]	2,4	11,35	40	80	-	-	47,90	153,55	225,25	-
Valencia	1,5	7,2	35	38,25	20	4,8	20	53	63,25	20
Sevilla[3]	1,5	-	27,94	19	0,65	3,65	-	-	-	-
Bizkaia[4]	1,30-1,75	-	46	39	-	3,35-4,50	-	93	81	-
Málaga[5]	1,55	8,3	39,95	27	27	3,6	-	-	-	-
Asturias[6]	1,2	9	42	7,85	6,65	-	86,8	216,1	-	-
Mallorca	1,8	15	10	20	-	5,4	-	-	-	-
Zaragoza	1,35	10	42,95	-	Gratuito	3,95	-	42,95	-	Gratuito
Gipuzkoa[2]	1,85	-	-	-	-	12,9	-	-	-	-
Bahía de Cádiz[2]	1,4	-	-	-	-	7,55	-	-	-	-
C. de Tarragona	1,5	12,25	46,6	-	10	-	34,85	98,8	-	-
Granada[7]	1,4	-	41	-	Gratuito	3	-	-	-	-
Almería[7]	1,35	-	-	-	-	7,25	-	-	-	-
Alicante	1,35	8,7	40	16,5	Gratuito	7,15	-	-	-	10
A Coruña[8]	1,2	-	-	-	-					
Valladolid[11]	1,5	-	-	22	Gratuito	1,5	-	38	22	Gratuito
Lleida[7]	1,2	10	20,1-40,2	-	2,65	1,2	15,25	29,1-58,2	-	2,65
C. de Pamplona[9]	1,35	-	30	24	-					
C. de Gibraltar[10]	1,5	-	-	-	-	6,95	-	-	-	-
Jaén	1,4	-	-	-	-	5,75	-	-	-	-
León	1,2	7,5	36,15	6,5	3-6,5					
Cáceres	1,1	8	29	-	-					

Table 3: Public transport fares by tariff zone and ticket type (euros), 2022 (original source: Table 40)

Gráfico 114. Evolución del coste del transporte por carretera en vehículo privado desglosado por componentes (céntimos de euros corrientes/vehículo-kilómetro). 2000-2022

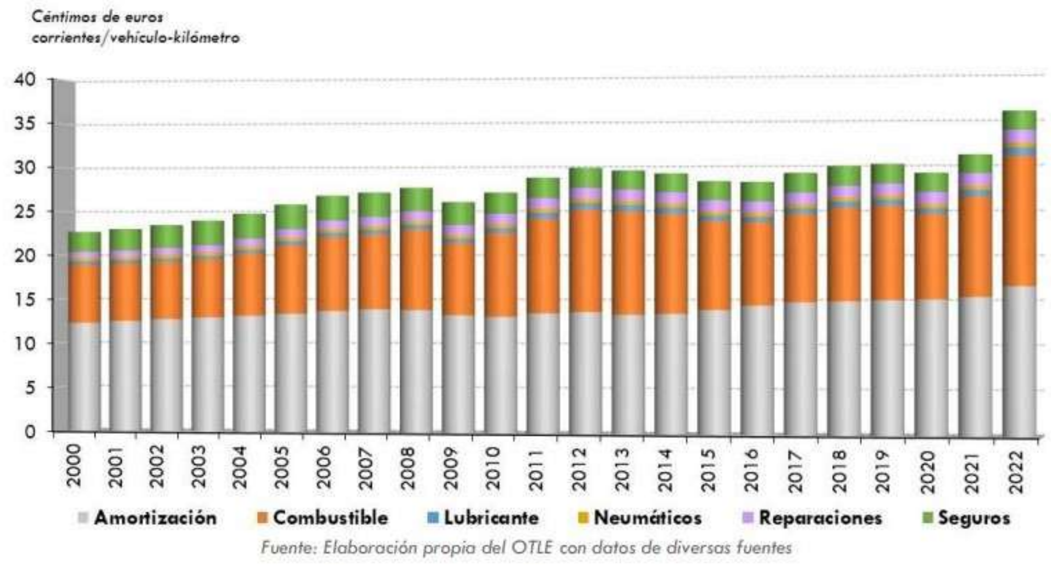


Figure 24: Evolution of private road transport costs by component (euro cents per vehicle-kilometre), 2000–2022 (original source: Graph 114)

CHAPTER 9. BIBLIOGRAPHY

1.- Lucas, K., Mattioli, G., Verlinghieri, E., & Guzman, A. (2016). *Transport poverty and its adverse social consequences. Proceedings of the ICE - Transport*, 169(6), 353-365.

