COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

CHARACTERIZATION OF NEW TECHNOLOGIES AND BUSINESS MODELS IN URBAN TRANSPORTASTION (*Madrid case study)*

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18 de julio de 2024

Madrid

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CARACTERIZACIÓN DE NUEVAS TECNOLOGÍAS Y MODELOS DE NEGOCIO EN EL TRANSPORTE URBANO

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Palabras Clave: Transporte, Emisiones, Movilidad Sostenible, Descarbonización

RESUMEN DEL PROYECTO

Caracterización y estudio los diversos elementos involucrados en la descarbonización del transporte urbano, enfocándose específicamente en la ciudad de Madrid. Este proyecto examina la evolución de las tecnologías existentes y la aparición de nuevos modelos de negocio y vectores energéticos alternativos en esta demanda de transporte. Considerará no solo los aspectos técnicos relacionados con la reducción de emisiones, sino también los factores económicos que enmarcan y posicionan estas opciones como soluciones viables.

Introducción

En los últimos años, la descarbonización del transporte se ha convertido en un objetivo central en la transición hacia una economía sostenible. El transporte urbano desempeña un papel fundamental en este proceso, presentando múltiples alternativas tecnológicas para reducir las emisiones.

El objetivo principal de este trabajo es caracterizar y estudiar los diversos elementos que rodean la descarbonización del transporte urbano, con un enfoque en la ciudad de Madrid. Se analizará la evolución de las tecnologías existentes, así como la aparición de nuevos modelos de negocio y vectores energéticos alternativos, considerando tanto aspectos técnicos como económicos.

En cuanto a las emisiones de gases de efecto invernadero, Madrid, al igual que todas las áreas metropolitanas, se enfrenta al desafío de una alta dependencia del transporte privado, el principal emisor de GEI en el sector transporte en España. En cuanto a la contaminación local, enfrenta desafíos relativos a la la contaminación del aire por los altos niveles de emisiones nocivas resultantes de la combustión de los combustibles tradicionales . La ciudad busca abordar estos problemas a través de políticas de movilidad sostenible, la promoción del uso del transporte público y la adopción de tecnologías más limpias.

Para ello, el estudio comenzará caracterizando las alternativas tecnológicas de transporte, tanto tradicionales como emergentes, y asociando sus emisiones correspondientes. Posteriormente, se analizarán otros factores relevantes, como el kilometraje, la ocupación

y la vida útil de los vehículos, así como los aspectos económicos relacionados con los diferentes vectores energéticos y modos de transporte.

De esta manera, se espera obtener un análisis exhaustivo que permita identificar oportunidades para una transición eficiente hacia un sistema de transporte urbano más sostenible en la ciudad de Madrid.

Metodología

A fin de abordar este proyecto de caracterización de tecnologías en el transporte urbano en Madrid, me aproximaría a la tarea siguiendo los siguientes pasos:

1. Definición de Objetivos: Comenzaría por delinear de manera clara y precisa los objetivos específicos del proyecto. Esto implicaría establecer metas tales como la identificación de las tecnologías existentes, la evaluación de su impacto ambiental y la proposición de mejoras para la movilidad urbana.
2. Recopilación de Datos Iniciales: El punto de partida sería la recolección de datos generales sobre el transporte urbano en España. Ello conllevaría profundizar en informes gubernamentales, estadísticas de tráfico y documentos relevantes de planificación urbana.
3. Identificación de Tecnologías: A continuación, procedería a elaborar un listado exhaustivo de las tecnologías asociadas al transporte urbano en Madrid. Dicho inventario podría abarcar desde los vehículos convencionales, el transporte público y las opciones de movilidad compartida, hasta las tecnologías emergentes como los vehículos eléctricos o las soluciones de Movilidad como Servicio (MaaS).
4. Análisis de Tecnologías Convencionales: Seguidamente, caracterizaría en detalle las tecnologías convencionales empleadas en el transporte urbano. Los aspectos clave a examinar incluirían la oferta y demanda, las emisiones, las tarifas, las áreas de cobertura y otros factores pertinentes.
5. Análisis de Tecnologías MaaS: Siguiendo una aproximación similar, realizaría una caracterización pormenorizada de las tecnologías vinculadas a la Movilidad como Servicio (MaaS). Este análisis abarcaría dimensiones como la oferta y demanda, las emisiones, las tarifas, las empresas de MaaS y las áreas de cobertura.
6. Análisis Comparativo: Posteriormente, llevaría a cabo un análisis comparativo para contrastar las tecnologías convencionales y las de MaaS. Ello permitiría identificar áreas de mejora, reconocer oportunidades para una integración eficiente y proponer posibles soluciones sostenibles.
7. Integración de Datos: Finalmente, integraría los datos obtenidos en un análisis económico y de emisiones, el cual se llevaría a cabo a través de una serie de cálculos en Excel. Dicho análisis incluiría una evaluación del Coste Total de Propiedad (TCO), un análisis de emisiones y un estudio del Coste de Abatimiento Marginal (MAC).

Resultados

Después de una exhaustiva búsqueda de información y caracterización de los distintos modos de transporte y vectores energéticos, las Tablas 1 a 4 muestra los datos obtenidos, separados para los modos convencionales y nuevos representados en este trabajo.

Table 1. Caracterización de los modos de transporte convencionales

CONVENTIONAL TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating Costs, €/year)**	**VAROM (Variable Operating Costs, €/km)**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
Diesel Car	24500	24500	732	0,129	diesel	1,18	12000	15
Gasoline Car	22000	22000	732	0,146	gasoline	1,18	12000	15
Electric Car	35000	32000	582	0,070	electricity	1,18	12000	15
Gasoline Motorcycle	7000	7000	122	0,083	gasoline	1,05	3000	12
Electric Motorcycle	8500	6800	113	0,037	electricity	1,05	3000	10
Natural Gas Urban Busl (GNC)	310000	310000	4650	0,200	natural gas	16,00	100000	10
Electric Urban Bus	550000	550000	8250	0,150	electricity	16,00	100000	15
Diesel Urban Bus	272500	272500	4087,5	0,200	diesel	16,00	100000	15
Hydrogen Urban Bus	1250000	1250000	18750	0,350	hydrogen	16,00	100000	10
Electric Metro (e.g., Madrid)	6377000	6377000	1655000	0,195	electricity	128,50	85000	30
Electric Tram (e.g., Zaragoza)	200000000	200000000	2700000	0,190	electricity	80,40	100000	30
Convencional Taxi (gasoline)	22000	22000	8950	0,021	gasoline	1,18	55000	7
Hybrid Electric Vehicle Taxi (HEV)	25000	20000	8950	0,021	gasoline (85%) + electricity (15%)	1,18	55000	7

Table 2. Caracterización de los nuevos modos de transporte

NEW MODES AND TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating**	**VAROM (Variable Operating**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
Shared electric car (driverless, Zity)	35000	32000	2240	0,070	electricity	1,20	18000	15
Shared gasoline car (driverless, Wible)	24500	24500	1715	0,146	gasoline	1,20	18000	15
Shared electric motorcycle	5000	4000	350	0,037	electricity	1,05	10000	5
Shared electric bicycle	1500	1200	100	0,057	electricity	1,00	2800	3
Shared electric scooter	200	160	100	0,086	electricity	1,00	2800	3
Hybrid car ride sharing (Uber)	30000	24000	1680	0,021	gasoline (85%) + electricity (15%)	1,20	60000	6
Electric car ride sharing (Uber)	35000	28000	1960	0,070	electricity	1,20	60000	6

Table 3. Caracterización de los modos de transporte convencionales II

CONVENTIONAL TECHNOLOGIES			
echnology	**Efficiency (MJ/v.km)**	**Emissions per v.km (gCO2eq/v.km)**	**Emissions per p.km (gCO2eq/p.km)**
Diesel Car	2,6	192,66	163,27
Gasoline Car	2,6	194,22	164,59
Electric Car	0,8712	112,55	95,38
Gasoline Motorcycle	1,26	94,12	89,64
Electric Motorcycle	0,54	69,76	66,44
Natural Gas Urban Busl (GNC)	9,76	475,80	29,74
Electric Urban Bus	2,304	297,65	18,60
Diesel Urban Bus	8,32	616,51	38,53
Hydrogen Urban Bus	4,96	466,24	29,14
Electric Metro (e.g., Madrid)	43,2	5581,01	43,43
Electric Tram (e.g., Zaragoza)	8,6832	1121,78	13,95
Convencional Taxi (gasoline)	2,6	194,22	164,59
Hybrid Electric Vehicle Taxi (HEV)	1,51	125,14	106,05

Table 4. Caracterización de los nuevos modos de transporte II

NEW MODES AND TECHNOLOGIES			
Name of technology	**Efficiency (MJ/v.km)**	**Emissions per v.km (gCO2eq/v.km)**	**Emissions per p.km (gCO2eq/p.km)**
Shared electric car (driverless, Zity)	0,871	112,550	93,792
Shared gasoline car (driverless, Wible)	2,600	194,220	161,850
Shared electric motorcycle	0,540	69,763	66,441
Shared electric bicycle	0,049	6,301	6,301
Shared electric scooter	0,054	6,976	6,976
Hybrid car ride sharing (Uber)	1,510	112,797	93,998
Electric car ride sharing (Uber)	0,871	125,139	104,282

Resultados del Análisis del Coste Total de Propiedad (TCO) de los Distintos Modos de Transporte

Con los datos anteriormente presentados, hemos obtenido los siguientes resultados del análisis del Coste Total de Propiedad (TCO)

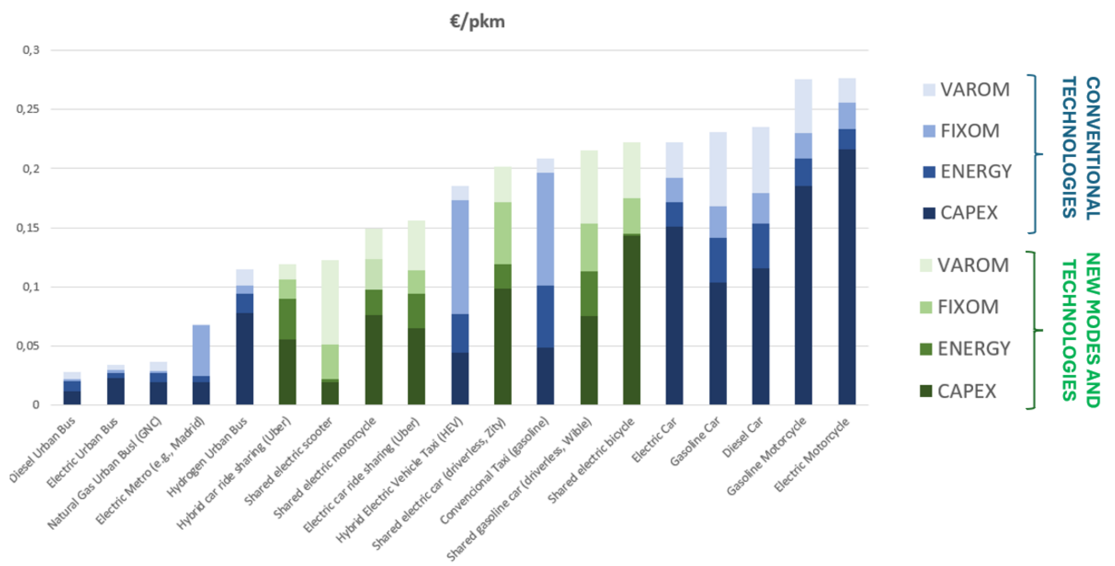

Illustration 1. Euros/pkm transporte (Elaboración: propia)

Resultados del Estudio de Emisiones de los Distintos Modos de Transporte

Después de un detallado análisis de las emisiones generadas por cada modo de transporte, hemos obtenido los siguientes resultados:

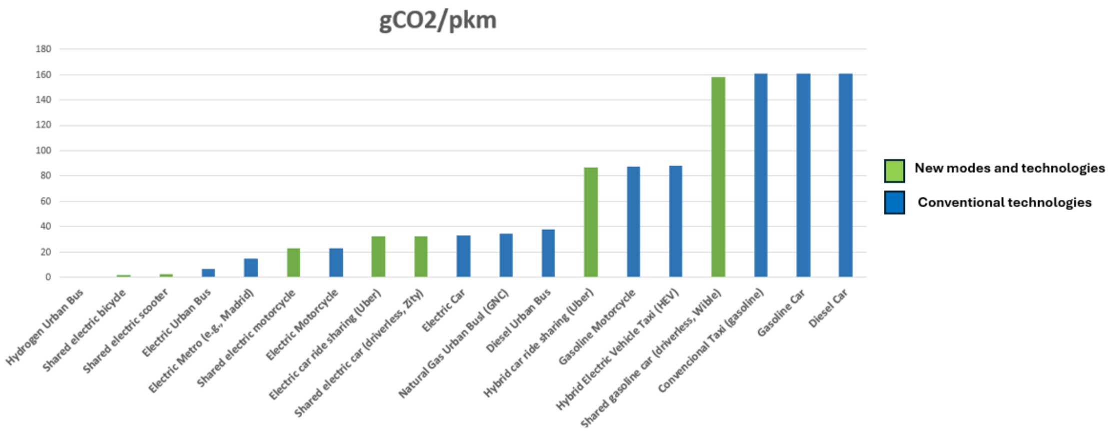

Illustration 2. gCO2/pkm transporte (Elaboración: propia)

Análisis del Coste Marginal de Abatimiento de los Distintos Modos de Transporte

El coste marginal de abatimiento se refiere al costo adicional por cada unidad de reducción de emisiones de contaminantes ($kgCO_2$). Los resultados del análisis del coste marginal de abatimiento, tomando como referencia el vehículo diésel, para cada modo de transporte son los siguientes:

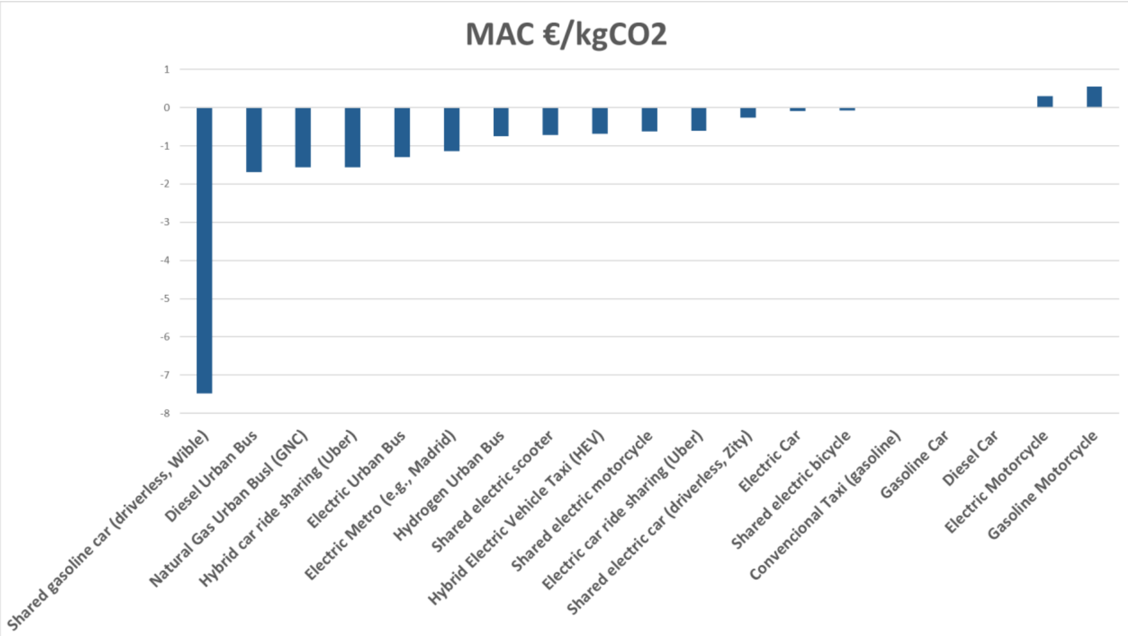

Illustration 3. MAC transporte (Elaboración: propia)

Conclusiones

A lo largo de este proyecto, hemos realizado una exhaustiva caracterización de las tecnologías convencionales y emergentes que conforman el sistema de transporte urbano de la ciudad de Madrid, aplicable a cualquier otra metrópolis. El análisis efectuado nos ha permitido alcanzar una comprensión integral de la situación actual y las tendencias futuras en este ámbito.

Los resultados obtenidos ponen de manifiesto que, si bien las tecnologías tradicionales como los vehículos de combustión interna y el transporte público convencional siguen desempeñando un papel fundamental y tienen un coste muy competitivo respecto a las nuevas tecnologías, el ecosistema de movilidad urbana se encuentra en un proceso de transformación acelerado. La irrupción de soluciones de Movilidad como Servicio (MaaS), vehículos eléctricos y otros desarrollos tecnológicos innovadores está generando nuevas oportunidades y desafíos para lograr una movilidad más sostenible, eficiente e integrada.

El análisis comparativo realizado ha permitido identificar áreas clave donde la integración entre las tecnologías convencionales y emergentes puede aportar beneficios significativos. Aspectos como la reducción de emisiones, la mejora de la accesibilidad, la optimización de la infraestructura y la diversificación de las opciones de transporte destacan como prioridades a abordar.

A partir de esta caracterización, se han formulado propuestas concretas de mejora que, de implementarse, contribuirían a potenciar el desarrollo de un sistema de transporte urbano más sostenible y resiliente en Madrid. Estas recomendaciones abarcan desde la expansión de las redes de transporte público eléctrico hasta el fomento de esquemas de movilidad compartida y la integración de plataformas de MaaS.

En definitiva, el presente estudio ha sentado las bases para comprender la dinámica actual y las tendencias futuras del transporte urbano en Madrid. Esperamos que los hallazgos y propuestas aquí expuestos puedan servir como activos valiosos para la toma de decisiones y la formulación de políticas públicas encaminadas a promover una movilidad urbana más eficiente, equitativa y respetuosa con el medio ambiente.

<u>Conclusiones finales:</u>

- Competitividad de Costes: El análisis ha revelado que algunas de las tecnologías emergentes son competitivas en coste con las tecnologías convencionales. Esto sugiere que la adopción de nuevas tecnologías no solo es viable desde una perspectiva medioambiental, sino también económica.
- Reducción de Emisiones: Todas las tecnologías emergentes evaluadas en el estudio han demostrado una significativa reducción de emisiones en comparación con el uso del coche privado. Esto refuerza la necesidad de priorizar estas alternativas para cumplir con los objetivos de sostenibilidad y reducción de contaminación urbana.
- Coste de Abatimiento Marginal: Todos los modos de transporte analizados presentan un coste de abatimiento marginal menor respecto al coche diésel, salvo las motocicletas privadas. Esto implica que, aunque algunas tecnologías puedan tener un coste inicial más alto, el beneficio en términos de reducción de emisiones y ahorro a largo plazo justifica la inversión.

CHARACTERIZATION OF NEW TECHNOLOGIES AND BUSINESS MODELS IN URBAN TRANSPORTATION.

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Key words: Transport, Emissions, Sustainable Mobility, Descarbonization.

ABSTRACT OF THE PROJECT

Characterization and study of the various elements involved in the decarbonization of urban transportation, specifically focusing on the city of Madrid. This project will examine the evolution of existing technologies and the emergence of new business models and alternative energy vectors. It will consider not only the technical aspects related to emissions reduction but also the economic factors that frame and position these options as viable solutions.

Introduction

In recent years, society has embarked on a complex transformation towards the decarbonization of the economy, with the decarbonization of the transport sector being a fundamental part of this process. Urban transport presents multiple alternatives for decarbonization, some already in practice and others that still require research to determine their contribution. Achieving an efficient transition requires the characterization of these new technologies, modes of transport, and business models within the urban transport domain.

The main objective of this Bachelor's Thesis is to characterize and study the various elements surrounding the decarbonization of urban transport, observing their contributions to this goal with a focus on the city of Madrid. It will address the evolution of existing technologies, as well as the emergence of new business models and alternative energy vectors. Not only will the technical aspects focused on emission reduction be considered, but also the economic aspects that frame and position these solutions as viable options.

Once the characterization is completed, the obtained data will be used to carry out an economic and emissions analysis. The study will begin by analyzing the challenges facing public transport in Madrid, and then propose feasible solutions. The city of Madrid aims to address these challenges through the implementation of sustainable mobility policies, the promotion of public transport use, and the adoption of cleaner technologies.

The first step of the research will be to characterize the various technological alternatives for transport, both traditional methods and new alternatives such as Mobility as a Service (MaaS). The next step will be to associate emissions with each of these technologies, analyzing their environmental impact. Subsequently, other relevant factors will be explored, such as annual mileage, occupancy, and vehicle lifespan. Additionally, the economic aspects related to the different energy vectors and modes of transport will be analyzed.

In this way, a comprehensive analysis is expected to be obtained, allowing the identification of opportunities for an efficient transition towards a more sustainable urban transport system in the city of Madrid.

