CarbonTrack360

Analysis Tool for Reflecting on the Environmental Impact of Transportation

Ineco Impulsa

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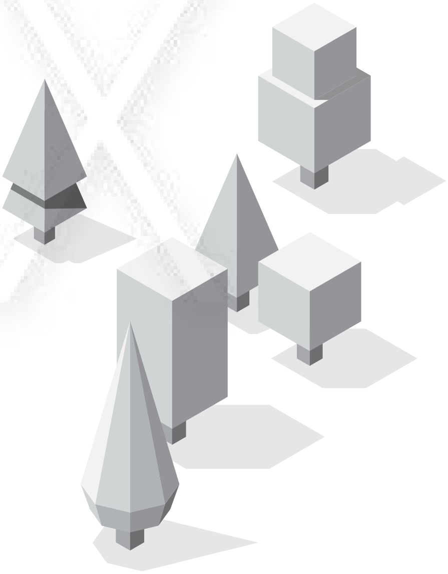


1 TRANSPORT AND CLIMATE: A 360º VIEW OF THE REAL IMPACT

Climate change, as one of the greatest and most significant global challenges, demands to be addressed with rigorous approaches, free from flags or slogans. Transport is an energy-intensive activity and contributes significantly to atmospheric emissions, especially to Greenhouse Gas (GHG) emissions. In Spain, the transport subsector was responsible for 32.5% of these emissions in 2023, with road transport accounting for 30.1% of the total and domestic air transport contributing 1.2%.

These figures, which already focus on this sector, only include the operational emissions of transport, as those from other stages of the life cycle of infrastructure and vehicles (construction, maintenance, refurbishment, and dismantling) are recorded in other categories.

If we truly want to move towards climate goals, we need to look at the impact of transport more comprehensively, considering all stages of its lifecycle. This will help us, on the one hand, to make more realistic decisions and, on the other, to focus technological advances on those activities that can truly make a difference in reducing pollutant emissions from the transport system.

Nowadays, there are many tools that allow the calculation of greenhouse gas (GHG) emissions during the operational phase of transport. Environmental impact studies also include estimates of the emissions generated during construction. However, there is still a lack of a tool that allows for the global measurement of all emissions throughout the entire life cycle, taking into account the infrastructure as the central point through which vehicles and passengers circulate. It is precisely in that infrastructure where it would be possible to obtain a comprehensive view of the environmental impact of the transport system.

Moreover, the accumulated calculation of emissions allows for an appreciation of their temporal profile in each mode, without losing the perspective of future and efficiency.

LIFECYCLE EMISSIONS

The National Emission Inventories, responsible for reporting greenhouse gas and pollutant emissions, only provide data for the operational phase of transport. In the current context of climate emergency, analysing the impact of a mode of transport solely from an operational perspective is insufficient. It is essential to adopt a life cycle assessment (LCA) approach to GHG emissions, which considers everything from the extraction of raw materials, the manufacturing of materials, transport, construction, operation and maintenance, to demolition and waste management.

This comprehensive approach allows for the identification of the true critical emission points over time, many of which are concentrated in stages prior to transport, such as the intensive use of cement, steel, or asphalt. Ignoring these phases can lead to erroneous decisions, such as prioritising solutions that appear to be sustainable in their operational phase but involve a high carbon footprint in their construction. Moreover, the LCA allows for the comparison of design alternatives, materials, and technologies from a climate perspective, facilitating more informed decisions that are aligned with decarbonisation objectives and the prioritisation of emission reduction measures in the most intensive phases of each alternative.

In the case of transport infrastructure, where investments are intensive and assets have a long useful life, this analysis becomes even more relevant, as it allows for the anticipation of future impacts and the design of resilient and low-carbon infrastructures from their conception.

Incorporating the life cycle into climate assessment not only improves the accuracy of the analysis but also promotes a culture of environmental responsibility throughout the planning and execution process of infrastructures and allows for action in accordance with the sustainable development goals and the transport policies of the European Union.

The life cycle of transport encompasses all stages from its conception to its dismantling, considering the associated economic, social, and environmental impacts.

The first phase, which does not generate emissions directly but is essential for making the best decisions from the start, is Planning and Design, in which transport needs are identified, feasibility studies are conducted, and the infrastructure is technically designed. It is crucial to consider the environmental and social impacts from the outset to minimise future negative effects.

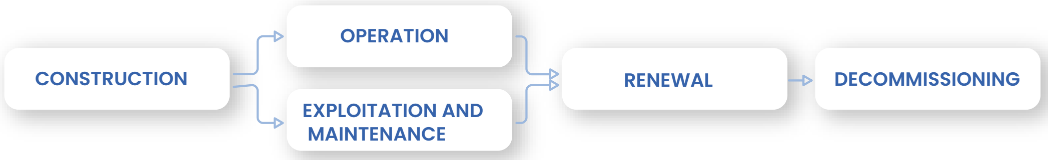
1. Construction stage

Includes the execution of the necessary civil works to materialise the infrastructure. This stage usually involves a significant consumption of natural resources and energy, as well as the generation of emissions and waste both from the construction machinery and from the emissions derived from the production of the materials themselves. The manufacturing of vehicles could also be included here, although for the moment they have not been included in the Carbontrack360 tool.

2. Operation, exploitation and maintenance stage

During the useful life of the infrastructure, transport operations take place, and on the infrastructure and vehicles, operation and maintenance activities are carried out to ensure their functionality and safety. All these activities also generate environmental impacts.

STAGES OF THE TRANSPORT LIFE CYCLE



Source: Own elaboration

3. Renewal stage

Once the useful life cycle is covered, transport infrastructures can be renewed, which involves both civil works and the replacement of equipment. In the case of vehicles, they also require certain activities and replacements, with the impacts that this entails. For the moment, this stage has not been included in the Carbontrack360 tool.

4. Decommissioning stage

Finally, both infrastructure and vehicles should be dismantled. This phase involves waste management and the possible recovery of materials, as well as the assessment of the need for new investments.