2.- Mattioli, G. (2017). *"Forced car ownership" in the UK and Germany: Socio-spatial patterns and potential economic stress impacts. Social Inclusion*, 5(4), 147-160. https://doi.org/10.17645/si.v5i4.1081

3.- Social Exclusion Unit. (2003). *Making the Connections: Final Report on Transport and Social Exclusion*. Office of the Deputy Prime Minister.

4.- Gomide, A., Leite, S., & Rebelo, J. (2005). Public transport and urban poverty: A synthetic index of adequate service. *Documento de Trabajo*.

5.- Benevenuto, R., & Caulfield, B. (2020). Measuring access to urban centres in rural Northeast Brazil: A spatial accessibility poverty index. *Journal of Transport Geography*, 82, 102553. https://doi.org/10.1016/j.jtrangeo.2019.102553

6.- Dodson, J., & Sipe, N. (2007). Oil vulnerability in the Australian city: Assessing socioeconomic risks from higher urban fuel prices. *Urban Studies*, 44(1), 37-62. https://doi.org/10.1080/00420980601023810

7.- Tao, S., He, S. Y., Kwan, M.-P., & Luo, S. (2020). Does low income translate into lower mobility? An investigation of activity space in Hong Kong between 2002 and 2011. *Journal of Transport Geography*, 82, 102583. https://doi.org/10.1016/j.jtrangeo.2019.102583

8.- Alonso-Epelde, E., García-Muros, X., González-Eguino, M. (2023). Transport poverty indicators: A new framework based on the household budget survey. *Energy Policy*, 181, 113692. https://doi.org/10.1016/j.enpol.2023.113692

9.- Allen, J., & Farber, S. (2019). Sizing up transport poverty: A national scale accounting of low-income households suffering from inaccessibility in Canada, and what to do about it. *Transport Policy*, 74, 214-223. https://doi.org/10.1016/j.tranpol.2018.11.018

10.- Cebollada, À. (2006). Aproximación a los procesos de exclusión social a partir de la relación entre el territorio y la movilidad cotidiana. *Documents d'Anàlisi Geogràfica*, 105-121.

11.- Litman, T. (2021). Transport affordability: Evaluation and improvement strategies. *Victoria Transport Policy Institute*, 46.

12.- Fransen, K., Neutens, T., Farber, S., De Maeyer, P., Deruyter, G., & Witlox, F. (2015). Identifying public transport gaps using time-dependent accessibility levels. *Journal of Transport Geography*, 48, 176-187. https://doi.org/10.1016/j.jtrangeo.2015.09.008

13.- European Commission. (2020). *Sustainable and smart mobility strategy – putting European transport on track for the future* (COM/2020/789 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

14.- European Commission. (2021). *Proposal for a regulation of the European Parliament and of the Council establishing a Social Climate Fund* (COM/2021/568 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0568

15.- Ayuntamiento de Sevilla. (2022). *Renta neta media por persona y por hogar por distrito. Servicio de Estadística*. Based on INE experimental statistics. Retrieved from internal municipal datasets.

16.- Ministerio de Transportes, Movilidad y Agenda Urbana. (2024). *Informe anual 2023 del Observatorio del Transporte y la Logística en España (OTLE)* (p. 164, Gráfico 114). https://cdn.transportes.gob.es/portal-web-drupal/OTLE/elementos_otle/informe_anual_2023_(mayo_2024).pdf

17.- Ministerio de Transportes, Movilidad y Agenda Urbana. (2022). *Observatorio de costes y financiación del transporte público urbano colectivo* (Tablas 7, 20 y 40). Gobierno de España. https://observatoriomovilidad.es/wp-content/uploads/2024/03/InformeOMM-2022-23-def.pdf

18.-Rodrigue, J.-P. (2023). *Graph theory: Measures and indices*. The Geography of Transport Systems. https://transportgeography.org/contents/methods/graph-theory-measures-indices/

19.- Movotiv. (2023). *Mobility and transportation statistics*. https://movotiv.com/statistics

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