Methodology

To embark on this project of characterizing technologies in urban transportation in Madrid, I would proceed with the following steps:

1. **Defining Objectives:** I would start by clearly defining the specific objectives of the project. This involves outlining goals such as the identification of existing technologies, evaluation of their environmental impact, and suggesting improvements for urban mobility.
2. **Gathering Initial Data:** The initial step would be to collect general data on urban transportation in Spain. This entails delving into government reports, traffic statistics, and relevant urban planning documents.
3. **Identification of Technologies:** Next, I would compile a comprehensive list of technologies associated with urban transportation in Madrid. This could encompass conventional vehicles, public transportation, shared mobility options, and emerging technologies like electric vehicles or Mobility as a Service (MaaS) solutions.
4. **Analysis of Conventional Technologies:** I would proceed to characterize conventional technologies utilized in urban transportation. Key aspects to examine include supply and demand, emissions, fares, coverage areas, and other pertinent factors.
5. **Analysis of MaaS Technologies:** Following a similar approach, I would conduct a detailed characterization of technologies linked to Mobility as a Service (MaaS). This analysis would cover areas such as supply and demand, emissions, fares, MaaS companies, and coverage areas.
6. **Comparative Analysis:** A comparative analysis would be conducted to contrast conventional and MaaS technologies. This involves identifying areas for improvement, recognizing opportunities for efficient integration, and proposing potential sustainable solutions.
7. Integration of the data obtained in an economic and emissions analysis carried out through a series of calculations in Excel. This will include a Total Cost of Ownership (TCO) analysis, emissions analysis, and a Marginal Abatement Cost (MAC) analysis.

Table 5. Organizational chart

	January		February		March		April		May	
	Week 1-2	Week 3-4	Week 1-2	Week 3-4	Week 1-2	Week 3-4	Week 1-2	Week 3-4	Week 1-2	Week 3-4
Information research										
Annex B										
Identification of Technologies										
Analysis of Conventional Technologies										
Analysis of MaaS Technologies										
Comparative Analysis										
Proposal of Improvements and Solutions										
Integration to calculation model										
Conclusions										
Document Drafting										

Results

After an exhaustive search for information and characterization of the various modes of transportation and energy vectors, we have obtained the following data:

Table 6. Characterization of Conventional Modes of Transportation

CONVENTIONAL TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating Costs, €/year)**	**VAROM (Variable Operating Costs, €/km)**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
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Electric Motorcycle	8500	6800	113	0,037	electricity	1,05	3000	10
Natural Gas Urban Busl (GNC)	310000	310000	4650	0,200	natural gas	16,00	100000	10
Electric Urban Bus	550000	550000	8250	0,150	electricity	16,00	100000	15
Diesel Urban Bus	272500	272500	4087,5	0,200	diesel	16,00	100000	15
Hydrogen Urban Bus	1250000	1250000	18750	0,350	hydrogen	16,00	100000	10
Electric Metro (e.g., Madrid)	6377000	6377000	1655000	0,195	electricity	128,50	85000	30
Electric Tram (e.g., Zaragoza)	200000000	200000000	2700000	0,190	electricity	80,40	100000	30
Convencional Taxi (gasoline)	22000	22000	8950	0,021	gasoline	1,18	55000	7
Hybrid Electric Vehicle Taxi (HEV)	25000	20000	8950	0,021	gasoline (85%) + electricity (15%)	1,18	55000	7

Table 7. Characterization of New Modes of Transportation

NEW MODES AND TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating**	**VAROM (Variable Operating**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
Shared electric car (driverless, Zity)	35000	32000	2240	0,070	electricity	1,20	18000	15
Shared gasoline car (driverless, Wible)	24500	24500	1715	0,146	gasoline	1,20	18000	15
Shared electric motorcycle	5000	4000	350	0,037	electricity	1,05	10000	5
Shared electric bicycle	1500	1200	100	0,057	electricity	1,00	2800	3
Shared electric scooter	200	160	100	0,086	electricity	1,00	2800	3
Hybrid car ride sharing (Uber)	30000	24000	1680	0,021	gasoline (85%) + electricity (15%)	1,20	60000	6
Electric car ride sharing (Uber)	35000	28000	1960	0,070	electricity	1,20	60000	6

Table 8. Characterization of Conventional Modes of Transportation II

CONVENTIONAL TECHNOLOGIES			
ɘchnology	Efficiency (MJ/v.km)	Emissions per v.km (gCO2eq/v.km)	Emissions per p.km (gCO2eq/p.km)
Diesel Car	2,6	192,66	163,27
Gasoline Car	2,6	194,22	164,59
Electric Car	0,8712	112,55	95,38
Gasoline Motorcycle	1,26	94,12	89,64
Electric Motorcycle	0,54	69,76	66,44
Natural Gas Urban Busl (GNC)	9,76	475,80	29,74
Electric Urban Bus	2,304	297,65	18,60
Diesel Urban Bus	8,32	616,51	38,53
Hydrogen Urban Bus	4,96	466,24	29,14
Electric Metro (e.g., Madrid)	43,2	5581,01	43,43
Electric Tram (e.g., Zaragoza)	8,6832	1121,78	13,95
Convencional Taxi (gasoline)	2,6	194,22	164,59
Hybrid Electric Vehicle Taxi (HEV)	1,51	125,14	106,05

Table 9. Characterization of New Modes of Transportation II

NEW MODES AND TECHNOLOGIES			
Name of technology	Efficiency (MJ/v.km)	Emissions per v.km (gCO2eq/v.km)	Emissions per p.km (gCO2eq/p.km)
Shared electric car (driverless, Zity)	0,871	112,550	93,792
Shared gasoline car (driverless, Wible)	2,600	194,220	161,850
Shared electric motorcycle	0,540	69,763	66,441
Shared electric bicycle	0,049	6,301	6,301
Shared electric scooter	0,054	6,976	6,976
Hybrid car ride sharing (Uber)	1,510	112,797	93,998
Electric car ride sharing (Uber)	0,871	125,139	104,282

Results of the Total Cost of Ownership (TCO) Analysis for Different Transportation Modes

After an exhaustive search for information and a careful characterization of different transportation modes, we have obtained the following results for the Total Cost of Ownership (TCO) analysis:

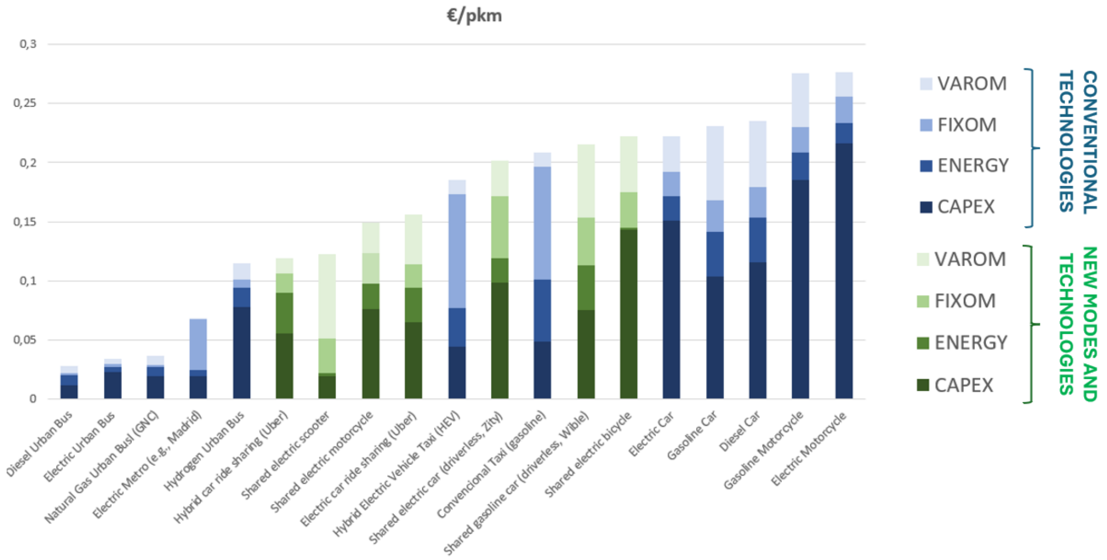

Illustration 4. Euros/pkm transport

Results of the Emissions Study for Different Transportation Modes

After a detailed analysis of the emissions generated by each mode of transportation, we have obtained the following results:

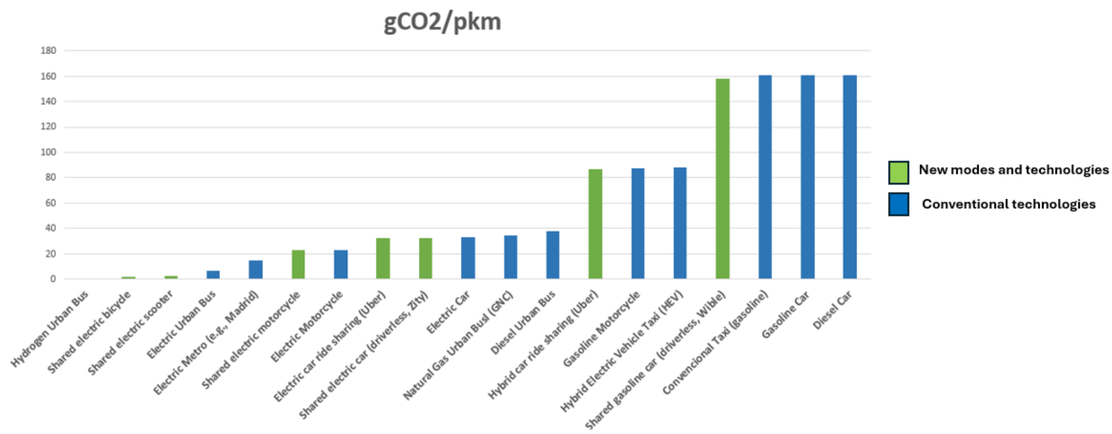

Illustration 5. gCO2/pkm transport

Marginal Abatement Cost Analysis for Different Transportation Modes

The marginal abatement cost refers to the additional cost for each unit of pollutant emission reduction ($kgCO_2$). The results of the marginal abatement cost analysis for each mode of transportation are as follows:

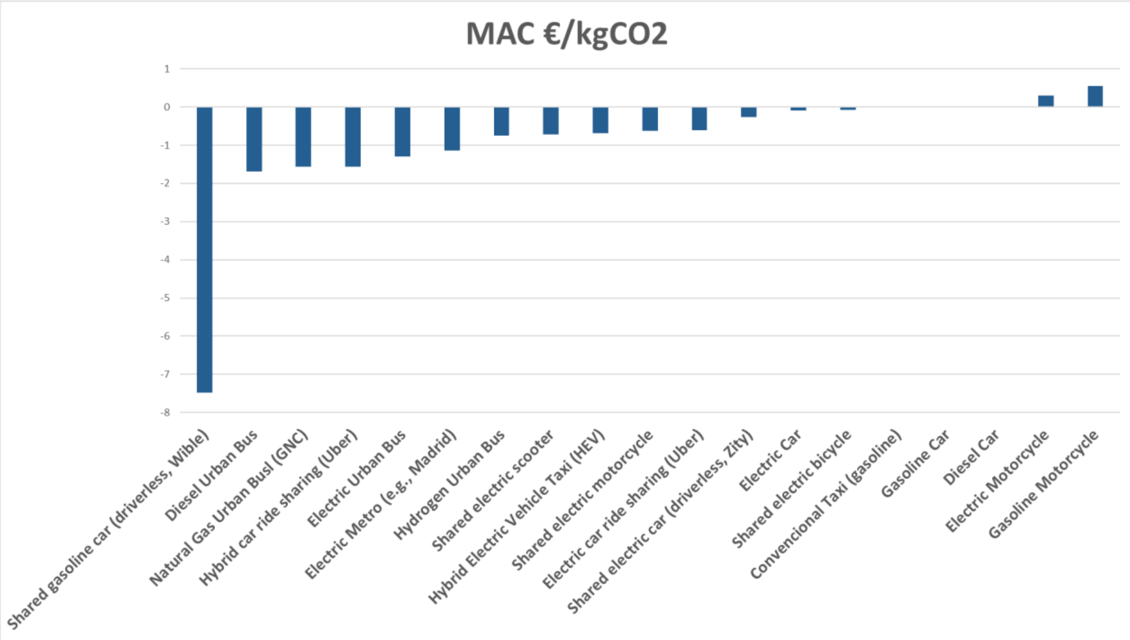

Illustration 6. MAC transport

Conclusions

Throughout this project, we have conducted an exhaustive characterization of the conventional and emerging technologies that make up the urban transportation system of the city of Madrid. The analysis carried out has allowed us to reach a comprehensive understanding of the current situation and future trends in this area.

The results obtained show that, while traditional technologies such as internal combustion vehicles and conventional public transport continue to play a fundamental role, the urban mobility ecosystem is undergoing an accelerated transformation process. The emergence of Mobility as a Service (MaaS) solutions, electric vehicles, and other innovative technological developments is generating new opportunities and challenges to achieve more sustainable, efficient, and integrated mobility.

The comparative analysis carried out has allowed the identification of key areas where the integration between conventional and emerging technologies can bring significant benefits. Aspects such as emission reduction, improved accessibility, infrastructure optimization, and diversification of transportation options stand out as priority issues to be addressed.

Based on this characterization, specific improvement proposals have been formulated that, if implemented, would contribute to enhancing the development of a more sustainable and resilient urban transportation system in Madrid. These recommendations range from the expansion of electric public transport networks to the promotion of shared mobility schemes and the integration of MaaS platforms.

In summary, this study has laid the groundwork for understanding the current dynamics and future trends of urban transportation in Madrid. We hope that the findings and proposals presented here can serve as valuable inputs for decision-making and the formulation of public policies aimed at promoting more efficient, equitable, and environmentally friendly urban mobility.

Final Conclusions:

- Cost Competitiveness: The analysis has revealed that some emerging technologies are cost-competitive with conventional technologies. This suggests that the adoption of new technologies is viable not only from an environmental perspective but also from an economic one.
- Emission Reduction: All emerging technologies evaluated in the study have demonstrated significant emission reductions compared to the use of private cars. This reinforces the need to prioritize these alternatives to meet sustainability goals and reduce urban pollution.
- Marginal Abatement Cost: All modes of transportation analyzed present a marginal abatement cost compared to diesel cars. This implies that, although some technologies may have higher initial costs, the benefits in terms of emission reduction and long-term savings justify the investment.

CHAPTER 1: INTRODUCTION

1.1 Introduction

During the past years, society has embarked on a complex route towards the decarbonization of the economy, of which a fundamental part is the decarbonization of transportation. Urban transportation proposes multiple alternatives for its decarbonization, some already in practice and others that still require investigation to determine their contribution. Achieving an efficient transition necessitates the characterization of these new technologies, modes, and business models within urban transportation.

The main objective of this Final Degree Project (TFG) is to characterize and study the different elements surrounding the decarbonization of urban transportation and observe their contributions to this goal focusing on the city of Madrid. It will address the evolution of existing technologies, as well as the emergence of new business models and alternative energy vectors. It will not only consider technical issues focused on emissions reduction but also the economic aspects that frame and position it within viable options.
Once the characterization is complete, we will use the data obtained to conduct an economic and emissions analysis

To carry out this project, it will be necessary to first analyze the challenges faced by public transportation in Madrid and subsequently propose viable solutions.

Urban transport in Madrid faces a series of challenges, with air pollution emerging as a pressing issue. Traffic congestion during peak hours significantly contributes to high levels of pollutants, impacting air quality and residents' health.

Reliance on private transportation and a lack of sustainable options result in harmful emissions, adversely affecting the environment. The compromised air quality not only diminishes citizens' quality of life but also exacerbates public health issues.

Limited infrastructure in certain areas can lead to traffic concentrations, further elevating pollutant emissions. Additionally, ineffective integration between different modes of public transportation encourages the populace to opt for private vehicles, increasing pollution.

The city of Madrid aims to address these challenges by implementing sustainable mobility policies, promoting the use of public transportation, and adopting cleaner technologies. Investments in environmentally friendly infrastructure and raising awareness about the importance of reducing emissions are integral components of efforts to mitigate pollution stemming from urban transport.

The first step of our research will involve characterizing various technological transportation alternatives, drawing from both traditional transportation methods and new alternatives such as Mobility as a Service (MaaS). The subsequent step will be to associate emissions with each technology, analyzing their environmental impact. Following that, we will explore other factors surrounding these technologies, such as annual mileage, occupancy, and lifespan. Additionally, we will analyze the economic aspects associated with different energy vectors and modes of transportation.

1.2 Motivation

The motivation behind undertaking this work lies in the recognition of the vital importance the urban transportation system holds for the daily lives of Madrid's citizens and its significant impact on various aspects of society. By undertaking the characterization of transportation technologies, I aim to contribute to the comprehensive improvement of this crucial system.
The characterization of technologies influencing urban transportation in Madrid is crucial in the current context, as the transportation system plays a fundamental role in the daily lives of citizens and has a significant impact on various social, economic, and environmental aspects. This work gains importance for several fundamental reasons:

- Improving Efficiency and Accessibility: Analysing and understanding technologies applied to urban transportation allows for identifying opportunities to improve efficiency and accessibility. Optimizing transportation systems contributes to reducing travel times, and congestion, and makes mobility more accessible for all citizens.
- Environmental Sustainability: In a global context of environmental concern, characterizing technologies in urban transportation is essential for proposing more sustainable solutions. Reducing emissions, promoting eco-friendly modes of transportation, and enhancing energy efficiency are key aspects to address current environmental challenges.
- Economic Impact: Understanding technologies applied to urban transportation also has economic implications. Improving efficiency and connectivity can boost the local economy, facilitate trade, and generate employment in transportation-related sectors.
- Quality of Life and Well-being: An efficient transportation system enhances the quality of life for citizens by offering faster, safer, and more comfortable mobility options. This directly influences the well-being of society by reducing the stress associated with daily commuting.
- Innovation and Technological Development: Analyzing technologies in urban transportation involves staying abreast of innovations and technological advances. This allows for anticipating future challenges, adopting cutting-edge solutions, and fostering technological development in the transportation sector.

In summary, the characterization of technologies in urban transportation in Madrid is not only essential to address current challenges but also provides a solid foundation to build a more efficient, sustainable transportation system that benefits society as a whole.

1.3 Objectives

The primary goal of this project is to analyze and explore various factors associated with the decarbonization of urban transportation and assess their impact on achieving this objective. The project will delve into the progression of current technologies, alongside the emergence of novel business models and alternative energy sources. It aims not only to examine technical aspects related to reducing emissions but also to evaluate the economic dimensions that contextualize and establish it as a viable choice among options.

For the completion of this work, we will undertake the following steps:

1. Contextualization of the current situation of urban transportation in Spain. Characteristics of the analyzed metropolitan areas.
2. Initial characterization comparing conventional technologies and technologies related to Mobility as a Service (MaaS).
3. Characterization of each traditional mode of transportation individually. Different categories will be addressed:
   a. Costs (CAPEX, FIXOM, VAROM)
   b. Efficiency and emissions
   c. Occupancy
   d. Annual mileage
   e. Lifespan
4. Characterization of each mode of transportation related to MaaS. Different categories will be addressed:
   a. Costs (CAPEX, FIXOM, VAROM)
   b. Efficiency and emissions
   c. Occupancy
   d. Annual mileage
   e. Lifespan

5. The data obtained in the research phase will be used to conduct an economic and emissions analysis based on Total Cost of Ownership (TCO), an emissions study, and Marginal Abatement Cost (MAC) analysis. Case study: current situation of urban transportation and new modes in Madrid.

1.4 Alignment with the Sustainable Development Goals (SDGs)

My project, which involves characterizing technologies in urban transportation in Madrid, aligns with several Sustainable Development Goals (SDGs) outlined by the United Nations. Here's how my work directly associates with key SDGs:

- **Goal 11: Sustainable Cities and Communities:**
  - ✓ My analysis and proposed improvements contribute to making cities inclusive, safe, resilient, and sustainable.
  - ✓ By addressing issues related to air quality and emissions in urban transport, I aim to reduce the adverse environmental impact of cities.
- **Goal 9: Industry, Innovation, and Infrastructure:**
  - ✓ My project involves analyzing technological advancements in transportation, contributing to the development of resilient infrastructure.
  - ✓ I aim to propose improvements and innovations in transportation technologies to support technological progress.

- **Goal 13: Climate Action:**
  - ✓ Focusing on technologies that can reduce emissions and promote eco-friendly transportation aligns to combat climate change.
- **Goal 3: Good Health and Well-being:**
  - ✓ Improving air quality and reducing emissions in urban areas through better transportation aligns to reduce the number of deaths and illnesses caused by hazardous chemicals and air pollution.
- **Goal 8: Decent Work and Economic Growth:**
  - ✓ My project may contribute to sustainable economic growth by proposing improvements that can positively impact local economies and generate employment in transportation-related sectors.
- **Goal 7: Affordable and Clean Energy:**
  - ✓ My focus on technological solutions and transportation improvements aligns with double the global rate of improvement in energy efficiency.
- **Goal 12: Responsible Consumption and Production:**
  - ✓ Analysing and proposing improvements in urban transportation technologies contributes to the efficient use of resources and promotes sustainable consumption.

Through my project, I am actively contributing to sustainable development, working towards creating a more inclusive, environmentally friendly, and economically viable urban transportation system in Madrid.

Illustration 7. SDGs

1.5 Resources

For my project on characterizing technologies in urban transportation in Madrid, I'll be tapping into a variety of resources to ensure a robust exploration of the subject. Here's my plan for resource utilization:

I'll start by delving into official reports and publications from municipal transportation departments, government agencies, and urban planning bodies. These documents will provide crucial insights into existing transportation technologies, policies, and the city's plans for its transportation infrastructure.

Exploring the official websites of transportation authorities in Madrid is another key aspect of my research. These platforms often contain detailed information on current transportation modes, infrastructure, and ongoing initiatives, giving me a comprehensive overview of the existing transportation landscape.

To gain a deeper understanding of the technological aspects, I'll refer to academic journals and articles related to urban transportation, technology, and sustainability. Academic research can offer in-depth analyses and insights into the latest advancements in transportation technology.

I'm excited to collaborate with an electric mobility observatory (OVEMS), where our focus is on studying electric vehicles and sustainable mobility. In this observatory, we collect data primarily from the DGT and EAFO and present it in an accessible manner on our website. Additionally, we have a model for forecasting the future electric vehicle fleet.