Within the carbon-emitting stages throughout the infrastructure life cycle, the most emitting phases for rail and air modes are identified:

INTENSIVE CARBON PHASES FOR RAIL AND AIR MODES

CONSTRUCTION

Extraction of raw materials

Transport of raw materials

Production of materials

Transport of materials

Emissions from construction machinery

Manufacturing of vehicles*

OPERATION AND EXPLOITATION

Energy consumption of the fleet in operation (trains/planes)

Operation of facilities (lines, stations and airports)

MAINTENANCE

Extraction of raw materials

Transport of raw materials

Production of materials

Transport of materials

Emissions from construction machinery

Vehicle maintenance*

RENEWAL*

Extraction of raw materials

Transport of raw materials

Production of materials

Transport of materials

Emissions from construction machinery

Vehicle renewal*

DISMANTILING*

Waste transport

Waste treatment

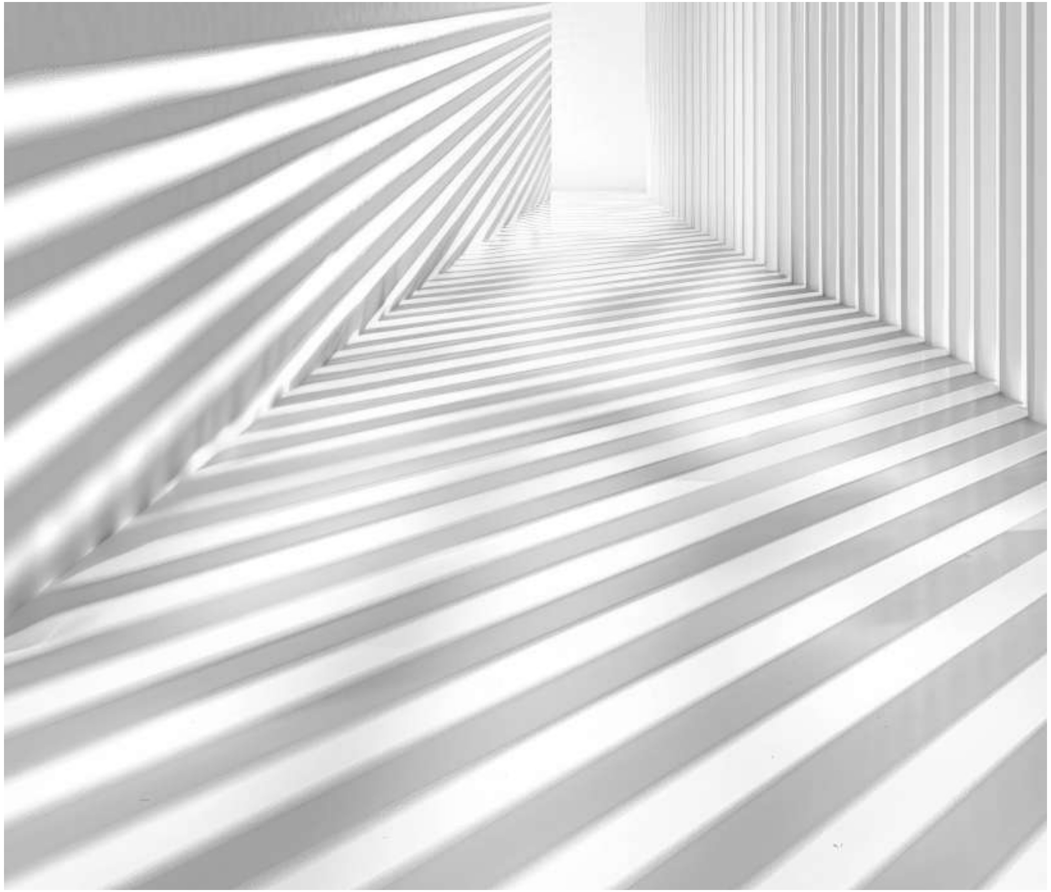
Machinery emissions

Vehicle scrapyard*

* Stages or phases not currently included in Carbontrack360.

Source: Own elaboration

The useful life of the infrastructure is perhaps the most important factor when comparing the emissions derived from the generation of materials during its life cycle because the embodied energy is generally amortised over the service life of the infrastructure. As a result, the lifespan of infrastructure and the annualised embodied emissions of materials have an inverse correlation, meaning that emissions decrease with a longer lifespan of the infrastructure.



RAILWAY MODE EMISSIONS

In the case of rail transport, attention is usually focused almost exclusively on its low emissions during the operational stage, especially when it runs on electricity from renewable sources. However, this view leaves out a key part of the train's climate impact: the construction of infrastructure. Tracks, tunnels, viaducts, and stations require large amounts of materials and energy for their construction, which generates a significant proportion of the total emissions. Therefore, if we want to compare the railway with other modes of transport in a neutral way, it is essential to consider its entire life cycle.

Construction stage

Within the construction phase, in the case of railway infrastructure, the most carbon-intensive activities are those related to materials (more than 80% of the total life cycle emissions of the railway infrastructure). This covers the carbon emissions resulting from the production process of construction materials, including the extraction of their raw components, their subsequent manufacturing process, and their transportation. These activities represent the upstream or frontal emissions of the life cycle impacts, which are also known as embodied or embedded emissions in a product or material.

Due to the volumes of materials used in railway works, most of the emissions from materials are due to concrete, steel, and earth and gravel, which are mainly used in the construction of the platform and superstructure, and in the electrification systems. From these materials, potential improvements are identified that could lead to a significant reduction in emissions during the construction phase.

Regarding the emissions resulting from the use of machinery, they increase depending on the roughness of the terrain and the structural requirements. The greater the number of structures (viaducts, tunnels, retaining walls, etc.), the higher the emissions will be, especially when extensive tunnelling work is required.

POTENTIAL IMPROVEMENTS REGARDING EMISSIONS IN MATERIALS

STEEL	CONCRETE	CEMENT	BALLAST	CATENARY
RECYCLED STEEL	**PRECAST CONCRETE**	**GEOPOLYMERIC CEMENT**	**RECYCLED BALLAST**	**RECYCLED ALUMINIUM CABLES**
		Partial substitution of clinker Use of materials that require a lower calcination temperature		Recycled aluminium cables
High durability, corrosion resistance, possibility of reuse	Reduce waste and energy consumption on site and achieve a 40 to 60% reduction in emissions.	Reduction of CO_2 emissions by up to 40%	Originating from demolition of works or crushed reusable stone materials	Lighter and recyclable alternative to copper

Source: Own elaboration

Operation Stage

In the case of high-speed rail, emissions during the operation stage are considered zero, as the entire high-speed network is electrified, and in Spain, all the energy consumed by high-speed rail is electrical energy with a Renewable Origin Guarantee (REGO).

Renewable REGO electricity is a certification mechanism regulated by the CNMC[1] (National Competition Commission) in Spain, which allows for the accreditation that a certain amount of electricity has been generated from renewable sources or high-efficiency cogeneration.

Although physically the electricity that circulates through the grid is a mixture of different sources, the acquisition of Guarantees of Origin ensures, in accounting terms, that the electricity consumption corresponds to renewable generation. This approach, consistent with the energy labelling methodologies adopted at the European level, allows rail transport to be classified as a mode of mobility with "zero operational emissions".

Maintenance phase of the railway infrastructure

Although less intensive in emissions than construction, it also significantly contributes to the carbon footprint of the railway system. This is mainly due to:

- The use of heavy machinery (diesel or electric).
- Transport of materials (ballast, rails, sleepers).
- Replacement of components and generated waste.
- Energy used in workshops and warehouses.

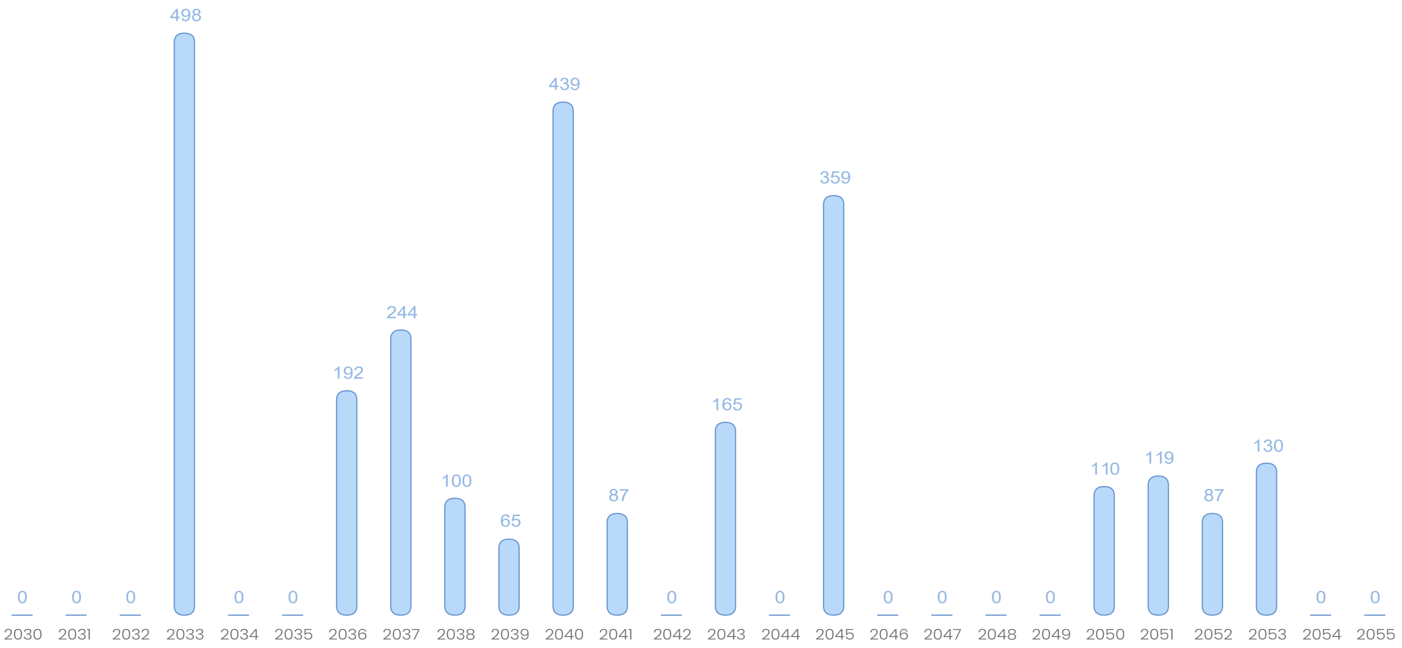
In this regard, it is considered that good maintenance also contributes to the minimisation of emissions during the operation of the infrastructure, as it allows for better management of traffic, speeds, and the energy consumption of the infrastructure in general, and enables the maximisation of its life cycle.

Railway infrastructure renovation phase

GHG emissions are generated, similar to the construction phase, especially linked to the manufacturing and transportation of materials, and their installation. In the case of the Spanish High-Speed Rail network, as the various elements of the 4,000 km network reach the end of their useful life, it is foreseeable that the renewal works will require a significant investment effort and, therefore, an increase in GHG emissions.

After 30 years since it was put into service, the comprehensive renovation works of the Madrid – Seville High-Speed line are already underway, aimed at refurbishing viaducts and tunnels, as well as superstructure elements, signalling and telecommunications installations, and other facilities. From 2033, the rest of the lines will reach 30 years since they were put into service, and will require new issues over the following decades. The proper quantification and optimisation of these will result in a reduced climate impact of the HS network.

HIGH-SPEED NETWORK (KM) CELEBRATES 30 YEARS SINCE BEING PUT INTO SERVICE



Source: Own elaboration

Decommissioning stage

The life cycle ends with the decommissioning stage of the infrastructure, in which the generation of emissions would be mainly associated with the movement of machinery necessary for the removal, transport, and treatment of the waste generated. The Carbontrack360 tool, for the moment, excludes the emissions generated in these two stages, but it is undoubtedly an area to delve into in the future.

Rail vehicles follow approximately the same stages already mentioned. The manufacturing of rolling stock generates emissions due to the production of materials such as steel, aluminium, and other components, as well as the energy used in the manufacturing process. Similarly, its maintenance during the operational phase and its subsequent renewal and scrapping also generate emissions. These emissions are reduced in comparison with the emissions linked to the infrastructure, and for the moment they are not included in the Carbontrack360 tool.

The railway mode must increase efforts in efficiency and improvement in construction by promoting low-carbon construction, especially in the phase of selection and use of eco-friendly materials, which is where most GHG emissions are generated. Despite the low or zero CO_2 emissions during its operation allowing for a more sustainable assessment of the railway mode, there is still significant room for improvement in global emissions during the construction and renovation stages to make this mode of transport more sustainable throughout its entire life cycle.