The information gathered from the observatory will be a cornerstone of my project, providing me with a solid and up-to-date understanding of the state of electric mobility in Madrid. Collaborating with reliable sources like the DGT and EAFO ensures the credibility and relevance of the data I will use in my analysis.

The observatory's website, where this data is reflected, will be a valuable tool to obtain specific details about electric mobility in the city. Moreover, the model forecasting the electric vehicle fleet will allow me to project trends and anticipate the future growth of this technology in Madrid.

Integrating these data and forecasts into my project will not only enrich the characterization of technologies in urban transportation but also support the promotion of sustainable solutions. This collaboration adds a practical and applied approach to my project, allowing me to gain a deeper understanding of the dynamics of electric mobility in the city and its evolution over time.

In summary, I'm excited to leverage this valuable collaboration with the observatory as a key tool in my project, contributing to the knowledge and promotion of sustainable mobility in Madrid.

1.6 State of the art

The city of Madrid has been chosen as a case study, showcasing similarities in terms of its area covered, population, and economic significance within Spain. Madrid demonstrates a clear emphasis on integrated policymaking, particularly in spatial, environmental, and transport strategies. These strategies involve the implementation of measures such as low-emission zones, parking license restrictions, and mobility stickers. The structure of the Madrid Metropolitan Area (MA) is notably monocentric, centered around the city of Madrid itself.

Encompassing 27 municipalities over approximately 5,335 square kilometers, the Madrid Metropolitan Area (MA) is the second most populous metropolis in the EU, boasting a population nearing 6.6 million [1]. Notably, it exhibits a relatively high population density by European standards, averaging 1,237 inhabitants per square kilometer. The density peaks in its central core, specifically the city of Madrid, with approximately 5,464 inhabitants per square kilometer.

Public transportation in Madrid plays a pivotal role in the mobility of its residents and visitors, serving as an essential component of daily life in the Spanish capital. Among the noteworthy pillars of this system are the efficient Metro service and the extensive bus network connecting various corners of the city. Madrid, renowned for its dynamism and geographical expanse, greatly benefits from these public transportation options, not only as a means of commuting but also as key catalysts for sustainability, traffic decongestion, and emissions reduction.

On average, 14.7 million trips occur daily in the Madrid Metropolitan Area during working days, with each trip lasting around 29 minutes. These journeys involve various transportation modes, with private car/motorcycle (39.0%), walking and biking (34.0%), and public transport (24.3%) being the primary ones. Inside Madrid City, there's a notable shift toward environmentally friendly modes, constituting 40.0% for active modes (walking and cycling), 34.8% for public transport, and 20.3% for private cars/motorcycles.[2].

In the urban landscape, 14.2% of travel experiences are multimodal, a percentage that rises to 33.3% in the metropolitan area. The Madrid Metropolitan Area boasts a dense, well-integrated multimodal public transport network, including 12 metro lines, 209 urban bus lines, 444 suburban bus lines, eight suburban rail lines, and four tram/light rail lines. Since 2010, the system has been supplemented with on-demand mobility services such as shared mobility, micro-mobility, and ride-hailing services, gaining widespread acceptance in the area.

These "emerging mobility services" are prevalent in the Madrid Metropolitan Area, surpassing the average in European metropolis. The metropolitan area hosts 35 shared mobility services, managing around 30 000 vehicles operated by 29 operators, both public and private. Notably, each shared mobility service operates within specific coverage zones, primarily concentrated in Madrid City, posing a challenge for residents in peripheral and suburban areas who cannot access these services for their last-mile trips.

Despite the complexity of the transport network, various travel planning applications, including Google Maps, Moovit, City Mapper, Chipi, MaaS Madrid, and Mi Transporte, currently facilitate navigation. However, none of these applications incorporates payment or e-ticketing integration. The most promising Mobility as a Service (MaaS) application to date is "Madrid Mobility360," initiated in 2018 by the Municipal Transport Company (EMT), responsible for Madrid's city bus services, and Bicimad (Madrid's bike-sharing system). It's essential to note that while this application shows potential, it is still in its early stages of development. [2]

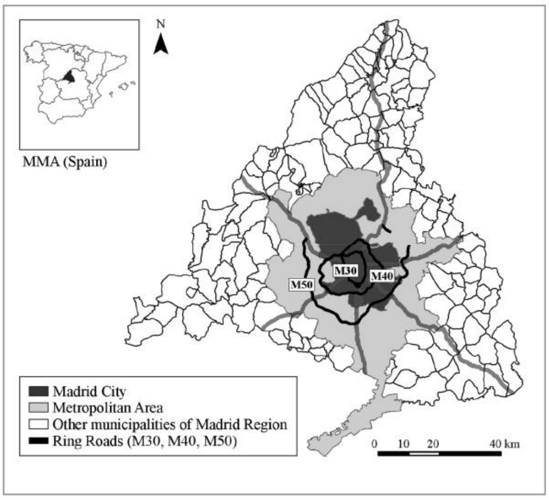

Illustration 8. Madrid Metropolitan Area

To characterize and study the different elements surrounding decarbonization, we need to distinguish between conventional technologies and those referred to as MaaS (Mobility as a Service) technologies.

Traditional urban transportation typically involves various standalone modes such as personal cars, public buses, trains, taxis, and walking, each operating independently with separate ticketing systems and often limited interoperability. This traditional system relies on fixed schedules, predetermined routes, and individual ownership or usage of vehicles.

On the other hand, Mobility as a Service (MaaS) is a user-centric approach to urban transportation, integrating various services like public transit, ridesharing, and micromobility into a single platform or app.

The key differences between traditional urban transportation and MaaS include [2]:

- **Integration:** Traditional transportation operates in silos, with separate services and payment systems. In contrast, MaaS integrates multiple modes of transport under one platform, providing a more seamless and user-friendly experience. MaaS consolidates all available transportation modes, both public and private, into a user-friendly 'travel package'.
- **User-Centric Approach:** MaaS prioritizes the user's convenience by offering a range of transportation options, personalized journey planning, and unified

payment systems. Traditional transport systems often lack this level of convenience and integration.

- **Sustainability and Efficiency:** MaaS aims to promote more sustainable transportation choices by encouraging the use of public transit, shared rides, and alternative modes of transport, reducing reliance on individual car usage. Traditional transportation methods may be less efficient and environmentally friendly due to their fragmented nature.
- **Technology Integration:** MaaS heavily relies on digital platforms, applications, and real-time data to provide users with information and access to different transportation options. Traditional transportation systems might lack this technological integration and ease of access.

MaaS represents a shift towards a more efficient, sustainable, and user-friendly urban transportation model, where the focus is on accessibility, convenience, and reducing reliance on individual car ownership in favor of shared and diverse transportation options [3].

Once we have categorized these two base categories, we will further explore the subtypes of urban transportation methods, aiming to categorize and thoroughly study existing technologies, new business models, and alternative energy sources.

<u>Transportation energy consumption</u> [4]

According to the International Energy Agency, transportation accounts for 26.2% of the world's total energy consumption. In the EU, transportation energy consumption accounted for 28.4% in 2020. Meanwhile, in Spain, final energy consumption due to transportation represented 36.2% of the total in 2020.

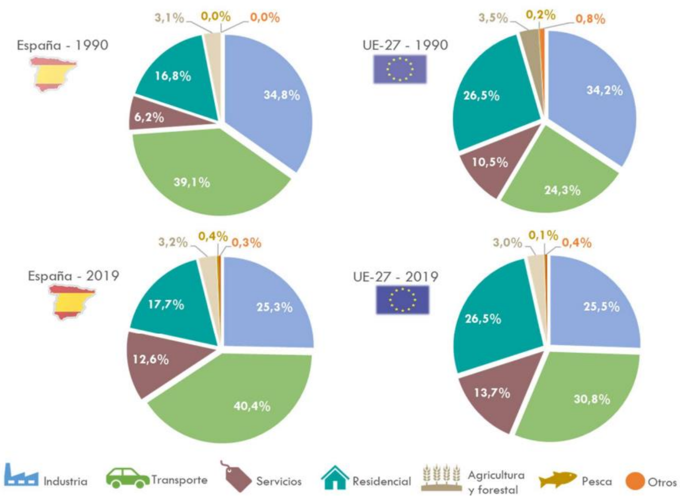

Illustration 9. Comparison of the share of energy consumed by sectors globally, in the EU, and in Spain (%). Years 1990 and 2019

Source: 'Sistema Español de Inventario de Emisiones del Ministerio para la Transición Ecológica'.

The detailed analysis of the energy consumption by each mode of transportation in the sector reveals that **road transportation** is the mode that consumes the most energy, accounting for 94.5% of the total transportation sector in the EU countries. This trend is consistent across most EU countries, as in Spain accounting with 92%.

The significance of this data lies in the stark contrast between Spain's excellent performance across various sectors in terms of energy consumption and the shortcomings observed in the transportation sector, where much improvement is still needed. Spain excels in the energy, industrial, and other sectors, but transportation remains a problematic area requiring urgent attention.

Spain, in addition to being a geographically extensive country, is characterized by its high density of transportation due to its strategic location as a gateway to Europe. This positioning makes it a crucial hub for international trade. Many products and resources from the Atlantic and other parts of the world enter Europe through Spain. Ships crossing the Atlantic from Latin America, Africa, and other regions often dock at Spanish ports before their goods are distributed throughout Europe.

Moreover, Spain shares land borders with France and Portugal, facilitating international trade by road and rail. This strategic location not only benefits Spain but also other European countries that rely on its routes and ports for global commerce. Spain's ports, such as the one in Algeciras, are among the busiest in the world, handling a vast amount of goods, including energy products, manufactured goods, and food, which are then transported across Europe.

International trade is vital for the Spanish economy. Spain exports products like automobiles, machinery, food, and beverages, requiring an efficient transportation infrastructure to deliver these products to international destinations. Similarly, it imports a wide variety of goods, from raw materials to finished products, which need to be distributed throughout the country and beyond its borders.

Therefore, the high demand for transportation in Spain is driven by its extensive territory, strategic geographical location as Europe's gateway, and its crucial role in international trade. To maintain and improve efficiency in these areas, it is imperative to invest more efforts in reducing fossil fuel consumption and emissions in the transportation sector. Despite the significant achievements in other sectors, transportation still presents major challenges that must be addressed to enhance energy sustainability and reduce environmental impact.

Table 10. Energy consumed by mode of transportation in Spain and in the European Union-27 (TJ)

	1990		2019	
	SPAIN	EU-27	SPAIN	EU-27
Road	688182	8441077	1208455	11306175
Railway	14114	312817	15814	221077
Air	22705	209216	42891	272598
Maritime	69644	217570	43264	177039
Total	794645	9180680	1310424	11976889

1 Terajoule (TJ)= 10^{12} *joules.*
Source: own elaboration based on data from: 'Sistema Español de Inventario de Emisiones del Ministerio para la Transición Ecológica'.

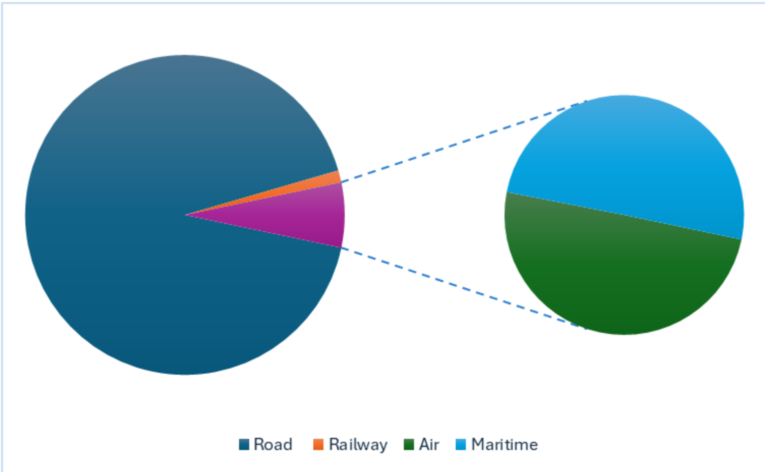

Illustration 10. Energy consumption by mode of transportation SPAIN 2019 (%)

Source: own elaboration based on data from: 'Sistema Español de Inventario de Emisiones del Ministerio para la Transición Ecológica'.

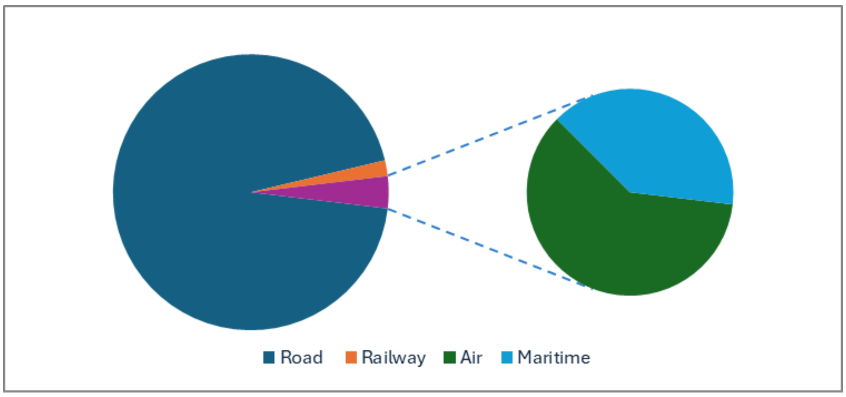

Illustration 11. Energy consumption by mode of transportation EU-27 20 (%)

Source: own elaboration based on data from: 'Sistema Español de Inventario de Emisiones del Ministerio para la Transición Ecológica'.

The predominant source of energy used to propel **vehicles on roads** is fossil fuel, primarily diesel and gasoline, with a limited percentage of electric vehicles or biofuels. In 2020, 92.5% of energy consumption came from diesel and gasoline, while 7.1% came from electricity and biomass, with the remainder from liquefied natural gas, compressed natural gas, and liquefied petroleum gases.

According to data provided by the Spanish Emissions Inventory System (SEI), in 2020, 54.7% of energy consumption in road transportation occurred on **non-urban roads**. Of these 579,310 TJ, 59.7% corresponded to passenger transportation, with the rest attributed to freight transportation. Moreover, it is important to note that between 1990 and 2019, the growth in energy consumption derived from passenger transportation on non-urban roads was much higher (+105.4%) than that of freight transportation (+37.5%).

Rail transportation is the most electrified mode, with 81.6% of its energy consumption coming from electricity, compared to 18.4% from diesel. Currently, the Adif (Administrador de Infraestructuras Ferroviarias) and Adif AV networks are electrified at 64.2%.

Domestic air transportation accounted for 2.0% of total energy consumption in 2020, according to data from the Spanish Emissions Inventory System, and is almost exclusively fueled by kerosene or jet fuel, with minimal use of aviation gasoline or biofuels.

In **coastal maritime navigation**, two main types of fuel are used: fuel oil (44.5% of energy consumption in 2020) and diesel (55.5%).

To assess the efficiency of transportation across the mentioned modes, we will utilize the indicator of Energy Consumption per Unit of Transport (TJ/million vehicle-kilometers). This metric measures the amount of energy consumed per million kilometers traveled by various modes of transportation. It serves as a valuable tool for comparing the energy efficiency of different transportation methods. A lower value of terajoules per million vehicle-kilometers indicates a more efficient use of energy in transporting goods or passengers.

Energy consumption per unit of transport (TJ/million vehicle-kilometers) by modes

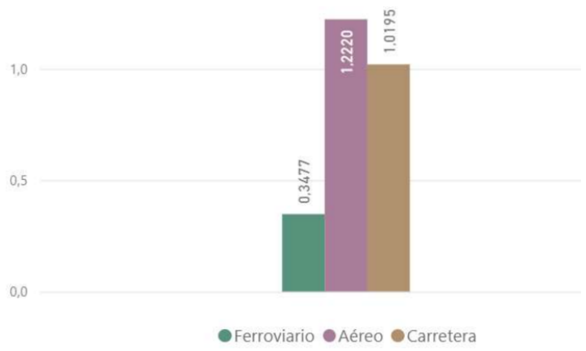

Illustration 12. Energy consumption per unit of transport (TJ/million vehicle-kilometers) by modes

Source: 'Sistema Español de Inventario de Emisiones del Ministerio para la Transición Ecológica'.

To compare the energy efficiency of each mode, consumption is compared with respect to the units of transportation for each. From the above graph, it is evident that the most energy-efficient mode of transportation is rail.

Emissions on urban transport [5]

Transportation, being an energy-intensive activity significantly contributes to atmospheric emissions. These emissions can be classified into two main groups:

- Greenhouse Gases (GHGs): GHGs may not necessarily be considered pollutants as they do not have a direct short- or medium-term effect on living organisms.
  The primary effect of their presence in the atmosphere in high concentrations is global warming and consequent climate change.
- Pollutants are grouped into acidifying substances, tropospheric ozone precursors, and particulate matter, and their presence in the atmosphere has direct negative effects on human health, animals, and vegetation.

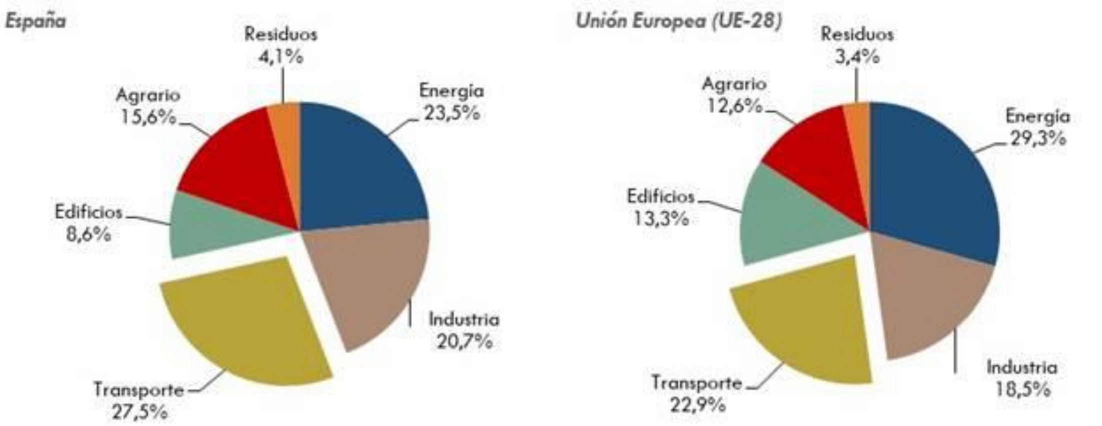

Illustration 13. Greenhouse gas emissions from transportation compared to other sectors. Spain and European Union (EU-28). 2018

Source: Spanish Inventory and Projection System for Greenhouse Gas and Air Pollutant Emissions (Ministry for Ecological Transition and the Demographic Challenge)

The graph above illustrates a trend where, like energy consumption, greenhouse gas emissions from the transportation sector in Spain carry a greater relative significance compared to the European Union average (27.5% versus 22.9%). On average across Europe, transportation emissions are approximately 6.5 percentage points lower than those from the energy industry. However, in Spain, the transportation sector's contribution exceeds that of the energy industry by 4 percentage points.

The significance of this data is similar to what we discussed regarding energy consumption: the need for Spain to modify and reduce emissions in the transportation sector. As mentioned earlier, Spain excels in reducing emissions across many sectors compared to the EU average, but transportation is not one of them.

The following table displays greenhouse gas emissions and pollutant emissions by mode of transportation, revealing that in all cases, the road mode exhibits the highest emissions, while also being the mode with the highest mobility.

Table 11. Greenhouse gas emissions and pollutant emissions by mode of transportation

Mode of Transportation	Greenhouse Gases (kt CO2 eq)	Pollutants		
		Acidifying Substances (million acid equivalents)	Tropospheric Ozone Precursors (t eq of NMVOC)	Particulate Matter (t)
Railway	253	91	5496	120
Air	3045	329	18323	132
Maritime	3160	1811	75876	3400
Urban Road	28249	1683	119695	17152
Rural Road-Passengers	30940	2084	120424	1977
Rural Road-Cargo	24469	1589	91432	994
Total Rural Road	55410	3673	211856	2970
Total Road	83659	5356	331551	20122
Total National Transport	90116	7586	431246	23774

Source: own elaboration based on Spanish Inventory and Projection System for Greenhouse Gas and Air Pollutant Emissions (Ministry for Ecological Transition and the Demographic Challenge)

- *kt CO2 eq: kilotonnes of carbon dioxide equivalent. This unit is used to express the amount of greenhouse gases emitted, equating their impact to that of carbon dioxide (CO2).*
- *Million acid equivalents: This unit is used to express the amount of acidifying substances emitted, which contribute to environmental acidification.*
- *t eq of NMVOC: tonnes of non-methane volatile organic compound equivalents. This unit is used to express the amount of tropospheric ozone precursors emitted, which contribute to ground-level ozone formation.*
- *t: tonnes. This unit is used to express the amount of particulate matter emitted, consisting of solid and liquid particles suspended in the air.*

Firstly, it is notable that the most significant emissions are recorded in road transport, both in urban and rural settings. Specifically, urban road transport emits a total of 28,249 kt CO2 eq, while rural road transport for passengers reports 30,940 kt CO2 eq. In terms of freight transport by road, emissions amount to 24,469 kt CO2 eq.

However, it is crucial to note that other modes of transportation also contribute significantly to emissions. For instance, air transport records 3,045 kt CO2 eq of greenhouse gases, reflecting the high energy demand associated with this mode of transportation. Similarly, maritime transport presents 3,160 kt CO2 eq of emissions, highlighting its impact on atmospheric pollution.
These data underscore the importance of considering emissions associated with each mode of transportation when designing policies for mitigation and environmental sustainability.