EMISSIONS IN AIR MODE

When discussing the climate impact of air transport, it is common to focus on the emissions produced during operation. And rightly so: that stage represents, by far, the majority of the total. However, if we want to compare the aeroplane with other modes of transport in a neutral way, it is important to also take into account the emissions associated with the construction and maintenance of airport infrastructures. In doing so, it is confirmed that the bulk of the impact remains in the operation, but coherence and the ability for comparative analysis are gained.

Thus, due to the characteristics and dimensions of airport infrastructures, the **construction stage** accounts for less than 5% of total emissions in the complete life cycle.

The emissions from the **operational stage** of domestic air transport in Spain accounted for 1.2% of the total emissions in the year 2023, and since 2005 these emissions have been reduced by 18.2%[2]. In Europe, the emissions from domestic air transport of each country accounted for 0.42% of the total emissions in 2023 (a lower percentage than in Spain) and similarly decreased by -20.2% since 2005 . This difference is mainly due to the territorial extension of Spain and the existence of two archipelagos that rely heavily on-air transport.

In this regard, it is important to highlight that, according to the rules established within the framework of the United Nations Framework Convention on Climate Change (UNFCCC) and the International Civil Aviation Organization (ICAO), emissions from international transport are not assigned to the total national emissions and are reported separately (pro memoria) due to the cross-border nature of international air transport and to avoid double counting.

Currently, some actions are being developed that will significantly contribute to the reduction of emissions during the operational phase.

The use of sustainable aviation fuels will reduce emissions in the medium and long term

In September 2023[4], the European Parliament approved the RefuelEU initiative, whose main objective is to promote the use of sustainable aviation fuels (SAF), including synthetic aviation fuels, biofuels[5], and recycled carbon fuels, which replace conventional fuels, are fully miscible with them, and are compatible with existing aircraft engines.

It is important to clarify that SAFs release CO_2 during their combustion. However, this carbon comes from renewable sources (biomass, organic waste, captured CO_2, used oils, etc.) and was therefore previously absorbed from the environment during the growth of the plants or the production of the raw material. In general, net GHG emissions are reduced by between 50% and 80% compared to traditional fuels, depending on the type of SAF and its production process.

TYPOLOGY OF SUSTAINABLE AVIATION FUELS (SAF)

SYNTHETIC AVIATION FUEL

Liquid or gaseous fuels other than biofuels and biogas, whose energy content comes from sources other than biomass and are renewable

BIOFUEL

Produced from used cooking oil or animal fats

ADVANCED BIOFUELS

Produced from other raw materials such as algae, biomass, bio-waste, and others

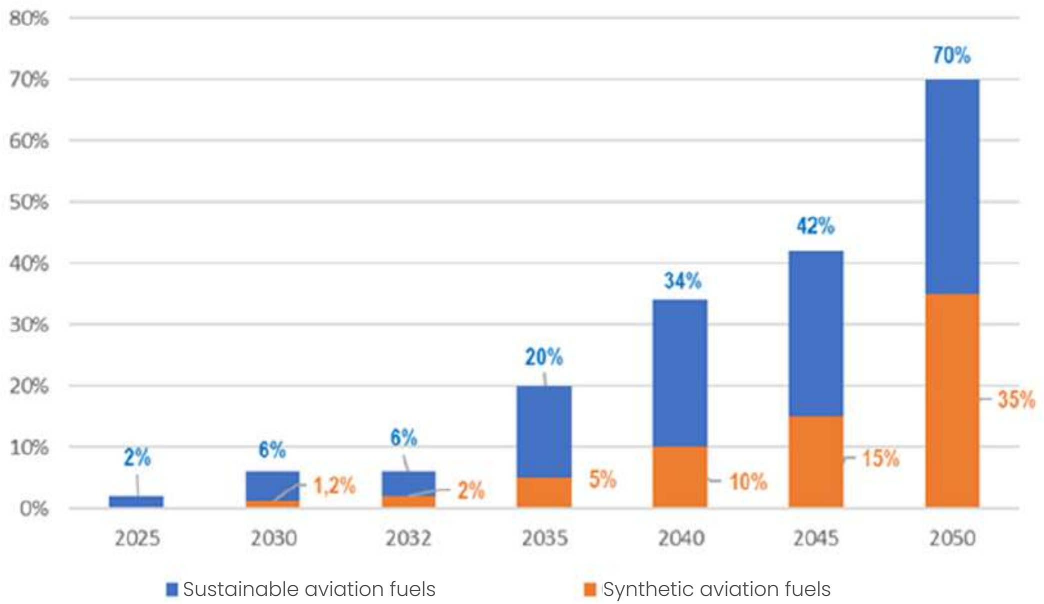
RECYCLED CARBON-BASED AVIATION FUEL

Produced from non-renewable liquid or solid waste streams that are not suitable for material recovery or from non-renewable residual gases produced as an

Source: ReFuelEU Aviation and Directive 2018/2001 on the promotion of the use of energy from renewable sources

The ReFuelEU Aviation Regulation establishes EU-wide obligations for aviation fuel suppliers, air operators, and airports to increase the SAF used on flights departing from airports above certain traffic thresholds (800,000 pax/year or 100,000 t/year). Specifically, from 2025, aviation fuel suppliers must provide a minimum blend of 2% SAF with conventional fuels to Union airports, which will gradually increase to at least 70% by 2050, and the share of synthetic aviation fuels will rise from 1.2% in 2030 to 35% in 2050.

PERCENTAGE OF MINIMUM SUSTAINABLE AVIATION FUELS THAT MUST BE AVAILABLE AT EUROPEAN UNION AIRPORTS



ReFuelEU AviationReFuelEU Aviation and Directive 2018/2001 on the promotion of the use of energy from renewable sources

In total, according to EASA[6], compliance with the mandate for the supply of sustainable aviation fuels under ReFuelEU Aviation could reduce net CO_2 emissions by at least 65 million tonnes (47%) by 2050.

But the challenge lies not only in its distribution, but also in its production. In 2023, in Spain, 25,221 m3 of SAF for aviation were produced, according to statistics from the Ministry for Ecological Transition and the Demographic[7] Challenge, which represents 0.3% of the total aviation fuels consumed, according to CORES statistics. Globally, in 2024, SAF production accounted for 0.53% of aircraft fuel use. It is necessary to significantly expand production capacity to meet future mandates and targets, since, although the 4.1 million m3 of SAF required under ReFuelEU Aviation could be supplied in 2030, production would need to be rapidly increased thereafter.

There is clearly a path for improvement in SAF production, in which Spain has great potential for leadership due to several factors, such as its abundance of natural resources, its technological capacity, and its commitment to sustainability and renewable energy. In the early stages of this development, public sector momentum could be decisive for consolidating a competitive national industry, accelerating the deployment of productive capacities, and positioning Spain as a European reference in the production of sustainable aviation fuels.

Management of air traffic and the use of new technology will also contribute, although to a lesser extent, to the reduction of emissions.

Improving air traffic efficiency through optimising its management can help reduce route distances, delays and waiting times in the air, and therefore, fuel consumption and greenhouse gas emissions.

In 2024, the new Single European Sky Regulation (SES2+)[8] was approved with the aim of strengthening air traffic safety standards, contributing to the sustainable development of the air transport system, and improving the overall performance of air traffic management and air navigation services for general air traffic in Europe. In other words, it establishes a legal framework that promotes a more efficient and sustainable management of airspace.

In this regard, the Traffic[9] Management Master Plan will be a key tool in the decarbonisation of air transport, and it is estimated that it could save up to 400 million tonnes of CO2 by 2050.

In 2017, ICAO approved a new standard that set maximum limits for CO_2 emissions per unit of work (such as per passenger-kilometre) for new aircraft, which encourages the design and use of more fuel-efficient planes, thereby directly reducing CO_2 emissions. This regulation came into force in 2020 for the design of new aircraft and from 2028 it will be mandatory for aircraft in production. It is expected to generate an average reduction of 4% in fuel consumption during the cruise phase of the new aircraft.

These technological and airspace management improvements will be developed and implemented over the coming decades. The emissions trading scheme (ETS) will serve as a lever for its implementation and, at the same time, will stabilise operational aviation emissions in the short term.

Since 2013, aviation has been subject to the emissions trading system (EU ETS)[10] , which is governed by the principle that "the polluter pays". Airlines must surrender emission allowances to cover their emissions, although they had free emission allowances. One of the key aspects of the reform proposed in the Fit for 55 legislative package is that these rights will be gradually phased out from 2026 to 2034, and, in addition, an aviation emissions cap will be imposed.

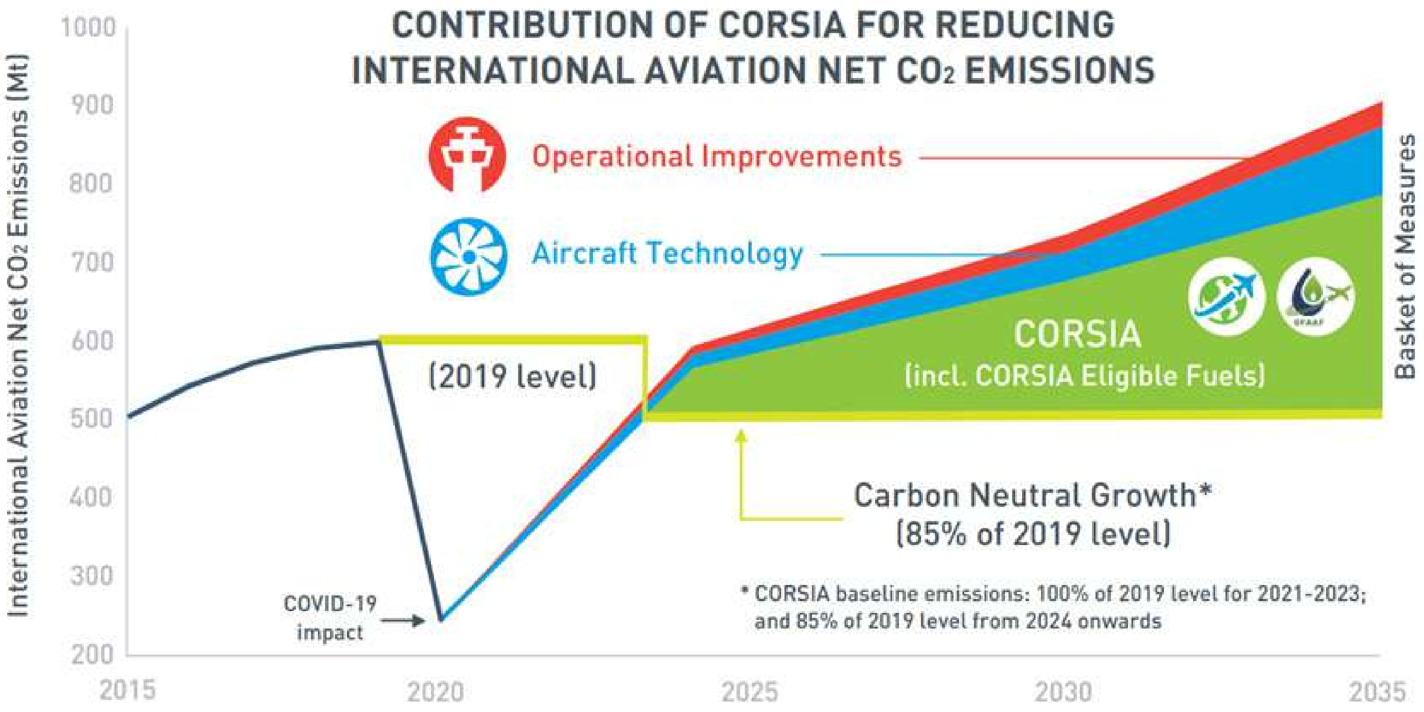
During the period 2013-2023, the EU ETS resulted in a net reduction of CO_2 emissions in aviation by 206 million tonnes through the financing of emission reductions in other sectors, of which 47 million tonnes were in the period 2021-2023[11]. This represented 35% of the total CO_2 emissions reduced during that period within the framework of the EU ETS.

This system only applies to flights within the European Economic Area (EEA). However, to limit GHG emissions from international air transport, ICAO has developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Its main objective is to stabilise CO_2 emissions from the aviation sector at 2020 levels, through the offsetting of emissions that exceed a certain threshold. The scheme is implemented in phases: a pilot phase (2021-2023), an initial voluntary phase (2024-2026), and a mandatory phase from 2027 for the majority of countries (fig. next page).