In the following graph, it can be observed that from 2007 to 2018, greenhouse gas emissions produced in transportation have decreased from 108,020 to 90,116 kilotonnes of CO2 equivalent, representing a decrease of -16.6%. However, between 2015 and 2017, the average annual growth was 3.5%, although in 2018 the growth rate decreased to 1.4%.

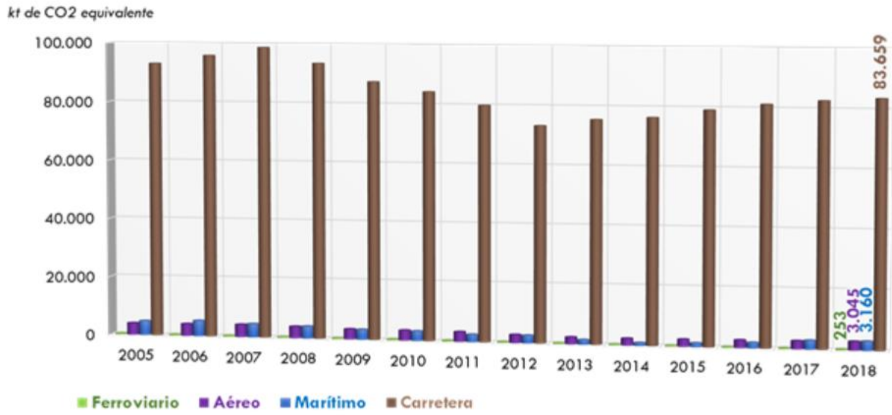

Illustration 14. Greenhouse gas emissions (kt of CO2 equivalent). Transportation sector. 2005-2018

Source: Spanish Inventory and Projection System for Greenhouse Gas and Air Pollutant Emissions (Ministry for Ecological Transition and the Demographic Challenge)

This graph serves to underscore the notable contribution of road transportation to greenhouse gas emissions. The subtle fluctuation observed from 2007 onwards can be attributed to the economic downturn experienced in Spain during the period spanning 2007 to 2014.

Table 12. Variation 2007-2018 of greenhouse gas emissions and pollutant emissions.

	Greenhouse Gases (kt CO2 eq)	Pollutants		
		Acidifying Substances (million acid equivalents)	Tropospheric Ozone Precursors (t eq of NMVOC)	Particulate Matter (t)
Variation 2007-2018	-16.6%	-45%	-50%	-37%

Source: own elaboration based on Spanish Inventory and Projection System for Greenhouse Gas and Air Pollutant Emissions (Ministry for Ecological Transition and the Demographic Challenge)

Regarding the rest of the air pollutants, their evolution from 2007 to 2018 is as follows:

Acidifying substances: they have decreased from 13,718 to 7,586 million acid equivalents, representing a reduction of -45%. It is worth noting that acidifying substance emissions had been decreasing since 2005, and since 2013, emissions have stabilized with slight year-to-year variations.

Tropospheric ozone precursors: there has been a significant decline, dropping from 862,887 to 431,246 tonnes equivalent of NMVOC, constituting a reduction of -50%. Tropospheric ozone precursor emissions have decreased notably until 2014, after which emissions stabilized. However, in 2018, the emissions of these pollutants reached the lowest value recorded.

Particulate matter emissions: they have decreased from 37,934 to 23,774 tonnes, a reduction of -37%, showing a significant decline from 2005 to 2013. This decrease is attributed to the decline of diesel as a fuel in railways and the evolution of regulations and particulate filter technologies in diesel vehicles, which significantly reduce particle emissions. Additionally, the discouragement of diesel engines has changed the proportion of diesel vehicles relative to gasoline or even electric ones. From 2013 onwards, the reduction has been more gradual, with a slight increase in 2016 and 2017, while in 2018, emissions decreased again.

As showed above, greenhouse gas (GHG) emissions in the transportation sector have shown a lesser reduction since 2007 compared to energy consumption, slightly higher. This is partly due to the constant emission factor of each fuel type, with minimal changes in fuel types used in transportation, except for the inclusion of biofuels since the early 21st century. However, emissions of other pollutants have decreased more than energy consumption, indicating an improvement in the environmental efficiency of the transportation sector.

This significant reduction is directly associated with the declining trend in road transportation emissions. Key factors contributing to this decrease include improvements in engine efficiency, emission reduction systems in exhaust gases, and the gradual introduction of alternative fuels. As new technologies advance and the vehicle fleet is renewed, a continuous improvement in the environmental efficiency of road transportation is expected.

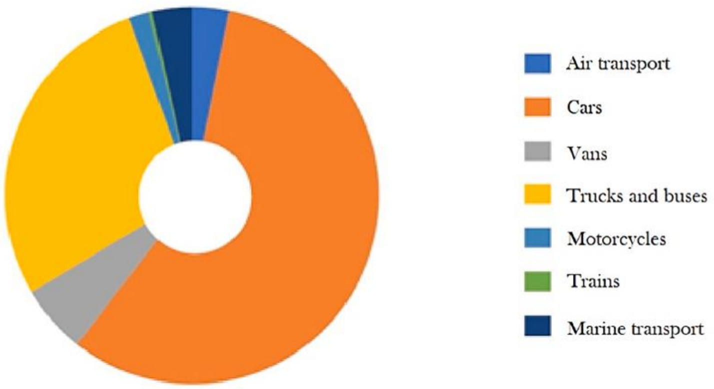

Illustration 15. CO2 emissions by mode of transportation in Spain (2017).

Source: MITECO (2020).

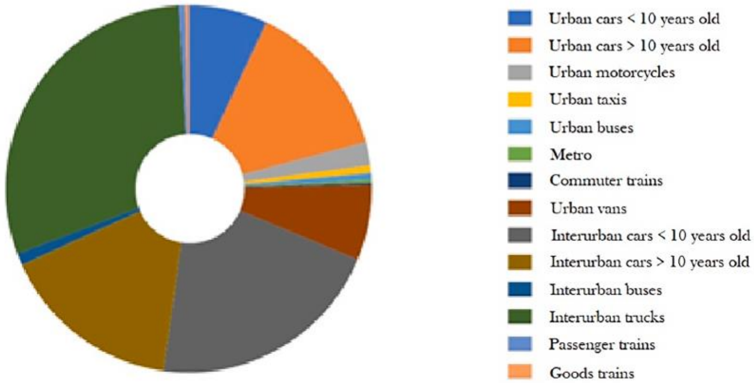

Illustration 16. CO2 emissions by mode of transportation and trips done in Spain (2017).

Source: MITECO (2020).

We will contrast various modes of passenger transport that are pertinent to urban mobility in their greenhouse gas (GHG) emissions per kilometer for transporting a single passenger. These modes encompass passenger cars, buses, trams, scooters, and both electric and traditional bicycles.

Approximately 23% of the worldwide CO2 emissions from fuel combustion are attributed to transportation [6]. What's even more concerning is that transportation stands out as the swiftest consumer of fossil fuels and the most rapidly expanding source of CO2 emissions. The swift urbanization in developing nations further intensifies the surge in energy consumption and CO2 emissions stemming from urban transport.

Taking into account occupancy factors and average consumption in urban and interurban use, as appropriate, it is observed that the CO2 emission per passenger-kilometer varies significantly depending on the type of vehicle we use.

It can be stated that electric modes are the most favorable in terms of associated CO2 emissions. For electric modes, the CO2 emissions associated with the generation of consumed electricity are taken into account, although they do not generate pollutants or CO2 at the point of use.

In terms of CO2 emissions per kilometer, the data reveals the following ranking[7]:
Cars contribute approximately 121 gCO2/km, while motorcycles emit 53 gCO2/km. Urban buses and conventional electric vehicles account for 49 gCO2/km and 43 gCO2/km, respectively.

In comparison, rail transportation shows lower emissions, with 33 gCO2/km for commuter trains, 32 gCO2/km for intercity routes, and 30 gCO2/km for subway and tram services. The most efficient option in terms of emissions is high-speed trains (AVE), with only 23 gCO2/km.

Within the realm of electric options, electric motorcycles demonstrate a significant reduction, emitting only 17 gCO2/km, while electric bicycles only 3 gCO2/km.

Electric cars exhibit emissions roughly one-third that of their thermal counterparts (gasoline or diesel), and the subway or high-speed train (AVE) outperform urban or interurban buses with reductions in CO2 emissions close to 30-40%, respectively. Individually used cars are very CO2-intensive, although when their occupancy increases to 3 or more passengers, the emission ratio per passenger-kilometer can approach or even be lower than thermal collective modes (bus). The electric pedal-assist bicycle is by far the vehicle that generates the least impact.

Table 13. Consumption and CO2 emissions per passenger and kilometer transported for each mode of transport.

TRANSPORT MODE	**ENERGETIC CONSUMPTION (goe/pkm)[1]**	**C02 EMISSIONS (gCO2/pkm)[2]**
Plane	63,5	192
Heat-powered car	49,7	121
Electric car	14,6	43
Heat-powered motorcycle	23	53
Electric motorcycle	4,9	14
Urban bus	19,3	49
Commuter train	9,4	33
Subway	8,5	30
AVE	8,0	24
Walking/ cycling	0	0
Electric bike	0,9	3

1 goe/pkm: grams of oil equivalent per passenger-kilometre
2 gCO2/pkm: grams of CO2 per passenger-kilometre

The data presented in the table reflect the energy consumption and CO2 emissions associated with each mode of transportation per kilometre and are based on an assumed average occupancy level for each mode. It is important to note that specific values may vary depending on the operational efficiency and actual occupancy of each transportation mode in practical situations. Results may be influenced by factors such as passenger capacity, fluctuating demand, and the specific characteristics of each transportation system in use. The provided data offers a general perspective and does not account for specific variations in occupancy during everyday usage.

Source: Energía y emisiones de CO2 por modos [8]

Now that we have discussed the various emissions associated with different modes of transportation, we will analyze the circumstances and characteristics that surround urban transport. We will explore other factors surrounding these technologies, such as companies, fares, and coverage areas.

To discuss the characteristics surrounding mobility, we will rely on Household Mobility Surveys (EDM, Encuestas Domiciliarias de Movilidad), which enable the collection of essential data for public transportation planning with services tailored to the actual travel demand. These surveys are conducted on a representative sample of the population, allowing the characterization of their movements based on the reasons for travel and the modes of transportation used. [9]

Table 14. Characteristics of mobility in metropolitan areas

	Trips on a workday (Millions)"	**Average travel time (min)**	**Average travel distance (km)**	**Number of trips per person per day**	**Intermodal trips (%)**
Madrid 2018	15,85	25,5	7,1	2,4	8,5

On a working day in Madrid in 2018, a total of 15.85 million trips were made. The average travel time was 25.5 minutes, covering an average distance of 7.1 kilometers per trip. Each person made, on average, 2.4 trips per day. Additionally, 8.5% of the trips were intermodal, involving the combination of different modes of transportation.

Table 15. Characteristics of mobility in metropolitan areas based on gender.

	Public transport passengers based on gender (%)	
	Men	**Women**
Madrid 2018	47,7	52,3

The distribution of public transport passengers in Madrid in the year 2018 based on gender was 47.7% male and 52.3% female.

Table 16. Characteristics of mobility in metropolitan areas by age groups

	Public transport passengers based on age (%)		
	<16 years	**16-65 years**	**>65 years**
Madrid 2018	12,1	74,2	13,7

The distribution of public transport passengers in Madrid in 2018, categorized by age, was as follows: 12.1% were under 16 years old, 74.2% were between 16 and 65 years old, and 13.7% were over 65 years old.

We will also analyze the demand for public transportation trips by mode of transport for each of the areas under examination. The following modes of public transportation will be referred to: urban buses in the capital city, urban buses in other municipalities (in the metropolitan area), metropolitan buses, metro, tram/light rail, Cercanías RENFE (commuter rail), and regional railways (FGC, FGV, Euskotren, SFM).

Table 17. Annual public transportation trips (millions). Year 2021.

	Urban buses	Other urban buses	Metropolitan bus	Subway	tram/light rail	Commuter trains	Total
Madrid	296,5	178,5		447,4	11,6	160,1	1,094
	475			619,1			

This table details trips by mode of transportation. In 2021, a total of 1,094 million public transportation trips were recorded in Madrid. Out of these, 475 million trips were conducted by bus, while 619 million were by rail modes. Regarding bus trips, 296.5 million were on urban buses, and 178.5 million were on metropolitan buses. As for rail modes, a significant majority occurred on the subway, totaling 447.4 million trips, and 160.1 million were accounted for on commuter trains.

Table 18. Annual passenger kilometers in public transportation (millions). Year 2021.[1]

	Urban buses	Other urban buses	Metropolitan bus	Subway	Tram/light rail	Commuter trains	Total
Madrid	744,2	2368,0		2818,3	58,0	2762,0	8750,5
	3112,2			5638,3			

In 2021, the total annual passenger kilometers for public transportation in Madrid amounted to 8,750.6 million. Urban buses accounted for 744.2 million passenger kilometers, while other urban buses and metropolitan buses contributed significantly with 2,368.0 million. As for rail modes, a significant majority occurred on the subway, totaling 2,818.3 million trips. The tram/light rail services reached 2,762.0 million. Total buses collectively accounted for 3,112.2 million passenger kilometers. Combining buses and railways, the total distance covered by passengers in public transportation throughout Madrid was 8,750.5 million passenger kilometers.

Table 19. An estimated average distance of trips (km). Year 2021.

	Urban buses	Other urban buses	Metropolitan bus	Subway	tram/light rail	Commuter trains
Madrid	2,5	13,3		6,3	5,0	17,2

[1] The indicator passenger-kilometres provides combined information on both the demand and the distance travelled by passengers, which is highly valuable when analysing public transportation demand.

This table captures the estimated average distance of trips taken on public transportation in various metropolitan areas. This distance is calculated as the quotient of passenger kilometers and the number of trips. The average travel distances in Madrid in 2021 were as follows: 2.5 km for urban buses, 6.3 km for the subway, 13.3 km for metropolitan buses, 17.2 km for Cercanías RENFE (commuter trains), and 5 km for narrow gauge railways and regional railways.

Once the context of urban transport in Madrid has been provided, we will proceed to investigate each mode of transportation more thoroughly on an individual basis. We will strive to cover all data related to supply, demand, fares, coverage areas, emissions, and the economic aspect. This part of the research will be conducted in a more advanced stage of the TFG.

Conventional Urban Transportation Technologies in Spain:

- Conventional buses (diesel or gasoline)
- Trams
- Metro/Subway
- Commuter trains *(cercanías)*
- Conventional taxis
- Private cars (diesel or gasoline)
- Motorcycles and mopeds (diesel or gasoline)
- Conventional bicycles

New Urban Transportation Technologies in Spain based on MaaS:

- Shared Electric Vehicles (carsharing)
- Shared Electric Scooters
- Shared Electric Bicycles
- Carpooling Platforms
- Integrated Mobility Applications
- Ride-hailing services (such as Uber or Cabify)
- Autonomous Vehicles for Public Transport
- Integrated Payment Systems and Fare Structures in MaaS

Conventional Urban Transportation Technologies in Spain:

- Conventional buses are public transportation vehicles that operate on predefined routes, making stops at various locations to pick up and drop off passengers. An example of a company providing conventional bus services is *Empresa Municipal de Transportes de Madrid (EMT).*
- Trams are light rail transportation systems that operate on rails or dedicated tracks in urban areas. They usually have fixed stops and offer an efficient way to travel around the city. An example of a tram service is the *Zaragoza Tram.*

- The metro or subway is an underground rapid transit system that provides fast and efficient transportation services within densely populated urban areas. It typically has multiple lines and stations throughout the city. An example is the *Madrid Metro.*
- Commuter trains are passenger rail services that connect urban areas with suburbs and outlying areas. They offer frequent services and are popular for daily commuting. *Renfe Cercanías* is an example of a commuter train service.
- Conventional taxis are hired vehicles with drivers that offer personalized transportation services. They usually operate on demand and can be a convenient option for short trips within the city. An example is *Radio Taxi Barcelona.*
- Private cars are privately owned vehicles that individuals use for commuting within the city, offering flexibility in travel schedules.
- Motorcycles and mopeds are two-wheeled vehicles powered by internal combustion engines and are primarily used for individual commuting within the city, often owned privately.
- Conventional bicycles are human-powered vehicles with two wheels that are used for short commutes and as a form of active and sustainable transportation in cities. *BiciMAD* is an example of a bicycle rental service in Madrid.

New Urban Transportation Technologies in Spain based on MaaS:

- Carsharing is a service where electric vehicles can be rented for short periods, paying only for the duration of use. *ZITY* is an example of a car-sharing service in Madrid.
- Shared electric scooters are electric personal mobility devices shared among users and are a popular option for short trips within the city. *Lime* offers electric scooter services in various Spanish cities.
- Shared electric bicycles are electric bicycles that can be rented for short periods and offer a sustainable and efficient way to travel around the city. *BiciMAD eléctrica* provides electric bicycle rental services in Madrid.
- Carpooling platforms connect drivers traveling in the same direction with passengers looking to share the journey and expenses. *BlaBlaCar* is a popular carpooling platform in Spain.
- Integrated mobility applications provide information about various transportation options, including public transportation schedules, bike routes, ride-hailing services, and more, to facilitate urban travel. *Moovit* is an example of a mobility app offering transportation information in Spain.
- Ride-hailing services, such as *Uber,* provide on-demand transportation services where users can request a ride through a mobile app and be picked up by a private driver in a vehicle.
- Integrated payment systems and fare structures in MaaS allow users to pay for various transportation services seamlessly through a single platform or app, simplifying the payment process and facilitating urban travel. *Tarjeta Multi* is an

example of a public transportation card valid in Madrid for multiple modes of transportation.

CHAPTER 2: EXCEL DATA ANALYSIS

To carry out an accurate characterization of transportation technologies, we have created tables that cover various parameters, crucial for the precision of the emissions and cost models. Some of the feature are purely economic (CAPEX, VAROM, FIXOM), while some others describe the way in which technologies function in the system (occupation, efficiency, annual mileage, lifespan). Finally, the emissions of each technology are calculated based on their use of fuels (efficiency) and the emissions resulting from the use of these fuels. Both conventional technologies and new models and energy vectors are included.

The tables cover the following parameters:

1. Investment Cost 2024 (CAPEX): The initial cost required to acquire the technology in 2024. This parameter helps evaluate the short-term investment needed.
2. Investment Cost 2030 (CAPEX): The estimated investment cost required to acquire the technology in 2030. This helps foresee the evolution of costs and the potential decrease over time due to technological advancements.
3. FIXOM (Fixed Operating Costs, €/year): Annual fixed operating costs, regardless of vehicle usage. These include insurance, taxes, and fees. This parameter is crucial for understanding expenses that do not vary with vehicle usage.
4. VAROM (Variable Operating Costs, €/km): Variable operating costs that depend on the distance traveled with the vehicle. These include maintenance, parking, and tolls. Although energy could be included here, it is excluded for clarity.
5. Energy Vector: The type of energy used by the technology (e.g., gasoline, diesel, electricity, hydrogen). This parameter is essential for evaluating the energy source and its impact on performance and emissions.
6. Efficiency (MJ/v.km): The energy efficiency of the technology measured in megajoules per vehicle-kilometer. This parameter indicates how much energy is required to move the vehicle a given distance and is key for assessing energy consumption.
7. Occupancy: The average number of passengers the vehicle can carry. This data is fundamental for calculating emissions and costs per passenger-kilometer.
8. Annual Mileage (km/year): The average distance the vehicle travels in a year. This parameter helps estimate annual operating costs and the total emissions of the vehicle.
9. Lifespan (years): The expected duration of the vehicle in years. This parameter is important for calculating the amortization of the initial investment and costs over time.
10. Emissions per v.km (gCO2eq/v.km): Greenhouse gas emissions per vehicle-kilometer, measured in grams of CO2 equivalent. This parameter is essential for evaluating the vehicle's environmental impact in terms of direct emissions.
11. Emissions per p.km (gCO2eq/p.km): Greenhouse gas emissions per passenger-kilometer, measured in grams of CO2 equivalent. This parameter adjusts emissions according to the number of passengers, providing a more accurate perspective of the environmental impact per person transported.

These tables enable a comprehensive and detailed evaluation of transportation technologies, facilitating informed decision-making regarding investments, policies, and strategies for reducing emissions and optimizing costs.

Table 20. Conventional technologies data 1

CONVENTIONAL TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating Costs, €/year)**	**VAROM (Variable Operating Costs, €/km)**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
Diesel Car	24500	24500	732	0,129	diesel	1,18	12000	15
Gasoline Car	22000	22000	732	0,146	gasoline	1,18	12000	15
Electric Car	35000	32000	582	0,070	electricity	1,18	12000	15
Gasoline Motorcycle	7000	7000	122	0,083	gasoline	1,05	3000	12
Electric Motorcycle	8500	6800	113	0,037	electricity	1,05	3000	10
Natural Gas Urban Busl (GNC)	310000	310000	4650	0,200	natural gas	16,00	100000	10
Electric Urban Bus	550000	550000	8250	0,150	electricity	16,00	100000	15
Diesel Urban Bus	272500	272500	4087,5	0,200	diesel	16,00	100000	15
Hydrogen Urban Bus	1250000	1250000	18750	0,350	hydrogen	16,00	100000	10
Electric Metro (e.g., Madrid)	6377000	6377000	1655000	0,195	electricity	128,50	85000	30
Electric Tram (e.g., Zaragoza)	200000000	200000000	2700000	0,190	electricity	80,40	100000	30
Convencional Taxi (gasoline)	22000	22000	8950	0,021	gasoline	1,18	55000	7
Hybrid Electric Vehicle Taxi (HEV)	25000	20000	8950	0,021	gasoline (85%) + electricity (15%)	1,18	55000	7

Table 21. New modes and technologies data 1

NEW MODES AND TECHNOLOGIES								
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**	**FIXOM (Fixed Operating**	**VAROM (Variable Operating**	**Energy Vector**	**Occupancy**	**Annual Mileage (km/year)**	**Lifespan (years)**
Shared electric car (driverless, Zity)	35000	32000	2240	0,070	electricity	1,20	18000	15
Shared gasoline car (driverless, Wible)	24500	24500	1715	0,146	gasoline	1,20	18000	15
Shared electric motorcycle	5000	4000	350	0,037	electricity	1,05	10000	5
Shared electric bicycle	1500	1200	100	0,057	electricity	1,00	2800	3
Shared electric scooter	200	160	100	0,086	electricity	1,00	2800	3
Hybrid car ride sharing (Uber)	30000	24000	1680	0,021	gasoline (85%) + electricity (15%)	1,20	60000	6
Electric car ride sharing (Uber)	35000	28000	1960	0,070	electricity	1,20	60000	6

Table 22. Conventional technologies data 2

CONVENTIONAL TECHNOLOGIES			
echnology	**Efficiency (MJ/v.km)**	**Emissions per v.km (gCO2eq/v.km)**	**Emissions per p.km (gCO2eq/p.km)**
Diesel Car	2,6	192,66	163,27
Gasoline Car	2,6	194,22	164,59
Electric Car	0,8712	112,55	95,38
Gasoline Motorcycle	1,26	94,12	89,64
Electric Motorcycle	0,54	69,76	66,44
Natural Gas Urban Busl (GNC)	9,76	475,80	29,74
Electric Urban Bus	2,304	297,65	18,60
Diesel Urban Bus	8,32	616,51	38,53
Hydrogen Urban Bus	4,96	466,24	29,14
Electric Metro (e.g., Madrid)	43,2	5581,01	43,43
Electric Tram (e.g., Zaragoza)	8,6832	1121,78	13,95
Convencional Taxi (gasoline)	2,6	194,22	164,59
Hybrid Electric Vehicle Taxi (HEV)	1,51	125,14	106,05

Table 23. New modes and technologies data 2

NEW MODES AND TECHNOLOGIES			
Name of technology	**Efficiency (MJ/v.km)**	**Emissions per v.km (gCO2eq/v.km)**	**Emissions per p.km (gCO2eq/p.km)**
Shared electric car (driverless, Zity)	0,871	112,550	93,792
Shared gasoline car (driverless, Wible)	2,600	194,220	161,850
Shared electric motorcycle	0,540	69,763	66,441
Shared electric bicycle	0,049	6,301	6,301
Shared electric scooter	0,054	6,976	6,976
Hybrid car ride sharing (Uber)	1,510	112,797	93,998
Electric car ride sharing (Uber)	0,871	125,139	104,282

CHAPTER 3 - DATA SOURCES

We will now proceed to explain in detail the derivation of each parameter, providing a deeper understanding of how they are calculated and what aspects are considered in their determination.

3.1. Investment Cost 2024 (CAPEX):

The CAPEX (capital expenditure) of a personal car varies significantly depending on the type of fuel it uses. On average, a diesel car costs approximately 24,500 €, while a gasoline car costs around 22,000 € [10]. In contrast, an electric car has a significantly higher cost, estimated at 35,000 € [11].

For motorcycles, the CAPEX also differs depending on the energy source. A gasoline motorcycle, taking a 125cc model as a reference, has an average cost of 7,000 € [12]. On the other hand, a similar electric motorcycle has an average cost of 8,500 € [13].

Urban buses show even greater variability in their investment costs depending on the technology they use. A natural gas urban bus has an investment cost of 310,000 €, based on the recent purchase of 200 natural gas buses by the Community of Madrid for a total of 62 million euros [14]. In comparison, a diesel urban bus has an investment cost of 272,500 €. This figure is derived from data indicating that compressed natural gas (CNG) buses are approximately 37,500 € more expensive than diesel buses [15].

The cost of an electric bus is considerably higher, reaching 550,000 euros. This data is based on the recent purchase of 150 electric buses by the Community of Madrid, with a total investment of 82 million euros [16]. Even higher is the cost of a hydrogen bus, which amounts to 1.2 million euros per unit [17].

Regarding rail transportation, the Madrid Metro, which is fully electric, has an investment cost of 6.377 million euros per train of five cars. This data is based on the recent acquisition of 50 trains (250 cars) for a total of 318.85 million euros by Transports Metropolitans de Barcelona (TMB) [18].
On the other hand, the cost of an electric tram, comparable to the Madrid light rail, is 200 million euros [19].

In the individual public transport sector, a conventional gasoline taxi has the same investment cost as a private car, that is, 22,000€ [10]. In contrast, a hybrid taxi costs 25,000 euros, similar to the price of a traditional hybrid car [20].
Regarding the investment cost of a shared self-driving electric car, such as those used by Zity, it is 35,000€. This figure is based on the cost of a Renault 4L, the most commonly used model by Zity Madrid [21].

The investment cost of a shared self-driving gasoline car, like those used by Wible, is 32,000€. This figure is based on the cost of a Kia Niro, the most commonly used model by Wible Madrid [22]. Nonetheless, to align this data with our analysis, we assume that the investment price for shared gasoline cars is the same as for personal gasoline cars.

As for the investment cost of a shared electric motorcycle, we refer to scooters from companies like Acciona or Cooltra, specifically 50cc models. Their cost is 5,000€, according to data provided by Acciona [23].

For the study of shared electric bicycles, we will use data from Bicimad as a reference, which indicates an investment cost of 1,500€ [24].

Regarding shared electric scooters, such as those used by Lime or Cabify, the data shows an investment cost of 200€. The Lime-S scooters are manufactured by Segway, from which this data is derived [25].

For hybrid ridesharing cars, such as those used by Uber, the investment cost is the same as for a private hybrid car. The same applies to electric ridesharing cars.

3.2. Investment Cost 2030 (CAPEX)

This parameter aims to predict the investment cost of different modes of transportation in 2030. To obtain these data, we rely on projections from Bloomberg's Electric Vehicle Outlook [26] and the International Energy Agency (IEA) [27].

The conclusions indicate that vehicles powered by traditional technologies, such as gasoline or diesel, remain stable in terms of costs. This stability is due to the well-established and optimized production costs for these vehicles. The technologies and manufacturing processes have been perfected over decades, resulting in efficiencies and economies of scale. Although the fossil fuel market can be volatile, there have not been drastic changes in production costs. Environmental regulations may increase costs, but improvements in engine efficiency and emission reduction technologies partially offset these increases.

In contrast, electric vehicles are in a phase of rapid technological evolution. The initially higher costs have been primarily due to the batteries, which represent a significant portion of the total vehicle cost. However, in recent years, the cost of lithium-ion batteries has significantly decreased due to technological advancements, economies of scale, and improvements in production processes. Electric vehicle manufacturers are also investing in new technologies and materials that increase efficiency and reduce battery costs. Additionally, government policies, subsidies, and tax incentives for electric vehicles are driving higher adoption, increasing production, and reducing costs through economies of scale.

In summary, while the production costs for diesel and gasoline vehicles have stabilized due to the maturity of their technologies, electric vehicles are experiencing continuous cost reductions driven by technological advancements, improvements in production efficiency, and supportive government policies.

We observe that electric cars are expected to see a 20% reduction in costs, resulting in a projected price of 28000€ by 2030. This cost is multiplied by 1,2, as 20% of cars require a battery replacement after 10 years, adding this cost to equalize the lifespan of an electric car with conventional cars. This same proportion is transferable to other electric-powered vehicles. Therefore, an electric motorcycle will cost 6800€, an electric bicycle 1200€, and an electric scooter 160€.

Table 24. CAPEX conventional technologies

CONVENTIONAL TECHNOLOGIES		
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**
Diesel Car	24500	24500
Gasoline Car	22000	22000
Electric Car	35000	32000
Gasoline Motorcycle	7000	7000
Electric Motorcycle	8500	6800
Natural Gas Urban Busl (GNC)	310000	310000
Electric Urban Bus	550000	550000
Diesel Urban Bus	272500	272500
Hydrogen Urban Bus	1250000	1250000
Electric Metro (e.g., Madrid)	6377000	6377000
Electric Tram (e.g., Zaragoza)	200000000	200000000
Convencional Taxi (gasoline)	22000	22000
Hybrid Electric Vehicle Taxi (HEV)	25000	20000

Table 25. CAPEX new modes and technologies

NEW MODES AND TECHNOLOGIES		
Name of technology	**Investment Cost 2024 € (CAPEX)**	**Investment Cost 2030 € (CAPEX)**
Shared electric car (driverless, Zity)	35000	32000
Shared gasoline car (driverless, Wible)	24500	24500
Shared electric motorcycle	5000	4000
Shared electric bicycle	1500	1200
Shared electric scooter	200	160
Hybrid car ride sharing (Uber)	30000	24000
Electric car ride sharing (Uber)	35000	28000

3.3. Fixed Operating Costs per Year (€/year)

As explained earlier, Fixed Operating Costs (FIXOM) are those that do not depend on the vehicle's mileage. These costs remain constant throughout the year regardless of the vehicle's usage. Fixed operating costs include insurance, which is the annual insurance premium for the vehicle; licensing and registration fees, which are the yearly costs to keep the vehicle legally registered; and parking fees, which are regular charges for a dedicated parking space or garage. These fixed costs are crucial for financial planning and budgeting as they provide a predictable expense that helps in assessing the overall cost of owning and maintaining a vehicle.

When discussing the fixed operating costs of a private car, there is a noticeable difference between traditional fuel vehicles and electric cars. A diesel or gasoline car incurs an average insurance cost of 532€ per year and around 200€ for parking, resulting in a total FIXOM of 732€ annually [28]. In contrast, an electric car benefits from a 75% tax reduction [29], resulting in a total FIXOM of 582€ annually.

When discussing motorcycles, we observe a similar trend. A private 125cc gasoline motorcycle has an annual insurance cost of 90€, an average of 20€ for the technical inspection (ITV), and 12€ in taxes, resulting in a total FIXOM of 122€ [30]. In contrast, electric motorcycles benefit from a tax reduction, with taxes amounting to only €. Therefore, the total FIXOM for electric motorcycles would be 113€ [30].

Regarding buses, regardless of the fuel type, they have a FIXOM that constitutes 15% of the investment cost [31]. Consequently, a CNG-powered bus has a FIXOM of 4650€, an electric bus has a FIXOM of 8250€, a diesel bus has a FIXOM of 4087€, and a hydrogen bus has a FIXOM of 18750€.

For the Madrid Metro, the 2022 annual financial report indicates that the taxes paid by Metro Madrid amount to 1,655 million euros, which we consider as the FIXOM.

In the case of the electric tram, we use the annual reports from the Zaragoza tram system, as it is essential for studying this technology despite not being in Madrid. The reports show an annual tax expenditure of 2,7 million euros, which we therefore take as the FIXOM for the electric tram [32].

Regarding gasoline and hybrid taxis, they incur a monthly self-employment tax of 600€ and an annual insurance cost ranging from 1500 to 2000 euros [33]. Using the average insurance cost of 1750€ annually, we calculate a total FIXOM of 8950€ per year based on these figures.

When analyzing new modes and technologies, we observe that both electric and gasoline-shared autonomous cars have a FIXOM that represents 7% of the investment cost. This 7% figure is derived from various factors, including insurance expenses and other operational costs. For instance, in the United States, it costs around 3300 USD per year per car for carpooling services like Uber. This estimation is based on the fact that Uber spends around 10% of its gross revenue on insurance [34]. Given that Uber spends $5 billion annually on insurance in the US, and approximately 1.5 million Ubers are operating, we arrive at the estimated cost per car [34]. In Spain, where insurance rates tend to be slightly cheaper, the cost could be around 2500€ per year. This translates to about 7-10% of the vehicle's total cost, which aligns with private individuals' spending on insurance for their vehicles. However, carpooling vehicles like Uber often cover more mileage and are at a higher risk of accidents, hence the slightly higher insurance costs.
Therefore, the FIXOM for a shared autonomous electric car is 1715€, while for a gasoline car, it is 2240€. The same trend is seen with shared electric motorcycles, which have a FIXOM of 350€.

Similarly, assuming a FIXOM of 5% of CAPEX, hybrid ridesharing cars and electric ridesharing cars have a FIXOM of 1680€ and 1960€, respectively.

When it comes to scooters and bicycles, insurance costs are typically lower compared to motor vehicles. For these modes of transportation, we could estimate insurance expenses at around 100 euros per year. This amount is akin to a basic liability insurance policy for an individual [35]. While the risk factors are different for scooters and bicycles compared to cars, insurance coverage is still essential to protect riders and others in case of accidents or injuries. Therefore, allocating approximately 100 euros per year for insurance would provide basic coverage for these shared mobility options.

Table 26. FIXOM conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**FIXOM (Fixed Operating Costs, €/year)**
Diesel Car	732
Gasoline Car	732
Electric Car	582
Gasoline Motorcycle	122
Electric Motorcycle	113
Natural Gas Urban Busl (GNC)	4650
Electric Urban Bus	8250
Diesel Urban Bus	4087,5
Hydrogen Urban Bus	18750
Electric Metro (e.g., Madrid)	1655000
Electric Tram (e.g., Zaragoza)	2700000
Convencional Taxi (gasoline)	8950
Hybrid Electric Vehicle Taxi (HEV)	8950

Table 27. FIXOM new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**FIXOM (Fixed Operating Costs, €/year)**
Shared electric car (driverless, Zity)	2240
Shared gasoline car (driverless, Wible)	1715
Shared electric motorcycle	350
Shared electric bicycle	100
Shared electric scooter	100
Hybrid car ride sharing (Uber)	1680
Electric car ride sharing (Uber)	1960

3.4. Variable Operating Costs per Year (€/km)

In addition to FIXOM, it's essential to consider VAROM (Variable Operating Costs) when evaluating the total cost of operating a vehicle. VAROM includes costs dependent on vehicle usage, measured in euros per kilometer (€/km). Maintenance costs cover regular servicing and repairs needed to keep the vehicle in good condition, such as check-ups, oil changes, and tire replacements. Tolls are charges for using specific roads, bridges, or tunnels, varying by route and region. Parking costs include fees for parking in various locations, which can significantly impact operating costs in urban areas. Understanding these variable costs helps provide a comprehensive view of the overall expenses associated with vehicle operation.

When we talk about a private car, it's important to distinguish between different types of fuel, such as gasoline, diesel, and electric. For a diesel car, the variable operating costs per kilometer are as follows: maintenance (0,011€/km), repairs (0,018€/km), tire replacement (0,01€/km), parking (0,06€/km), fines (0,02€/km), and tolls (0,01€/km), totaling 0,129€/km. On the other hand, for a gasoline car, the variable costs per kilometer are maintenance (0,011€/km), repairs (0.035€/km), tire replacement (0,01€/km), parking (0,06€/km), fines (0,02€/km), and tolls (0,01€/km), totaling 0,146€/km [36].

When it comes to electric cars, a 25% reduction in maintenance costs is expected [37], and parking expenses are also eliminated because electric cars can park for free in the city center of Madrid. Therefore, the maintenance cost will be 0,008€/km, repair costs will remain at 0,035€/km, fines will be 0,02€/km, and tolls will be 0,01€/km [36]. Therefore, the total VAROM for an electric car will be 0,07€/km.

When calculating the variable costs of a motorcycle, we utilize annual maintenance data divided by the mileage. For instance, considering a private 125cc gasoline motorcycle requiring an annual maintenance investment of 250€ and covering 3000 km per year, this results in a VAROM of 0,083€/km [38]. Similarly, for an electric motorcycle, with maintenance costs amounting to 110€ annually and covering the same mileage of 3000 km per year, the VAROM would be 0,037 €/km [30].

When it comes to buses, we differentiate variable costs based on their technologies. Natural gas (GNC) buses have a VAROM of 0,2 €/km, electric buses have a VAROM of 0,15 €/km, diesel buses have a VAROM of 0,2 €/km, and hydrogen buses have a VAROM of 0,35 €/km [31]. These variable costs reflect the different operational expenses associated with each bus technology.

When it comes to the Madrid Metro, we can calculate the VAROM (Variable Operating Costs per kilometer) by dividing the total maintenance cost by the product of the number of cars and the annual mileage. Based on data from the annual financial report of Metro Madrid, the maintenance cost amounts to 38,7 million euros, there are a total of 2341 cars, and the annual mileage is 85000 km [39]. Therefore, the VAROM of the Madrid Metro is calculated as follows:

$$\begin{aligned} VAROM &= (Maintenance\ Cost\ /\ (Number\ of\ Cars\ \cdot\ Annual\ Mileage)) \\ &= (38720349\ €\ /\ (2341\ cars\ \cdot\ 85000\ km)) \approx\ 0{,}19\ €/km \end{aligned}$$

This means that the Madrid Metro incurs approximately 0**,**19 €/km in variable operating costs**.**

It is reasonable to assume that the VAROM for an electric tram could be similar to that of a metro, as both systems share several technologies and components, such as electrical systems and track infrastructure. Therefore the VAROM of an electric tram is 0,19 €/km.

For taxis, both electric and gasoline-powered, we again perform the calculation by dividing the maintenance cost by the mileage. This yields a variable expense of 0,021 €/km [33].

The variable operating costs (VAROM) of driverless shared cars are set equal to those of private cars since they are measured in euros per kilometer (€/km). The only difference lies in the fact that shared cars typically cover more kilometers. The same principle applies to shared motorcycles and ridesharing cars.

Regarding shared electric bicycles, we use the company BiciMAD as a reference. From BiciMAD, we obtain maintenance costs of 1500€ annually per bicycle [40]. With the data indicating that 7500 bicycles are operating in Madrid and the assumption that each bicycle travels an average of 3,5 km per trip [41], we calculate the VAROM as follows:

First, we determine the total distance traveled by all bicycles annually:

$$Total\ Distance\ = 7500\ bikes\ \cdot\ 3{,}5\ km/trip$$

Next, we divide the annual maintenance cost by this total distance to find the VAROM:

$$VAROM = \ 1500\ €/(7500\ bikes \cdot 3{,}5\ km/trip) = \ 0{,}057$$

Therefore, the VAROM for shared electric bicycles is approximately 0,057 €/km.

Finally, to determine the VAROM for electric scooters, we assume a situation similar to that of bicycles. Since electric scooters have comparable maintenance needs and usage patterns, we can use analogous data and assumptions. For instance, if we have maintenance costs of 1500€ annually per scooter, a fleet of 5000 scooters [41], and each scooter travels an average of 3,5 km per trip, we can calculate the VAROM as follows:

$$Total\ Distance\ = 5000\ bikes\ \cdot\ 3{,}5\ km/trip$$

Next, we divide the annual maintenance cost by this total distance to find the VAROM:

$$VAROM = \ 1500\ €/(5000\ bikes \cdot 3{,}5\ km/trip) = \ 0{,}086$$

Therefore, by using similar assumptions, the VAROM for electric scooters is approximately 0,086 €/km.

Table 28. VAROM conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**VAROM (Variable Operating Costs, €/km)**
Diesel Car	0,129
Gasoline Car	0,146
Electric Car	0,070
Gasoline Motorcycle	0,083
Electric Motorcycle	0,037
Natural Gas Urban Busl (GNC)	0,200
Electric Urban Bus	0,150
Diesel Urban Bus	0,200
Hydrogen Urban Bus	0,350
Electric Metro (e.g., Madrid)	0,195
Electric Tram (e.g., Zaragoza)	0,190
Convencional Taxi (gasoline)	0,021
Hybrid Electric Vehicle Taxi (HEV)	0,021

Table 29. VAROM new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**VAROM (Variable Operating Costs, €/km)**
Shared electric car (driverless, Zity)	0,070
Shared gasoline car (driverless, Wible)	0,146
Shared electric motorcycle	0,037
Shared electric bicycle	0,057
Shared electric scooter	0,086
Hybrid car ride sharing (Uber)	0,021
Electric car ride sharing (Uber)	0,070

3.5. Energy Vector

An energy vector refers to a carrier or form in which energy is stored, transported, or used, such as electricity, natural gas, or hydrogen. It's essentially a medium through which energy is transferred or converted for various applications.

In our analysis, we have thoroughly examined traditional energy sources such as gasoline and diesel while also delving into the study of emerging energy vectors. Among these new vectors, we have investigated electricity, natural gas, and hydrogen as alternative and promising sources of energy.

Gasoline and diesel, as traditional energy sources, have been extensively used in the transportation industry and various other applications. However, we have recognized their limitations, including their dependence on fossil fuels, negative environmental impact, and the depletion of natural resources.

In response to these challenges, we have explored the advantages of new energy sources such as electricity. This energy source offers the potential for using electric vehicles, which are more energy-efficient and produce zero emissions at the point of use. Additionally, electricity can be generated from diverse sources such as solar, wind, or hydroelectric power, making it a more sustainable and renewable option.

Another energy vector we have investigated is natural gas. This resource has gained popularity due to its lower environmental impact compared to conventional fossil fuels. Natural gas is a versatile energy source that can be used in a wide range of applications, from transportation to electricity generation and household use. Its abundance and availability also play a significant role in considering it as a viable long-term energy source.

Finally, we have explored hydrogen as a promising energy vector. Hydrogen can be produced from various sources, such as water electrolysis or natural gas reforming, and its combustion only produces water vapor as a byproduct. This characteristic makes it an attractive option from an environmental perspective. Although hydrogen still faces challenges in terms of storage and distribution, active research and development of technologies are underway to overcome these barriers.