Stages of exploitation and maintenance of airport infrastructure, as well as the stages of renovation and, where applicable, dismantling, are of lesser importance compared to the operation of the air mode.

Similarly, the manufacturing, maintenance, and scrapping of aircraft are very minor compared to the total life cycle in this mode and have not yet been included in the Carbontrack360 tool.

As a general conclusion regarding air transport emissions, it can be highlighted that there are numerous initiatives from international and European public administrations to reduce emissions during the operational phase of air transport, and all of them will contribute to reducing the impact that this sector has on greenhouse gas emissions.



CONTRIBUTION OF CORSIA FOR REDUCING
INTERNATIONAL AVIATION NET CO_2 EMISSIONS
International Aviation Net CO_2 Emissions (Mt)
1000
900
800
700
600
500
400
300
200
2015
2020
2025
2030
2035
Operational Improvements
Aircraft Technology
(2019 level)
CORSIA
(incl. CORSIA Eligible Fuels)
Basket of Measures
COVID-19 impact
Carbon Neutral Growth*
(85% of 2019 level)
* CORSIA baseline emissions: 100% of 2019 level for 2021-2023; and 85% of 2019 level from 2024 onwards

5 CARBONTRACK360. MOTIVATION AND ASSUMPTIONS

CarbonTrack360 aims to be a tool for reflection, allowing the visualisation of the impact on GHG emissions in the air mode and high-speed rail at the various stages of development and operation of infrastructure and transport services.

The air mode, currently with higher emissions in operation compared to other modes, however, has a lower impact during the construction phase. High-speed rail, with zero emissions during operation since 2019, conversely has high emissions during the construction phase. Both modes have been competitors, especially in the peninsular area, as collective transport modes with similar features and aimed at similar types of journeys and travellers, which makes the comparison more relevant.

The road has been excluded from the exercise, despite being the mode that contributes the most to GHG emissions, because its infrastructures constitute a basic capital of accessibility and territorial cohesion that cannot be weighed in the same balance. In any case, it may be interesting in the future to add this mode to the comparison to find lessons learned and areas for improvement.

The complete life cycle analysis of transport infrastructure is an extensive field that is evolving and deepening, with numerous recent academic publications. This exercise does not aim to advance further in that knowledge, nor to replace it, but rather, on the contrary, to simplify it, contribute to its dissemination and generalise reflection in these terms in the field of GHG emissions.

For this reason, CarbonTrack360 is built on specific values and parameters, extracted from available sources, with the aim of making estimates of the evolution of emission accumulation in different scenarios.

The first phase, which does not generate emissions directly but is fundamental for making the best decisions from the start, is Planning and Design, in which transportation needs are identified, feasibility studies are conducted, and the infrastructure is technically designed. It is crucial to consider environmental and social impacts from the beginning to minimize negative effects in the future.

Simulator and real cases

CarbonTrack360 allows the simulation of a generic case of connection between two points, introducing a series of aspects regarding demand, modal distribution, and planned infrastructures (size of airports, type of terrain, distances).

The tool also allows for reflection on real cases: the evolution over the last 35 years, from the beginning of the construction of the Madrid-Seville AVE, of the network of airports and high-speed rail infrastructures, or certain characteristic corridors of our transport system.

Stages and activities included in the tool

The tool includes the stages of construction and maintenance of the infrastructure, and the operation of transport services.

The emissions generated during the renewal and dismantling stages of the infrastructures have not been taken into consideration due to a lack of verified information, despite the fact that the useful life of some of the subsystems would fall within the proposed time range.

Activities related to vehicles (railway rolling stock and aircraft) in their manufacture, maintenance, and dismantling have also not been included for the time being.

These are areas that could be explored further in the future, improving and completing the evaluations that are carried out.

Parameters

The analysis is largely based on the Technical Report conducted by the Directorate General for Quality and Environmental Assessment and Natural Environment of the Ministry for Ecological Transition and Demographic Challenge, Recommendations for the estimation of GHG emissions in the environmental assessment of transport plans and projects, from 2015, hereafter referred to as MITERD Recommendations. Despite not being recent, it is a well-established and comprehensive source, covering the different modes and stages, which ensures the relevance of the comparison.

For the analysis of GHG emissions during the operational stage of the air mode, the average emissions obtained from the ICAO Carbon Emissions Calculator (ICEC[12]) are used, along with the distances recorded from EUROCONTROL databases, and the air demand in each peninsular connection from 1989 to 2024 from statistical yearbooks and Aena records. The weighted result is an average emission of 124 g CO_2/pax·km, or 71 kg CO_2/pax journey.

In the railway mode, Adif Alta Velocidad has had contracts for the supply of renewable GdO energy for the railway system since 2019. Therefore, from that year onwards, emissions from high-speed rail operations are considered null. For previous years, the average emission factors from the MITERD Recommendations for 2020 are used, from which, to align the analysis with the air mode, emissions associated with the manufacturing and scrapping of vehicles, and other emissions from uses other than traction, are subtracted. The result is an emission factor up to 2019, of 20.68 g CO_2e/trip·km, from then on, zero.

To quantify the GHG emissions from airport infrastructure construction as well as its maintenance and operation, the parameters established in the MITERD Recommendations are used, making some assumptions about them.

In the case of the construction of high-speed rail infrastructure, emissions are strongly linked to earthworks during construction and the supply of materials for structures and tunnels. This makes them very sensitive to the orography on which the infrastructure is built, which is why the MITERD Recommendations provide a very wide range for emissions per kilometre of infrastructure, from 4,000 t CO_2/km for flat terrain to 24,000 for rugged terrain.

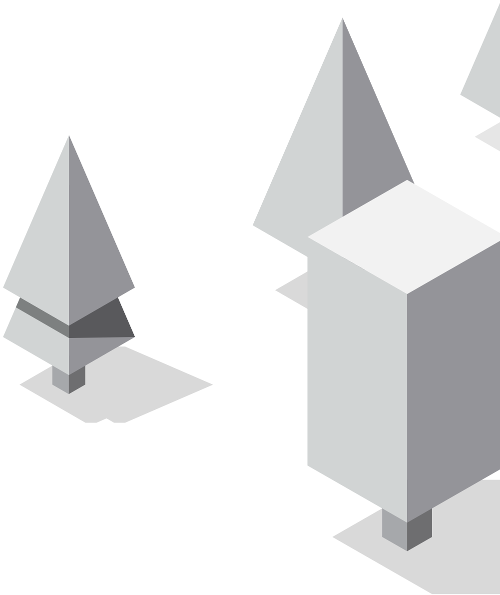
For the estimation of emissions in the construction of the high-speed network in recent decades, the construction cost per kilometre of each line has been taken as an indicator of the terrain's accident rate.