Table 30. Energy Vector conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Energy Vector**
Diesel Car	diesel
Gasoline Car	gasoline
Electric Car	electricity
Gasoline Motorcycle	gasoline
Electric Motorcycle	electricity
Natural Gas Urban Busl (GNC)	natural gas
Electric Urban Bus	electricity
Diesel Urban Bus	diesel
Hydrogen Urban Bus	hydrogen
Electric Metro (e.g., Madrid)	electricity
Electric Tram (e.g., Zaragoza)	electricity
Convencional Taxi (gasoline)	gasoline
Hybrid Electric Vehicle Taxi (HEV)	gasoline (85%) + electricity (15%)

Table 31. Energy Vector new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Energy Vector**
Shared electric car (driverless, Zity)	electricity
Shared gasoline car (driverless, Wible	gasoline
Shared electric motorcycle	electricity
Shared electric bicycle	electricity
Shared electric scooter	electricity
Hybrid car ride sharing (Uber)	gasoline (85%) + electricity (15%)
Electric car ride sharing (Uber)	electricity

3.6. Efficiency (MJ/v.km)

To calculate the efficiency of a transportation system in terms of megajoules per vehicle-kilometer (MJ/v*km), you need to know the amount of energy consumed by the vehicle to travel a specific distance. This efficiency can vary depending on the type of transport, the vehicle model, operational conditions, and other factors.

For the case of Compression Ignition (CI) vehicles, the efficiency is given as 2,6 MJ/vkm. For electric cars, the energy consumption is given as 0,242 kWh/vkm. To convert this to megajoules (MJ), you can use the conversion factor where 1 kWh = 3,6 MJ. [43]
Here's the calculation for electric cars:

$$0{,}242\ kWh/v \cdot km \cdot 3{,}6\ MJ/kWh\ =\ 0{,}8712\ MJ/v \cdot km$$

In the case of motorcycles, the efficiency value is 1,26 MJ/vkm for gasoline motorcycles, and 0,15 kWh/vkm for electric motorcycles [44]. Therefore, when converting to MJ/vkm, we have 0,15 kWh/vkm * 3,6 MJ/kWh = 0,54 MJ/v*km.

In the case of buses, the data found is in MJ/pkm, so we multiply by the occupancy of each vehicle to obtain MJ/vkm. For natural gas buses, the efficiency is 0,61 MJ/pkm, for

electric buses, it is 0,04 MJ/pkm, for diesel buses, it is 0,52 MJ/pkm, and for hydrogen buses, it is 0,31 MJ/pkm. Buses have an average occupancy of 16 passengers. [43]
Therefore, the calculations are:

- Natural Gas Bus: 0,61MJ/pkm×16passengers = 9,76 MJ/vkm
- Electric Bus: 0,04MJ/pkm×16passengers=0,64 MJ/vkm
- Diesel Bus: 0,52MJ/pkm×16passengers=8,32 MJ/vkm
- Hydrogen Bus: 0,31MJ/pkm×16passengers=4,96 MJ/vkm

For the metro case, we have a data point of 2 MWh per vehicle-kilometer (MWh/v*km) [45]. To convert it to megajoules (MJ), we multiply by 3,6. Since a typical metro consists of 6 cars, we multiply the result by 6 to obtain the total efficiency.

Therefore, the metro's efficiency would be:

$$2MWh/v \cdot km \cdot 3{,}6MJ/MWh \cdot 6cars = 43{,}2MJ/v \cdot km$$

For the electric tram, we'll follow a similar process. Given the data point of 0,03 MWh per vehicle-kilometer (MWh/v*km), we'll convert it to megajoules (MJ) by multiplying by 3,6. [43]

Therefore, the efficiency of the electric tram would be:

$$0{,}03MWh/v \cdot km \cdot 3{,}6MJ/MWh = 0{,}108MJ/v \cdot km$$

Regarding taxis, we'll apply the efficiency data of private cars since their operational characteristics and efficiency are expected to be comparable. Therefore, the efficiency values used for private cars can be directly applied to taxis.

For electric or gasoline shared self-driving cars, such as those found in services like Zity or Wible, we use the same data as for a private vehicle of their respective technologies. This same principle applies to ridesharing technologies, such as Uber.
In the case of shared electric bicycles, we have found the data of 2,18 kWh per 100 miles [46]. To convert this to MJ per vehicle-kilometer (MJ/v*km), we first multiply by 3,6 to convert to MJ and then convert miles to kilometers.

$$(2{,}18kWh/100\,miles) \cdot (3{,}6MJ/kWh/1{,}60934) = \ 0{,}049\ MJ/v * km$$

Finally, for electric scooters, the obtained data is 0,015 kWh per vehicle-kilometer (kWh/vkm) [47]. To convert this to MJ per vehicle-kilometer (MJ/vkm), we first convert kWh to MJ, then adjust as necessary.

$$0{,}015kWh/v \cdot km \cdot 3{,}6MJ/kWh = 0{,}054MJ/v \cdot km$$

Therefore, the efficiency of electric scooters is approximately 0,054 MJ per vehicle-kilometer (MJ/v·km).

Table 32. Efficiency conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Efficiency (MJ/v.km)**
Diesel Car	2,6
Gasoline Car	2,6
Electric Car	0,8712
Gasoline Motorcycle	1,26
Electric Motorcycle	0,54
Natural Gas Urban Busl (GNC)	9,76
Electric Urban Bus	2,304
Diesel Urban Bus	8,32
Hydrogen Urban Bus	4,96
Electric Metro (e.g., Madrid)	43,2
Electric Tram (e.g., Zaragoza)	8,6832
Convencional Taxi (gasoline)	2,6
Hybrid Electric Vehicle Taxi (HEV)	1,51

Table 33. Efficiency new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Efficiency (MJ/v.km)**
Shared electric car (driverless, Zity)	0,871
Shared gasoline car (driverless, Wible)	2,600
Shared electric motorcycle	0,540
Shared electric bicycle	0,049
Shared electric scooter	0,054
Hybrid car ride sharing (Uber)	1,510
Electric car ride sharing (Uber)	0,871

3.7. Occupancy

The average number of passengers a vehicle can carry varies depending on the type of vehicle. Let's explore the average occupancies for different types of vehicles [48]:

- Car (urban and interurban): Regardless of the technology used, urban and interurban vehicles have an average occupancy of 1.18 passengers. This means that, on average, there is slightly more than one passenger in these vehicles during a trip. Factors like the size of the car, the number of seats available, and the purpose of the journey can influence the exact occupancy.
- Private motorcycles: Private motorcycles generally have a lower average occupancy than cars. On average, a private motorcycle carries 1.05 passengers. This indicates that, in most cases, there is usually one rider with occasional instances of a second passenger.
- Buses: Buses are designed to transport a larger number of passengers. On average, buses have an occupancy of around 16 passengers. This figure takes into account the seating capacity of the bus as well as the possibility of standing passengers during peak times.
- Electric metro: Electric metro systems are commonly used in urban areas for mass transit. On average, an electric metro train carries approximately 128.5 passengers. This figure includes the seating and standing capacity of the trains.

- Electric tram: Similar to electric metro systems, electric trams are designed to accommodate a significant number of passengers. On average, an electric tram carries about 80.4 passengers.
- Taxis: Taxis typically have a similar average occupancy to private cars. With an average occupancy of 1.18 passengers, taxis follow the same trend as urban and interurban cars. The driver is not included in the occupancy count since they are responsible for operating the vehicle.
- Car-sharing: Car-sharing services involve multiple users sharing the same vehicle at different times. The average occupancy for car-sharing services is slightly higher than that of private cars. On average, car-sharing vehicles have an occupancy of 1.2 passengers. This minor increase accounts for instances where there might be more than one passenger utilizing the shared vehicle.
- Shared electric motorcycles: Similar to private motorcycles, shared electric motorcycles have an average occupancy of 1.05 passengers.
- Shared bicycles and scooters: Shared bicycles and scooters are designed for individual use, and as such, their average occupancy is one occupant. These vehicles are typically used by a single rider at a time.
- Ride-sharing (e.g., Uber): Ride-sharing services involve private cars operated by drivers who transport passengers. These vehicles have a slightly higher average occupancy compared to private cars. On average, ride-sharing vehicles have an occupancy of 1.2 passengers. This accounts for scenarios where additional passengers might share the ride with the driver.

Table 34. Occupancy conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Occupancy**
Diesel Car	1,18
Gasoline Car	1,18
Electric Car	1,18
Gasoline Motorcycle	1,05
Electric Motorcycle	1,05
Natural Gas Urban Busl (GNC)	16,00
Electric Urban Bus	16,00
Diesel Urban Bus	16,00
Hydrogen Urban Bus	16,00
Electric Metro (e.g., Madrid)	128,50
Electric Tram (e.g., Zaragoza)	80,40
Convencional Taxi (gasoline)	1,18
Hybrid Electric Vehicle Taxi (HEV)	1,18

Table 35. Occupancy new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Occupancy**
Shared electric car (driverless, Zity)	1,20
Shared gasoline car (driverless, Wible)	1,20
Shared electric motorcycle	1,05
Shared electric bicycle	1,00
Shared electric scooter	1,00
Hybrid car ride sharing (Uber)	1,20
Electric car ride sharing (Uber)	1,20

3.8. Annual mileage (km/year)

The annual mileage, measured in kilometers per year, can vary greatly depending on various factors such as individual driving habits, vehicle usage, and transportation needs. If we assume the same mileage for all types of vehicles, including cars, buses, etc., the average annual mileage can be estimated as follows:

- Cars: The average annual mileage for cars is estimated to be around 12 000 kilometers.[49]
- Motorcycles: Motorcycles typically have a lower annual mileage compared to cars. The average annual mileage for motorcycles is estimated to be around 3000 kilometers.[49]
- Buses: Buses, particularly those used for public transportation, tend to cover a significant distance due to their regular service. The average annual mileage for buses is estimated to be around 100000 kilometers.[49]
- Electric Metro: Electric metro systems are commonly used for mass transit in urban areas. The average annual mileage for electric metro trains is estimated to be around 85000 kilometers. [50]
- Electric Tram: Electric trams, similar to electric metro systems, also cover a considerable distance due to their role in public transportation. The average annual mileage for electric trams is estimated to be around 100000 kilometers.
- Taxis: Taxis are often used intensively for transportation services. The average annual mileage for taxis is estimated to be around 55000 kilometers. [51]

Regarding new technologies and ride-sharing platforms, here are the approximate annual mileage values:

- Car-sharing: Car-sharing services, where multiple users share the same vehicle at different times, typically have an average annual mileage of around 18000 kilometers.[52]
- Uber and other ride-sharing services: Drivers for platforms like Uber, taxis, or other transportation network companies often cover significantly higher distances compared to the average driver. On these platforms, drivers can accumulate up to five times more mileage than an average driver. Therefore, the average annual mileage for Uber or similar ride-sharing drivers can be estimated to be around 60000 kilometers. [53]

To obtain the annual mileage for shared motorcycles, bicycles, and scooters, we will perform a series of calculations based on estimations.

The approximate annual mileage for moto sharing can be calculated as follows:

Given that a moto-sharing company, like Cooltra, has a fleet of 500 motorcycles in Madrid [54] they complete a total of 1300 trips per day [55]. If we divide the total trips by the number of motorcycles, we get an average of approximately 2,6 trips per motorcycle per day. For simplicity, let's round this number to 3 trips per motorcycle per day.

If we assume that each trip has an average distance of 10 kilometers (within the urban center), this means that each motorcycle covers approximately 30 kilometers per day. By multiplying this value by the 365 days in a year, we get an approximate annual mileage of around 10000 kilometers per motorcycle in moto sharing.

The approximate annual mileage for shared bicycles can be calculated as follows:

Given that there are 6 million trips with a fleet of 7500 bicycles [56], we can divide the total number of trips by the number of bicycles to obtain an average of 800 trips per bicycle.

If we assume that each trip has an average distance of 3,5 kilometers, we can multiply the average number of trips per bicycle by the average distance per trip:

$$800\ trips/bicycle \cdot 3{,}5\ km/trip\ =\ 2800\ km/bicycle.$$

Therefore, the approximate annual mileage for shared bicycles would be around 2,800 kilometers per bicycle.
The annual mileage for shared scooters can be assumed to be similar to that of shared bicycles, based on the same average distance per trip. Therefore, we can estimate an annual mileage of approximately 2,800 kilometers per scooter.

Table 36. Annual Mileage conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Annual Mileage(km/year)**
Diesel Car	12000
Gasoline Car	12000
Electric Car	12000
Gasoline Motorcycle	3000
Electric Motorcycle	3000
Natural Gas Urban Busl (GNC)	100000
Electric Urban Bus	100000
Diesel Urban Bus	100000
Hydrogen Urban Bus	100000
Electric Metro (e.g., Madrid)	85000
Electric Tram (e.g., Zaragoza)	100000
Convencional Taxi (gasoline)	55000
Hybrid Electric Vehicle Taxi (HEV)	55000

Table 37. Annual mileage new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Annual Mileage(km/year)**
Shared electric car (driverless, Zity)	18000
Shared gasoline car (driverless, Wible)	18000
Shared electric motorcycle	10000
Shared electric bicycle	2800
Shared electric scooter	2800
Hybrid car ride sharing (Uber)	60000
Electric car ride sharing (Uber)	60000

3.9. Lifespan (years)

The average lifespan of a vehicle depends on many factors, including the type of technology, maintenance, and the vehicle's mileage.

In the case of diesel and gasoline particulate cars, they have an average lifespan of around 15 years.

Regarding electric vehicles, the lifespan is often associated with the battery's durability. The typical lifespan of an electric vehicle battery varies depending on factors such as the type of battery, usage patterns, and environmental conditions. While the exact lifespan can vary, it is common for electric vehicle batteries to retain a significant portion of their original capacity for around 8 to 10 years [57]. After this period, the battery's capacity may gradually decline, requiring replacement or refurbishment. Nonetheless, only 20% of electric cars require a battery replacement over their lifespan. Therefore, for electric cars, we assume a lifespan of 15 years and include this potential cost increase in the overall expenses.

Similar to cars, motorcycles' lifespan can also depend on various factors, including the technology used. While a 125cc gasoline-powered motorcycle has an average lifespan of around 12 years [58], an electric motorcycle may have a similar lifespan of around 10 years due to battery longevity [59].

Regarding buses, the useful life depends on the technology. Natural gas (CNG) and hydrogen buses have a useful life of 10 years, while diesel and electric buses last 15 years [60]. This is because diesel and electric technologies are more mature and reliable, leading to longer durability and lower maintenance requirements. Conversely, natural gas and hydrogen technologies, being relatively newer, may not yet offer the same level of durability and reliability.

In terms of rail transport, electric metro trains have a useful life of 30 years, as indicated by data from Metro Madrid [61]. Similarly, electric trams, such as those in Zaragoza, also have a useful life of 30 years [62].

Taxis, regardless of whether they are conventional gasoline or hybrid, typically have a useful life of around 7 years due to the high mileage and frequent usage they experience in urban environments, where they often operate continuously throughout the day [63]. In the realm of emerging technologies, such as self-driving shared cars, electric variants are estimated to have a useful life of approximately 15 years. Also gasoline-powered self-driving cars are projected to endure for around 15 years, aligning with the lifespan of traditional privately owned vehicles.

Regarding electric shared scooters, based on data provided by companies like Acciona, which supply these types of vehicles in Madrid, their useful life is estimated to be around 5 years [23]. This relatively shorter lifespan is influenced by factors such as the frequent and intensive usage these scooters endure in urban environments, as well as the evolving technology and battery degradation over time inherent to electric vehicles.

Shared electric scooters typically have a useful lifespan of around 3 years due to their extensive usage in urban environments [64]. This frequent and intensive usage contributes to wear and tear on components such as the battery, tires, and frame.

Similarly, the useful lifespan of shared electric bicycles is also estimated to be around 3 years, reflecting similar usage patterns and technological considerations.

Regarding the useful lifespan of Uber vehicles, considering their high mileage, it's estimated that they accumulate around 60000 km per year, based on data from individual Uber drivers. Given this extensive usage, Uber vehicles are typically retired with significantly higher mileage than privately owned cars. However, due to the wear and tear incurred from such intense usage, there's a limit to their operational life, typically ranging from 5 to 6 years. This balance between mileage and age ensures that Uber maintains a fleet of vehicles that meet safety and performance standards while managing operational costs effectively.

Table 38. Lifespan conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Lifespan (years)**
Diesel Car	15
Gasoline Car	15
Electric Car	15
Gasoline Motorcycle	12
Electric Motorcycle	10
Natural Gas Urban Busl (GNC)	10
Electric Urban Bus	15
Diesel Urban Bus	15
Hydrogen Urban Bus	10
Electric Metro (e.g., Madrid)	30
Electric Tram (e.g., Zaragoza)	30
Convencional Taxi (gasoline)	7
Hybrid Electric Vehicle Taxi (HEV)	7

Table 39. Lifespan new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Lifespan (years)**
Shared electric car (driverless, Zity)	15
Shared gasoline car (driverless, Wible)	15
Shared electric motorcycle	5
Shared electric bicycle	3
Shared electric scooter	3
Hybrid car ride sharing (Uber)	6
Electric car ride sharing (Uber)	6

3.10. Emissions per v.km (gCO2eq/v.km)

To calculate emissions per vehicle-kilometer (gCO2eq/v.km), we use the energy efficiencies obtained previously and multiply them by a series of conversion factors. These conversion factors relate the amount of energy consumed by the vehicle to the equivalent carbon dioxide emissions (gCO2eq) associated with that energy.

Table 40. Conversion factors

Energy Vectors	gCO2eq/MJ	Sources
Diesel	74,1	[65]
Gasoline	74,7	[65]
Electricity	129,19	[66]
Natural Gas	48,75	[65]
Hydrogen	94	[67]

Multiplying each technology by its corresponding factor, we obtain:

Table 41. Emissions per v.km conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Emissions per v.km (gCO2eq/v.km)**
Diesel Car	192,66
Gasoline Car	194,22
Electric Car	112,55
Gasoline Motorcycle	94,12
Electric Motorcycle	69,76
Natural Gas Urban Busl (GNC)	475,80
Electric Urban Bus	297,65
Diesel Urban Bus	616,51
Hydrogen Urban Bus	466,24
Electric Metro (e.g., Madrid)	5581,01
Electric Tram (e.g., Zaragoza)	1121,78
Convencional Taxi (gasoline)	194,22
Hybrid Electric Vehicle Taxi (HEV)	125,14

Table 42. Emissions per v.km new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Emissions per v.km (gCO2eq/v.km)**
Shared electric car (driverless, Zity)	112,550
Shared gasoline car (driverless, Wible)	194,220
Shared electric motorcycle	69,763
Shared electric bicycle	6,301
Shared electric scooter	6,976
Hybrid car ride sharing (Uber)	112,797
Electric car ride sharing (Uber)	125,139

We should note that for hybrid vehicles, we apply a weighting factor considering that they use 15% electricity and the remainder gasoline. [68]

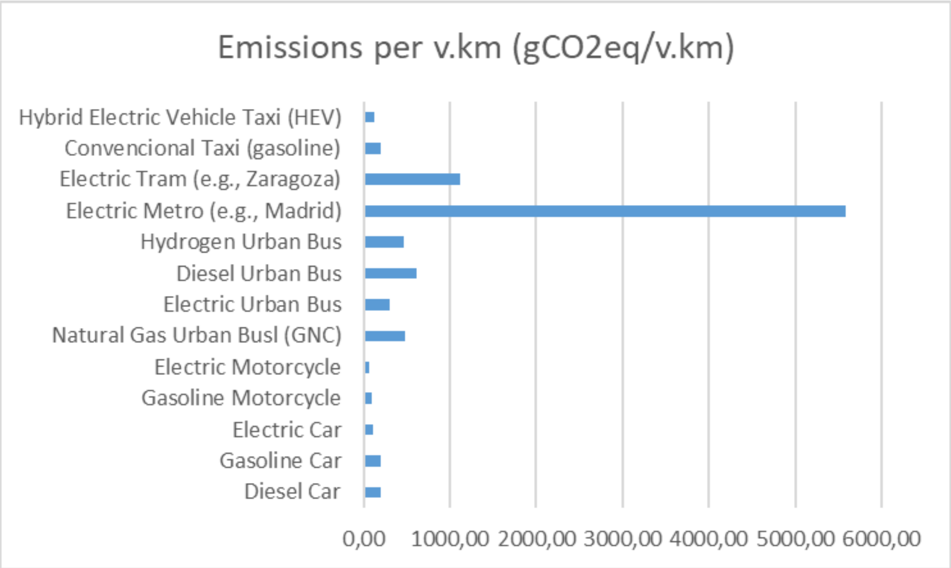

Illustration 17. Emissions per v.km conventional technologies

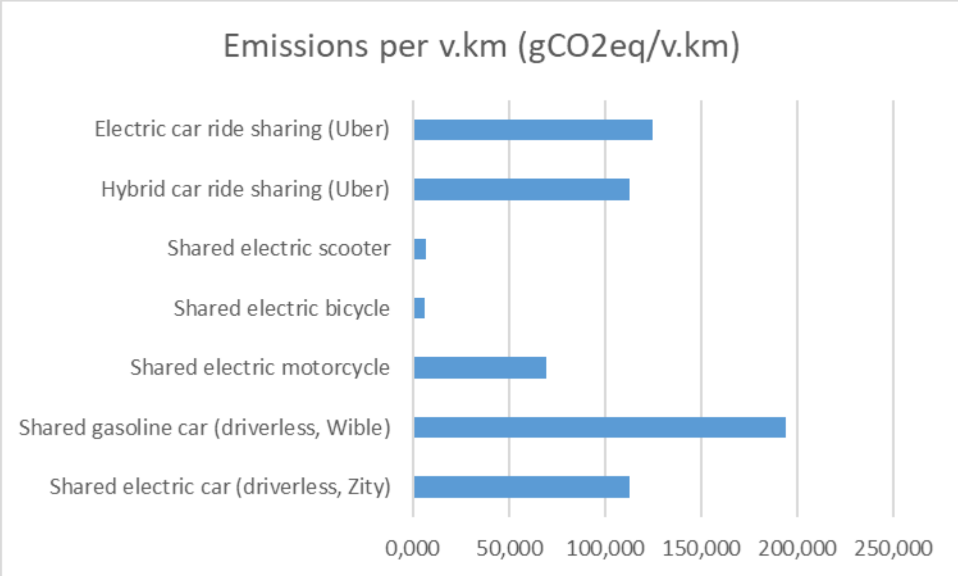

Illustration 18. Emissions per v.km new modes and technologies

3.11. Emissions per p.km (gCO2eq/p.km)

For emissions per passenger-kilometer (gCO2eq/p.km), we simply divide the emissions per vehicle-kilometer (gCO2eq/v.km) obtained previously by the occupancy, thus obtaining the following data:

Table 43. Emissions per p.km conventional technologies

CONVENTIONAL TECHNOLOGIES	
Name of technology	**Emissions per p.km (gCO2eq/p.km)**
Diesel Car	163,27
Gasoline Car	164,59
Electric Car	95,38
Gasoline Motorcycle	89,64
Electric Motorcycle	66,44
Natural Gas Urban Busl (GNC)	29,74
Electric Urban Bus	18,60
Diesel Urban Bus	38,53
Hydrogen Urban Bus	29,14
Electric Metro (e.g., Madrid)	43,43
Electric Tram (e.g., Zaragoza)	13,95
Convencional Taxi (gasoline)	164,59
Hybrid Electric Vehicle Taxi (HEV)	106,05

Table 44. Emissions per p.km new modes and technologies

NEW MODES AND TECHNOLOGIES	
Name of technology	**Emissions per p.km (gCO2eq/p.km)**
Shared electric car (driverless, Zity)	93,792
Shared gasoline car (driverless, Wible)	161,850
Shared electric motorcycle	66,441
Shared electric bicycle	6,301
Shared electric scooter	6,976
Hybrid car ride sharing (Uber)	93,998
Electric car ride sharing (Uber)	104,282

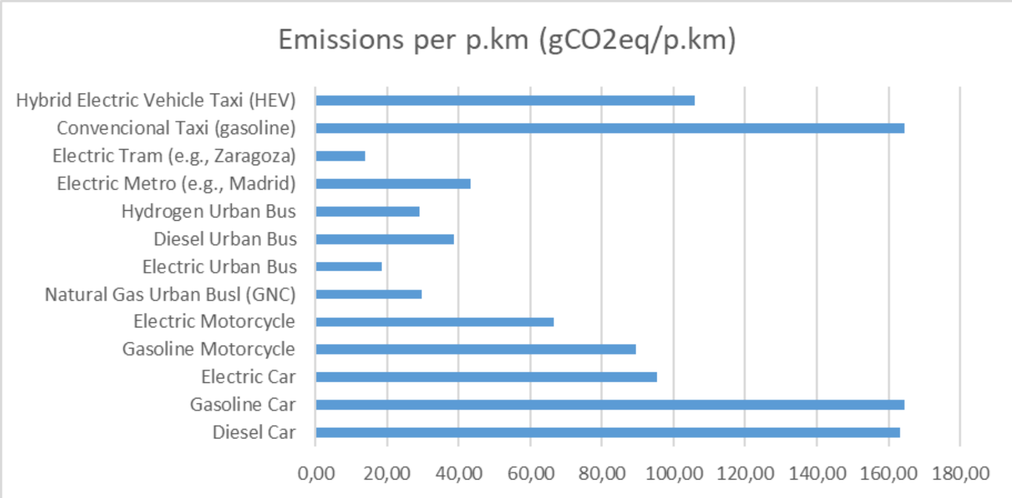

Illustration 19. Emissions per p.km conventional technologies

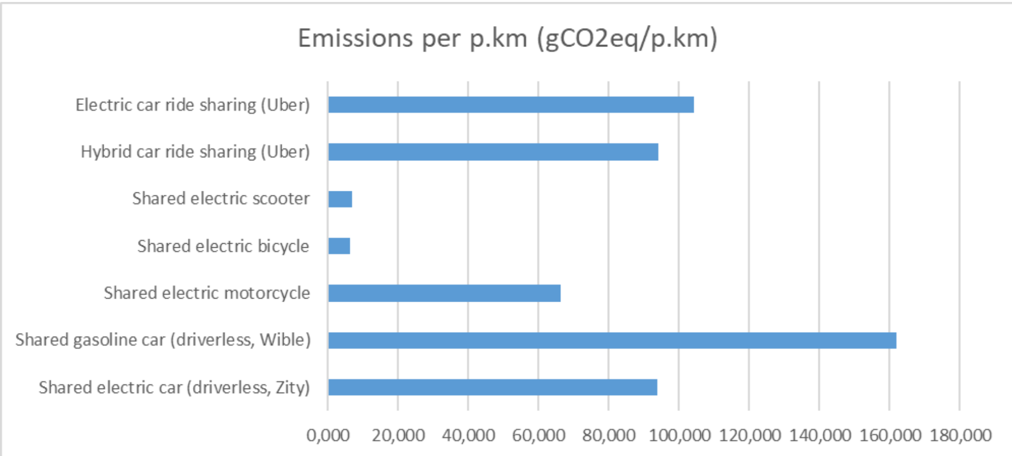

Illustration 20. Emissions per p.km new modes and technologies

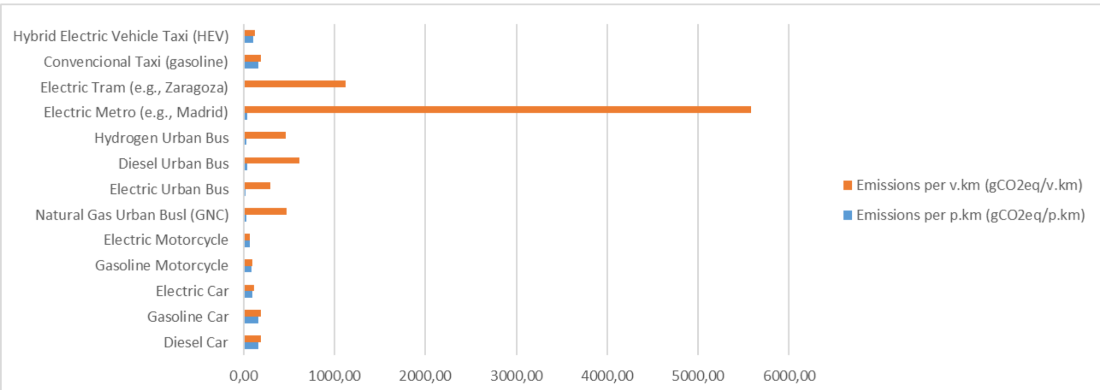

Illustration 21. Emissions v.km vs p.km

In this graph, we observe the comparison between emissions measured in vehicle kilometers (Emissions v.km) versus passenger kilometers (Emissions p.km). It is important to highlight that the key metric is emissions per passenger kilometer (Emissions p.km), as it better reflects the efficiency and environmental impact of different transportation modes. This metric takes into account the number of passengers transported, providing a more accurate measure of the emissions generated per person for each kilometer traveled. This focus on passenger emissions underscores the importance of maximizing passenger capacity to improve overall transportation efficiency and reduce per capita emissions.

CHAPTER 4: RESULTS AND ANALYSIS

4.1. Total Cost of Ownership (TCO)

In this section of the TFG, we will conduct a cost analysis based on the Total Cost of Ownership (TCO). This means we will analyze the total cost of owning an asset, including not only the initial purchase price but also all associated costs over the asset's lifetime. These costs include maintenance, repairs, insurance, energy, and other operational expenses. The goal is to provide a comprehensive and detailed view of the true costs to make informed and efficient investment decisions.

This analysis will include CAPEX, FIXOM, VAROM, and energy costs. CAPEX (Capital Expenditure) refers to the initial capital expenditure required to acquire the asset. FIXOM (Fixed Operating and Maintenance Costs) covers the fixed costs of operating and maintaining the asset. VAROM (Variable Operating and Maintenance Costs) encompasses the variable operating and maintenance costs that fluctuate with the asset's usage. Finally, energy costs refer to expenses related to energy consumption over the asset's lifetime.

We will use €/pkm (euros per passenger-kilometer) to compare all these costs in the same unit. Using this unit is crucial because it standardizes the costs across different transportation modes and scenarios, allowing for a direct comparison of efficiency and cost-effectiveness. By measuring costs per passenger-kilometer, we account for the number of passengers transported, providing a more accurate representation of the economic and environmental impact of each option. This standardized unit helps in evaluating the overall efficiency, helping decision-makers choose the most cost-effective and sustainable transportation solutions.

Therefore, CAPEX is divided by the number of passengers divided by the asset's years of useful life, and by the kilometers traveled. For future monetary units such as VAROM, FIXOM, and energy consumption, we will apply a 10% discount rate. Subsequently, we will divide by the number of passengers multiplied by the asset's years of useful life, and by the kilometers traveled.
This approach allows us to adjust future costs to present value, considering the time value of money (10% discount rate). By dividing these adjusted costs by the number of passengers, years of useful life, and kilometers traveled, we obtain a relevant and comparable measure in €/pkm (euros per passenger-kilometer).

The discount rate is a crucial factor when it comes to evaluating and comparing different technological alternatives, as it allows for taking into account the time value of money. A higher discount rate implies giving more weight to the initial cost (CAPEX) and less to the future operating costs (OPEX).

In the case of vehicles, if a high discount rate (10%) is used, the higher initial cost of the electric vehicle compared to an internal combustion vehicle has a more important weight in the evaluation. On the other hand, the lower operating costs of the electric vehicle over its lifetime are valued less. This makes the internal combustion vehicle appear more economical in this comparison.

Conversely, if a lower discount rate is used, more importance is given to future operating costs. In this case, the advantages of the lower OPEX of the electric vehicle become more relevant, and the difference in initial CAPEX between the two technologies carries less weight.

The key conclusion is that the electric car has a higher purchase cost (CAPEX) than the internal combustion vehicle, but then has much lower operating costs (OPEX) over its useful life. Therefore, the decision to opt for an electric or internal combustion vehicle will largely depend on how we value future money through the discount rate we use.

It is important to have an economic mindset that allows us to properly value money over time. If we apply a low discount rate, which gives more weight to future savings, then the electric vehicle will turn out to be the most cost-effective option in the long run. This shows that a correct understanding and application of economic concepts can make the electric car the best choice.

In order to express energy consumption in monetary units, it will be necessary to calculate euros/MJ. For this purpose, we use the following data:

Table 45. Energy in monetary terms

diesel	1,5	€/litro	44	MJ/litro
gasoline	1,5	€/litro	44	MJ/litro
electricity	0,2	€/kWh	3,6	MJ/kWh
natural gas	1,1	€/kg	56	MJ/kg
hydrogen	12	€/kg	142	MJ/kg

Table 46. €/MJ & gCO2/MJ

	€/MJ	**gCO2/MJ**
diesel	0,0341	73,0
gasoline	0,0341	73,0
electricity	0,0556	44,4
natural gas	0,0196	56,0
gasoline (85%) + electricity (15%)	0,0373	68,7
hydrogen	0,0845	0,0

We assume that hydrogen is 100% green, meaning it emits zero grams of CO2.

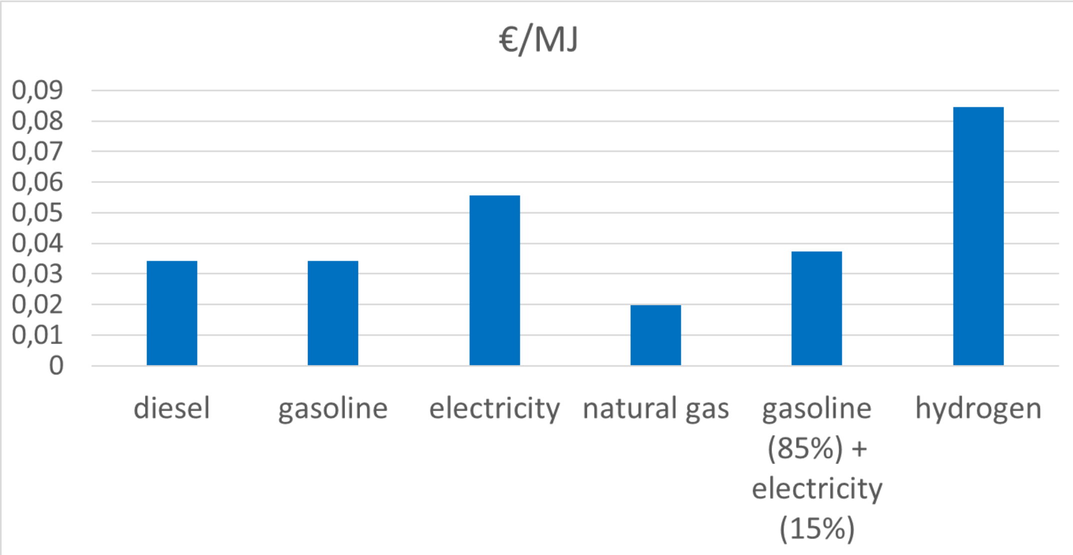

Illustration 22. €/MJ energy

We observe that the most cost-effective technology for transportation is natural gas, followed by diesel and gasoline. Electricity ranks next, with hydrogen being the least economical option. This hierarchy is influenced by several factors.

Firstly, natural gas benefits from its relative abundance and competitive pricing compared to traditional liquid fuels like diesel and gasoline. Additionally, Spain's well-established infrastructure for natural gas distribution enhances its accessibility and utilization across various sectors, including transportation.

Moreover, governmental policies and subsidies likely play a role in promoting natural gas as a cleaner and economically viable alternative. These measures may incentivize its adoption over less mature technologies such as electricity and hydrogen, which face higher infrastructure and development costs.

In Spain, hydrogen faces significant economic challenges that make it less competitive compared to other fuels such as natural gas, diesel, and gasoline. Several factors contribute to its high cost:

Firstly, the production of green hydrogen (generated from renewable energy sources) is still a costly process that requires advanced and specific technologies like electrolysis. These technologies are not yet mature, and do not yet enjoy large economics of scale.

Additionally, the costs associated with renewable energy necessary for producing green hydrogen can be volatile and often higher compared to conventional energy sources in the short term. This directly impacts the final cost of hydrogen.

Another key factor is the lack of adequate distribution and storage infrastructure for hydrogen. Establishing distribution networks and refueling stations for hydrogen also involves significant investments in technology and safety, increasing operational and capital costs.

However, the hydrogen production capacity in Spain is increasing at a very fast pace, due to the great potential the country has in terms of renewable electricity production from solar and wind power. In the coming years, the cost of hydrogen, following the current trend, could decrease to prices as low as 2 €/kg in the large facilities being built.

In terms of energy content electricity, in average, is still today more expensive than gasoline and diesel due to several factors. However, given that electric vehicles are considerably more efficient, the operation costs of these technologies are often cheaper than fossil fuel technologies The electricity market design in Europe is based on marginal prices, which means that the costliest technology of every hour in the market is the one setting the price for all the rest. This market incentivizes the development of cheaper technologies, especially renewables. However, in the process of decarbonizing the mix average prices can have a slower decrease than desired, especially when gas plants are still clearing day-ahead market prices and the gas has been subject of very high volatility following several geopolitical conflicts

It is worth noting that the 85% gasoline and 15% electricity parameter refers to the technology used in hybrid cars. This technology is slightly above more conventional technologies like diesel and gasoline in terms of costs, but it falls slightly below electricity in cost efficiency.

With all these data, we finally calculate the total euros per passenger-kilometer (€/pkm) for each mode of transportation.

Table 47. €/pkm

€/pkm	CAPEX	ENERGY	FIXOM	VAROM	Grand Total
Diesel Urban Bus	0,01135	0,00899	0,00130	0,00634	0,02798
Electric Urban Bus	0,02292	0,00406	0,00261	0,00475	0,03434
Natural Gas Urban Busl (GNC)	0,01938	0,00736	0,00179	0,00768	0,03620
Electric Metro (e.g., Madrid)	0,01946	0,00530	0,04300	0,00043	0,06819
Hydrogen Urban Bus	0,07813	0,01610	0,00720	0,01344	0,11486
Hybrid car ride sharing (Uber)	0,05556	0,03408	0,01694	0,01270	0,11927
Shared electric scooter	0,01905	0,00249	0,02961	0,07105	0,12219
Shared electric motorcycle	0,07619	0,02166	0,02527	0,02648	0,14960
Electric car ride sharing (Uber)	0,06481	0,02928	0,01976	0,04234	0,15619
Hybrid Electric Vehicle Taxi (HEV)	0,04402	0,03321	0,09591	0,01238	0,18552
Shared electric car (driverless, Zity)	0,09877	0,02045	0,05259	0,02958	0,20138
Convencional Taxi (gasoline)	0,04843	0,05224	0,09591	0,01238	0,20896
Shared gasoline car (driverless, Wible)	0,07562	0,03745	0,04026	0,06169	0,21503
Shared electric bicycle	0,14286	0,00225	0,02961	0,04737	0,22208
Electric Car	0,15066	0,02080	0,02084	0,03008	0,22238
Gasoline Car	0,10358	0,03809	0,02621	0,06274	0,23062
Diesel Car	0,11535	0,03809	0,02621	0,05543	0,23508
Gasoline Motorcycle	0,18519	0,02323	0,02199	0,04506	0,27547
Electric Motorcycle	0,21587	0,01756	0,02204	0,02146	0,27693

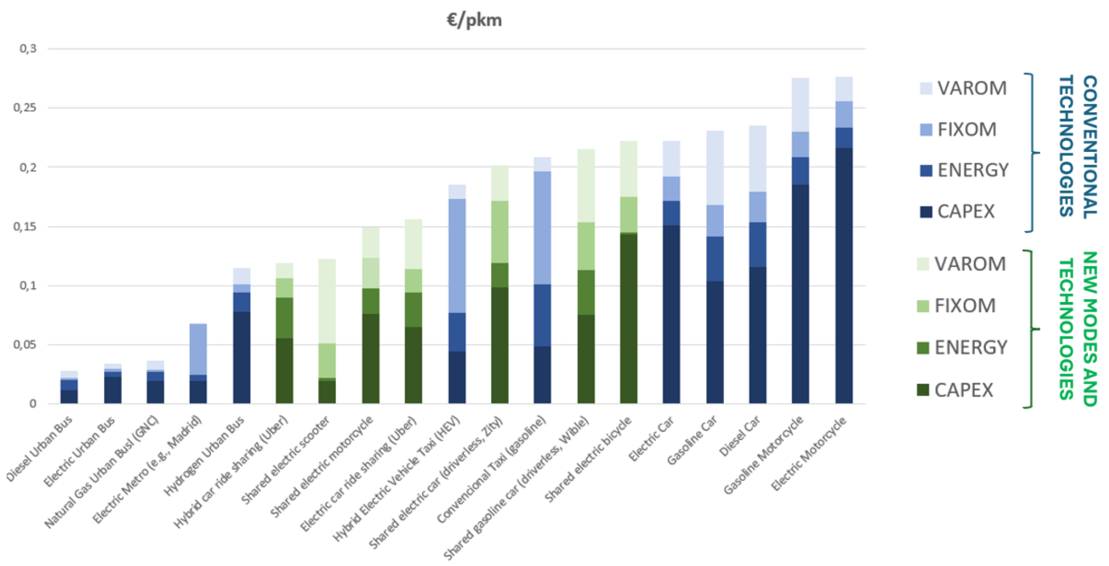

Illustration 23. €/pkm

This graph provides a breakdown of the cost per passenger-kilometer for each technology, distinguishing between the contributions from energy costs, fixed operational costs (FIXOM), variable operational costs (VAROM), and capital expenditure (CAPEX).

By examining these components, we can evaluate and compare the efficiency of each technology.

The conclusions drawn from the analysis are as follows:

- The most cost-effective technologies are public transportation compared to private transportation.
- Within public transportation, diesel buses are the most economical option due to their lower initial cost and established infrastructure. Electric and natural gas buses, while offering environmental benefits, face challenges such as higher acquisition costs and less developed charging infrastructure.
- The electric metro is a very economical option in terms of energy efficiency and initial investment costs. However, it incurs higher maintenance and personnel costs, which slightly increases its overall cost compared to diesel, electric, and natural gas buses.
- The hydrogen bus, despite being a more economical option compared to private transportation and newer shared transportation modes, is much more expensive than other buses (diesel, electric, natural gas), including the metro, due to the high investment costs associated with its technology.
- Regarding new modes and technologies, the most cost-efficient options are shared electric scooters and shared electric motorcycles. Shared electric scooters have low investment costs, fixed costs, and energy costs, but they incur higher variable operational costs (VAROM) compared to other modes.
- When considering taxis, the most cost-effective choices are shared ridesharing options like Uber, with hybrid models being the most economical, followed by electric variants. Although their initial investment costs are comparable, electric taxis incur higher variable operational costs (VAROM) due to potential battery replacement expenses. Among traditional taxis, hybrids are the most efficient, followed by gasoline-powered models.
- When it comes to shared driverless cars, electric ones are more efficient than gasoline-powered ones due to their lower energy consumption.
  Despite the higher cost of electricity per megajoule (€/MJ) compared to traditional energy sources, electrified modes of transportation are more cost-effective in the long term due to their significantly lower energy consumption. For example, an electric vehicle typically consumes much less energy per kilometer traveled compared to a diesel vehicle, often about three times less.
  This efficiency translates into lower fuel costs over the lifetime of the vehicle, even though electricity may be more expensive per unit of energy.