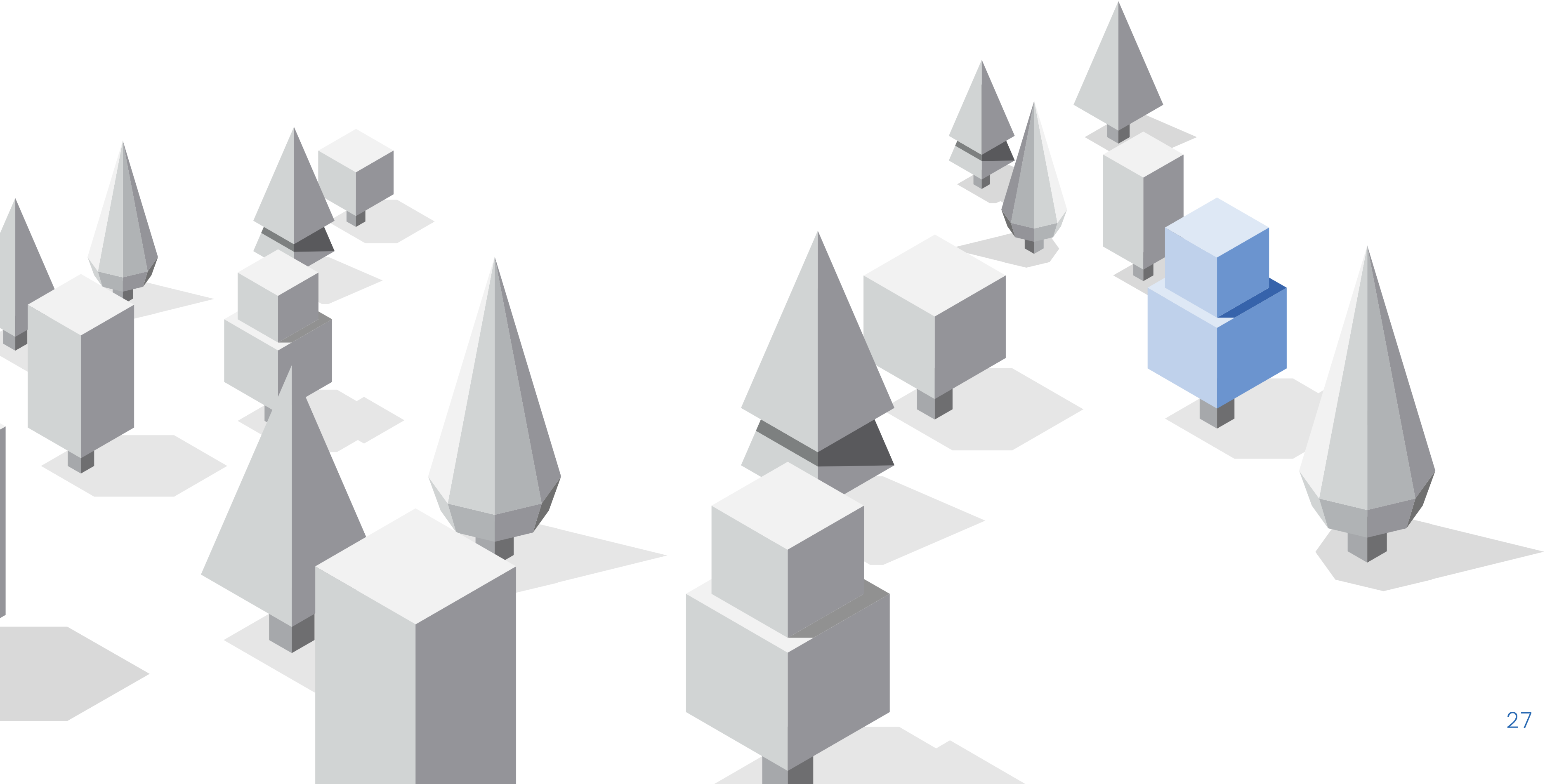
The maintenance emissions of the High-Speed infrastructure are also taken from the MITERD Recommendations.

Other considerations

The relationship between infrastructure and demand volumes is a topic that is not settled, and therefore the calculator makes some assumptions and also allows the user to modify them. However, no limits are set on the demand that could be managed at an airport depending on its size, nor on the demand that could be transported on a high-speed line.

CarbonTrack360 does not aim to close the debate, but to enrich it and make it more operational, offering a neutral comparison between very different modes of transport in their development and operation. Below are some exercises based on the calculator that yield concrete results and allow for the extraction of relevant conclusions.