Table 48. Efficiency car

Name of technology	Efficiency (MJ/v.km)
Diesel Car	2,6
Gasoline Car	2,6
Electric Car	0,8712

$$\frac{Efficiency_{diesel/gasoline}}{Efficiency_{Electric}} = \frac{2,6}{0,87} = 3$$

- Electric bicycles have a higher cost than expected primarily due to their initial investment, which is comparatively high considering the annual mileage and usage. Despite having minimal energy costs limited to charging stations, the overall cost per kilometer is relatively high. Therefore, they are not the most cost-effective mode of transportation.

- Regarding cars, as mentioned earlier, the most cost-effective option is the electric car. Despite its higher initial investment cost, its energy consumption and overall lifetime costs are lower. Following electric cars are gasoline-powered cars, which have lower initial costs but higher long-term expenses. Diesel cars are also competitive, with lower initial costs than gasoline but higher long-term costs.
- When it comes to private motorcycles, this mode of transportation is considered the least efficient for several reasons. Motorcycles typically have very low mileage and occupancy rates close to 1, meaning they mostly transport one person at a time. This low utilization results in poor cost amortization despite relatively low energy costs. Furthermore, motorcycles have a high initial investment cost, making it challenging to recover that cost over their lifetime due to their low mileage and occupancy. Specifically, electric motorcycles, despite having lower energy costs compared to gasoline-powered ones, are generally more expensive due to their higher initial acquisition cost. This situation contrasts with the general trend where the economic efficiency of a mode of transportation often relates to lower operating costs and quicker amortization of the initial cost. In summary, private motorcycles, especially electric ones, face significant challenges in being economically viable due to their low usage efficiency, high initial cost, and, in the case of electric motorcycles, higher acquisition costs.
- The overarching conclusion is that public transportation proves to be the most cost-effective choice, followed by emerging shared transportation technologies, and finally, private transportation. When considering fuels, electricity emerges as a more economical option compared to traditional fossil fuels. Therefore, transitioning to decarbonized forms of energy not only promotes environmental sustainability but also offers significant cost savings.

In conclusion, we have explored various aspects of transportation and energy, focusing on efficiency, costs, and sustainability. We have observed that public transportation and new shared models are generally more cost-effective than private transport, underscoring the importance of resource efficiency. Furthermore, the transition to cleaner energy sources, such as electricity, not only promotes environmental sustainability but can also lead to significant long-term savings. This analysis highlights the need to consider both economic and environmental factors when making decisions about mobility and energy consumption in the future.

4.2. Emissions

To calculate emissions in gCO2/km, we start by using the previously obtained data of gCO2 per megajoule (gCO2/MJ). We then multiply this value by the efficiency in megajoules per vehicle-kilometer (MJ/vkm). After that, we divide by the occupancy rate to obtain the emissions per passenger. This method allows us to determine the emissions per person per kilometer, providing a clear comparison across different modes of transportation.

Table 49. Calculation of emissions

Name of technology	Efficiency (MJ/v.km)	gCO2/MJ	gCO2/v.km	Occupancy	gCO2/p.km
Diesel Car	2,6	73,0	189,8	1,18	160,85
Gasoline Car	2,6	73,0	189,8	1,18	160,85
Electric Car	0,8712	44,4	38,72	1,18	32,81
Gasoline Motorcycle	1,26	73,0	91,98	1,05	87,60
Electric Motorcycle	0,54	44,4	24	1,05	22,86
Natural Gas Urban Busl (GNC)	9,76	56,0	546,56	16,00	34,16
Electric Urban Bus	2,304	44,4	102,4	16,00	6,40
Diesel Urban Bus	8,32	73,0	607,36	16,00	37,96
Hydrogen Urban Bus	4,96	0,0	0	16,00	0,00
Electric Metro (e.g., Madrid)	43,2	44,4	1920	128,50	14,94
Convencional Taxi (gasoline)	2,6	73,0	189,8	1,18	160,85
Hybrid Electric Vehicle Taxi (HEV)	1,51	68,7	103,76217	1,18	87,93
Shared electric car (driverless, Zity)	0,871	44,4	38,72	1,20	32,27
Shared gasoline car (driverless, Wible)	2,600	73,0	189,8	1,20	158,17
Shared electric motorcycle	0,540	44,4	24	1,05	22,86
Shared electric bicycle	0,049	44,4	2,1678061	1,00	2,17
Shared electric scooter	0,054	44,4	2,4	1,00	2,40
Hybrid car ride sharing (Uber)	1,510	68,7	103,76217	1,20	86,47
Electric car ride sharing (Uber)	0,871	44,4	38,72	1,20	32,27

Table 50. Emissions CO2/p.km

Name of technology	gCO2/pkm
Hydrogen Urban Bus	0,00
Shared electric bicycle	2,17
Shared electric scooter	2,40
Electric Urban Bus	6,40
Electric Metro (e.g., Madrid)	14,94
Shared electric motorcycle	22,86
Electric Motorcycle	22,86
Electric car ride sharing (Uber)	32,27
Shared electric car (driverless, Zity)	32,27
Electric Car	32,81
Natural Gas Urban Busl (GNC)	34,16
Diesel Urban Bus	37,96
Hybrid car ride sharing (Uber)	86,47
Gasoline Motorcycle	87,60
Hybrid Electric Vehicle Taxi (HEV)	87,93
Shared gasoline car (driverless, Wible)	158,17
Convencional Taxi (gasoline)	160,85
Gasoline Car	160,85
Diesel Car	160,85

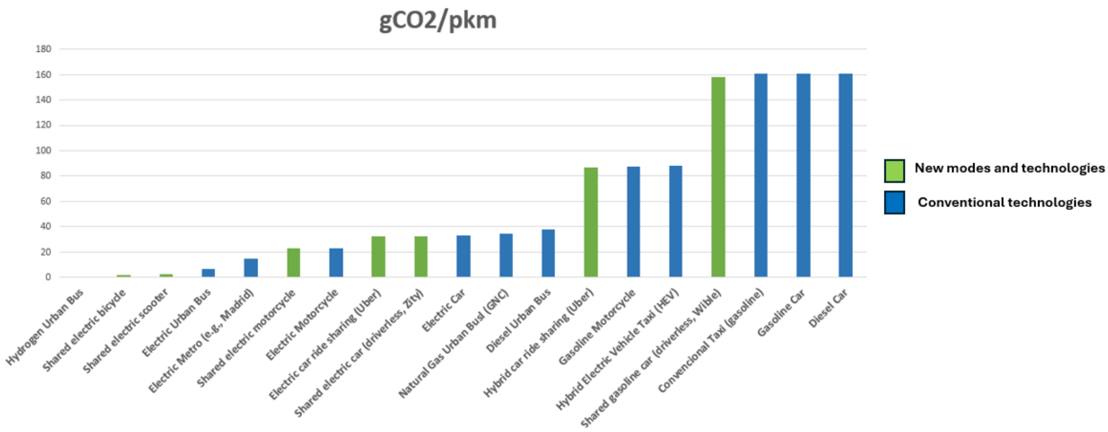

Illustration 24. gCO2/p.km

The conclusions drawn from these data are as follows:

- As we mentioned earlier, we assume that hydrogen is 100% green hydrogen. This means it emits zero emissions because it is produced using renewable energy sources, which do not generate carbon dioxide or other greenhouse gases during production.
- Electric buses emit less CO2 compared to natural gas and diesel buses primarily due to the energy source used for their operation. Electric buses run on electricity, which can be generated from renewable sources such as solar, wind, or hydroelectric power. These renewable energy sources do not emit CO2 during electricity generation, resulting in nearly zero emissions directly from the vehicle. On the other hand, natural gas buses also have lower emissions than diesel buses because natural gas produces less CO2 per unit of energy compared to diesel. However, they still emit greenhouse gases during combustion.
- In terms of shared transportation modes, shared electric bicycles generate the least emissions, followed by shared electric scooters, and finally shared electric motorcycles.
- The metro emits more greenhouse gases than an electric bus primarily due to its reliance on electricity generated from various sources, which may include fossil fuels in some regions. However, compared to traditional buses powered by diesel or natural gas, the metro typically emits fewer emissions per passenger-kilometer traveled. This is because metros are generally more efficient in transporting larger numbers of passengers over fixed routes, reducing the emissions per person compared to individual or smaller-capacity vehicles like buses or cars.
- Electric ridesharing cars (such as Uber) and shared driverless cars (such as Zity) emit less CO2 than private electric cars. This is expected due to their higher occupancy rates and greater mileage. The same applies to shared gasoline and diesel cars compared to private ones.
- Electric motorcycles emit more CO2 than public transportation but less than shared car technologies and taxis. However, gasoline motorcycles emit more CO2 than both private and shared electric cars.

- An electric car emits five times less CO2 than a gasoline or diesel car primarily due to its energy source. Electric cars run on electricity, which can be generated from renewable sources like solar, wind, and hydroelectric power. These renewable sources produce little to no CO2 during electricity generation. In contrast, gasoline and diesel cars rely on fossil fuels, which release a significant amount of CO2 when burned. Additionally, electric cars are more efficient in converting energy into movement, further reducing overall emissions compared to their internal combustion engine counterparts.

4.3. Marginal Abatement Cost (MAC)

I will analyze Marginal Abatement Costs (MAC) to assess the economic efficiency of emission reduction strategies in this study. MAC represents the additional cost required to reduce one unit of greenhouse gas emissions, such as carbon dioxide (kgCO2). This analysis is essential for comparing different mitigation options and determining the most cost-effective approaches to achieve environmental targets. By evaluating MAC, we can inform policy decisions, optimize resource allocation, and promote sustainable development practices aimed at mitigating climate change effectively and economically.

To calculate the Marginal Abatement Cost (MAC), we measure it in euros per kilogram of CO2 (€/kgCO2). This is achieved by dividing euros per passenger-kilometer (€/pkm) by grams of CO2 per passenger-kilometer (gCO2/pkm), using a conventional diesel car as a reference, as it is the most commonly used mode of transport and emits the most CO2. The Marginal Abatement Cost (MAC) is calculated as the ratio between the increase in the Total Cost of Ownership (TCO) per passenger-kilometer (€/pkm) and the decrease in specific emissions per passenger-kilometer (gCO2/pkm). Simply put, it involves dividing the difference in costs (cost delta) between two technologies by the difference in emissions (emissions delta) between those same technologies.
This approach allows us to quantify the additional cost incurred to reduce emissions for each kilogram of CO2 emitted. What we are comparing is how much other technologies cost compared to a diesel car for each gram of CO2 that we avoid per passenger-kilometer.

Normalization and data standardization are crucial to ensure a fair comparison across different transportation technologies. This process involves normalizing data based on emissions per passenger-kilometer (gCO2e/pkm) and costs per passenger-kilometer (€/pkm). Normalization helps account for variations in the number of passengers and kilometers traveled, providing a clear basis for comparison.

This allows us to obtain the following data:

$$MAC = \frac{\left(^{€}/_{pkm}\right) - 0{,}2351}{160{,}8475 - (^{gC02}/_{pkm})} \cdot 1000 = €/\mathrm{kgC02}$$

Table 51. MAC calculations

	€/pkm	gCO2/pkm	MAC (€/kgCO2)
Hydrogen Urban Bus	0,1149	0,0000	-0,7474
Shared electric bicycle	0,2221	2,1678	-0,0820
Shared electric scooter	0,1222	2,4000	-0,7125
Electric Urban Bus	0,0343	6,4000	-1,2997
Electric Metro (e.g., Madrid)	0,0682	14,9416	-1,1438
Shared electric motorcycle	0,1496	22,8571	-0,6195
Electric Motorcycle	0,2769	22,8571	0,3032
Electric car ride sharing (Uber)	0,1562	32,2667	-0,6135
Shared electric car (driverless, Zity)	0,2014	32,2667	-0,2621
Electric Car	0,2224	32,8136	-0,0992
Natural Gas Urban Busl (GNC)	0,0362	34,1600	-1,5699
Diesel Urban Bus	0,0280	37,9600	-1,6853
Hybrid car ride sharing (Uber)	0,1193	86,4685	-1,5570
Gasoline Motorcycle	0,2755	87,6000	0,5513
Hybrid Electric Vehicle Taxi (HEV)	0,1855	87,9340	-0,6798
Shared gasoline car (driverless, Wible)	0,2150	158,1667	-7,4824
Convencional Taxi (gasoline)	0,2090	160,8475	0,0000
Gasoline Car	0,2306	160,8475	0,0000
Diesel Car	0,2351	160,8475	0,0000

The data derived from this analysis will be presented with units on the Y-axis indicating Euros per kg of CO2 (€/kgCO2). Positive values (€/kgCO2) indicate a cost associated with emissions reduction and higher values denote higher costs per kg of CO2 reduced. In contrast, negative values (€/kgCO2) represent net savings, indicating that implementing the measure not only reduces CO2 emissions but also results in cost savings, such as through improved energy efficiency measures.

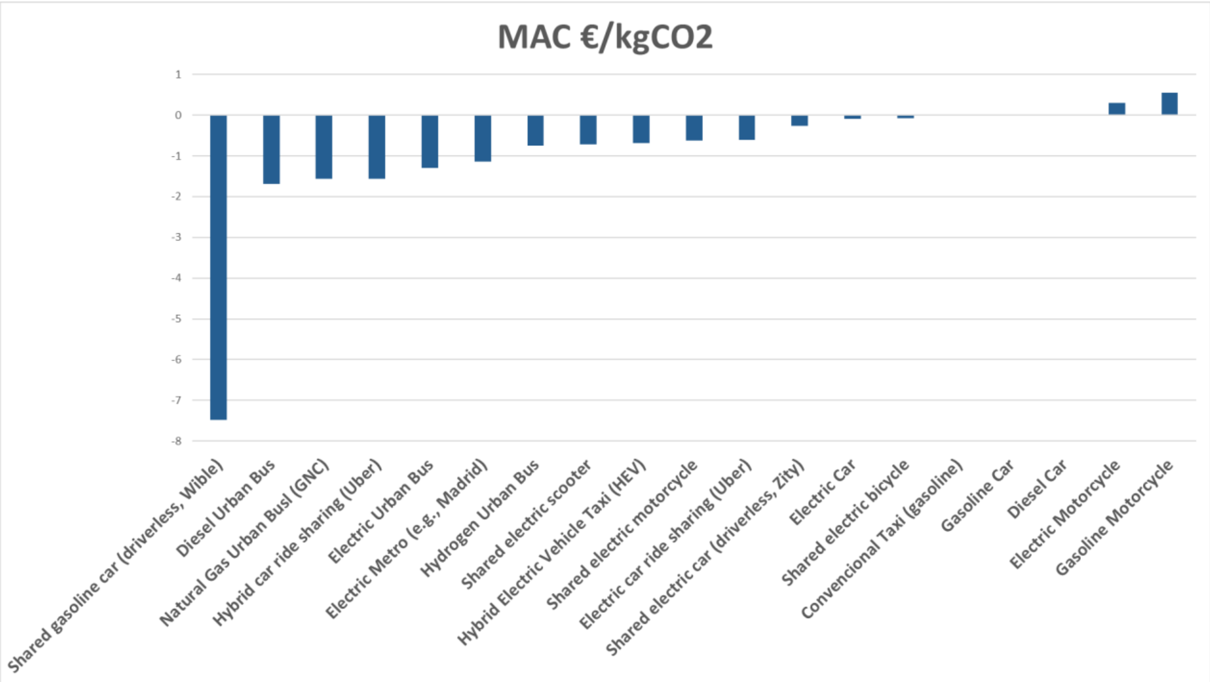

Illustration 25. MAC

Based on the detailed analysis of marginal abatement costs (MAC) for various transportation technologies, several nuanced conclusions can be drawn:

- Every alternative to diesel cars, except for private motorcycles, proves more economical both in operation costs and in CO2 savings per passenger-kilometer. Therefore, investing in the expansion of buses, shared technologies, or any other decarbonization strategy results in significant cost savings. In summary, decarbonization efforts not only reduce emissions but also offer financial benefits.

- All analyzed technologies exhibit similar savings in terms of euros per kilogram of CO2 avoided, except for shared gasoline cars like Wible, which offer extremely low €/kgCO2 savings. The difference in CO2 emissions between a gasoline Wible and a diesel car is minimal, resulting in a rapid tendency towards infinity in terms of €/kgCO2 saved. Additionally, the cost difference between a Wible and a regular gasoline car is insignificant, making the cost per kg of CO2 saved very low. Implementing Wibles instead of regular cars could save a lot of money, but it would not significantly reduce total CO2 emissions. Therefore, the potential for system-wide CO2 reduction is limited due to the impracticality of optimally installing a large number of Wibles.

- Efficiency of Urban Buses: Compressed natural gas (CNG) and diesel urban buses exhibit the lowest CO2 abatement costs per kilogram. This is due to their mature technology and optimization in minimizing emissions per passenger-kilometer, benefiting from economies of scale and operational efficiency.

- Shared Electric Transport: Shared electric transportation options such as electric bicycles, electric scooters, and electric urban buses also show negative marginal abatement costs. This indicates not only CO2 reduction benefits but also net economic savings due to lower operational and maintenance costs compared to internal combustion vehicles.

- Individual Vehicles: In contrast, individual vehicles like gasoline motorcycles and private cars, whether gasoline or diesel, demonstrate positive or neutral marginal abatement costs. This implies that while they may reduce CO2 emissions, it doesn't necessarily result in direct economic savings due to higher investment costs in cleaner technologies and potential additional costs associated with maintenance and operation.

These findings underscore the importance of considering both economic and environmental aspects when selecting emission reduction strategies in the transportation sector. Opting for cleaner and more efficient technologies not only helps mitigate climate change but also has the potential for significant long-term economic benefits, especially when implemented at scale in urban and metropolitan settings.

CHAPTER 5: CONCLUSIONS

Decarbonization Saves Money

The comprehensive analysis of the Total Cost of Ownership (TCO) and the Marginal Abatement Cost (MAC) across various transportation technologies reveals a fundamental conclusion: decarbonization is not only environmentally beneficial but also results in significant long-term economic savings. The following key conclusions are derived from the study.

Decarbonized alternatives have a higher investment cost and lower operation costs during their lifespan.

Transitioning to cleaner transportation technologies, such as electric vehicles, natural gas buses, and shared transportation modes, proves to be economically advantageous when considering TCO. While electric vehicles have a higher initial cost (CAPEX) compared to internal combustion vehicles, their operating and maintenance costs (OPEX) are significantly lower over their lifespan. This cost difference becomes more pronounced when applying a low discount rate, which gives greater weight to future savings, making electric vehicles the most cost-effective option in the long run.

Mass transport and emerging technologies the most competitive

Using euros per passenger-kilometer (€/pkm) as a metric allows for uniform comparison across different transportation modes. The data indicates that public transportation, in general, is more economical than private transportation. Among public transport options, diesel buses are the most cost-effective due to their low initial cost and established infrastructure. However, electric and natural gas buses offer significant environmental benefits despite higher acquisition costs and less developed charging infrastructure.

Emerging shared transportation technologies, such as electric scooters and shared electric motorcycles, are highly cost-efficient. These options not only reduce traffic congestion but also have lower operating and maintenance costs. Ridesharing services (like Uber and Zity) and electric autonomous cars also show superior efficiency compared to private counterparts due to higher occupancy rates and greater mileage.

Fossil Fuels and Alternative Fuels

The analysis of costs and emissions across different fuels reveals that natural gas could be the cheapest decarbonization option with respect to diesel, since natural gas implies a slightly lower emissions per MJ. However, it is worth noting that natural gas decarbonization potential is very limited, since its savings in emissions are narrow, for which it cannot be considered a long-term alternative. Electricity, although more expensive per megajoule (€/MJ), is more economical in the long term due to its lower energy consumption per kilometer traveled. Hydrogen production and distribution face significant economic challenges, making it the least competitive option in the Spanish market.

Marginal Abatement Costs (MAC)

Evaluating the marginal abatement costs shows that all alternatives to diesel cars, except for private motorcycles, are more economical in both operating costs and CO2 savings per passenger-kilometer. This highlights the importance of investing in the expansion of urban buses, shared technologies, and other decarbonization strategies, as they not only reduce emissions but also provide substantial financial benefits.

Implications for Policy and Planning

Government policies and subsidies play a crucial role in promoting cleaner and more economically viable technologies. Incentivizing the use of alternative fuel vehicles (natural gas vehicles, electric vehicles, hydrogen fuel-cell, etc.), as well the use of some emerging technologies and modes (such as shared transportation modes) can accelerate the transition to a more sustainable and cost-effective transportation system. However, the impact they have on the overall urban transport system strongly depends on the way these technologies are being used. For instance, shared vehicles fuelled by fossil fuels may not have such a positive impact. Also, if shared mobility is substituting mass transport, which is the cheapest and most efficient set of technologies, their impact can also be negative. For that reason, policy should be driven by technological assessments like the one presented in this work, exploiting the benefits of these new alternatives in the system. Also, during the phase in which these technologies are not as competitive as the conventional ones, policy schemes can help overcome the extracost and improve the efficiency of the system in a faster a more sustainable way.

Conclusion

The primary conclusion from this analysis is clear: decarbonizing transportation is both an environmental necessity and an economic opportunity. By considering both costs and emissions, transitioning to cleaner and more efficient transportation technologies offers a viable path to reducing CO2 emissions, improving energy efficiency, and achieving significant economic savings. The adoption of policies and practices that favor decarbonization will enable cities and countries to move toward a more sustainable and prosperous future.

In summary, decarbonizing transportation not only protects the environment but also provides considerable financial savings. Integrating economic and environmental factors into decision-making about mobility and energy consumption can lead to more efficient and sustainable transportation solutions, benefiting both the economy and the planet.

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