IDENTIFY THE KEYS TO CLIMATE EFFICIENCY

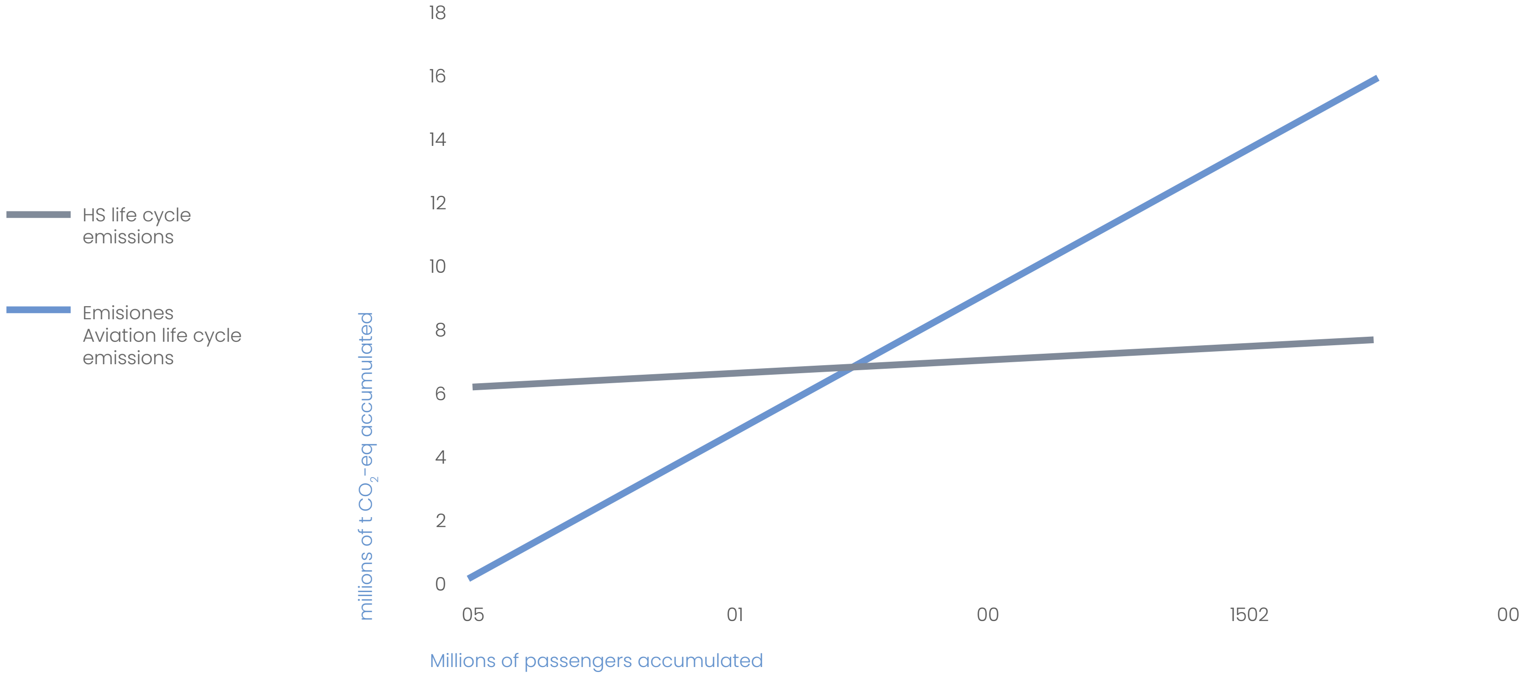
Demand, a key factor in emissions efficiency.

As an example, the generic case of the connection between two distant points (600 km) is taken, and it is assumed, on one hand, the construction of two airports, one “large” and one “medium”, and on the other, the construction of a high-speed railway line between both points, with the terrain between them being of medium difficulty.

The accumulated emissions from the construction of the railway mode would be slightly over 6 million tonnes of CO_2e, while those attributable to this relationship from the construction of airports would not reach 150,000 tonnes. However, in the operation, maintenance, and exploitation stage, railway emissions stabilise, with a slight increase due to the annual maintenance of the infrastructure, while those of the air mode are proportional to the number of passengers (and therefore, of flights).

The point at which the accumulated emissions lines of the rail mode and the air mode intersect represents the efficiency threshold, from which the emissions generated in the construction of the High-Speed line plus the emissions from its maintenance would be lower than those that would have been generated by the construction of the airports and the operation of the flights necessary to transport a number X of passengers, in this case, 74 million (fig. on the next page).

ACCUMULATED GHG EMISSIONS ACCORDING TO ACCUMULATED DEMAND



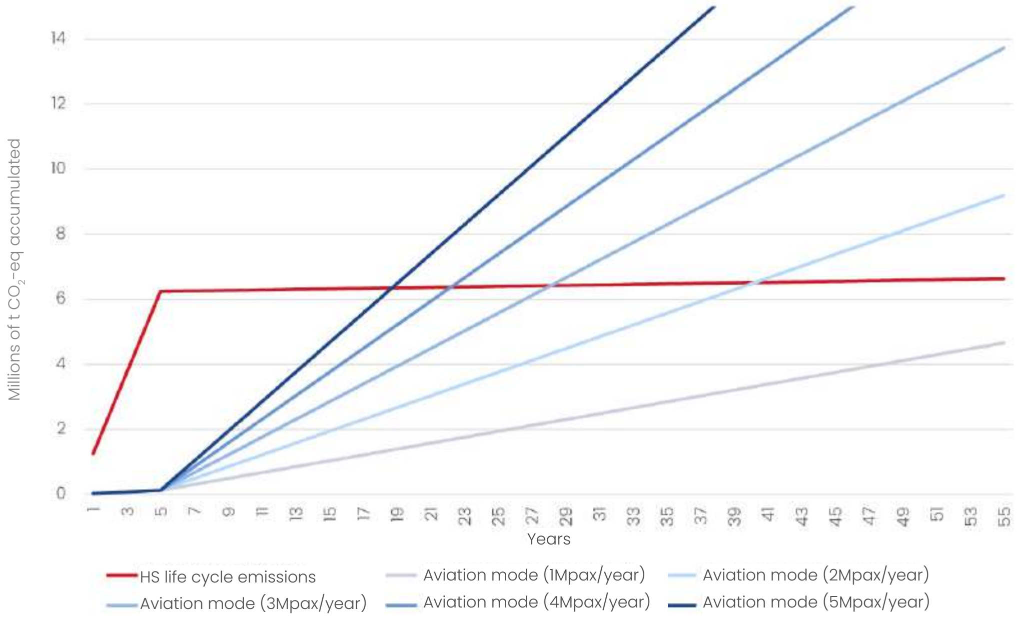
When putting this reasoning in a temporal perspective, one can see how the climate efficiency of each mode depends on its annual demand. While, for 1 million passengers a year, the air mode would accumulate fewer emissions than the railway even in 50 years of operation, for 5 million passengers a year, it would exceed in 14 years of operation the emissions generated by the construction of the railway infrastructure (fig. on the right).

A threshold of efficiency that is stable with respect to distance but not with respect to terrain type.

Distance is a factor that works against both modes when considering the life cycle: in the air mode, because the journey distance increases and therefore the GHG emissions of each flight. In the railway mode, because GHG emissions increase due to the construction of the infrastructure.

This double effect leads to obtaining efficiency thresholds (the number of accumulated travellers from which the emissions of the air mode would exceed those of the rail mode) similar in relationships of very different distances.

ACCUMULATED GHG EMISSIONS OVER TIME BY MODE AND ACCORDING TO DEMAND



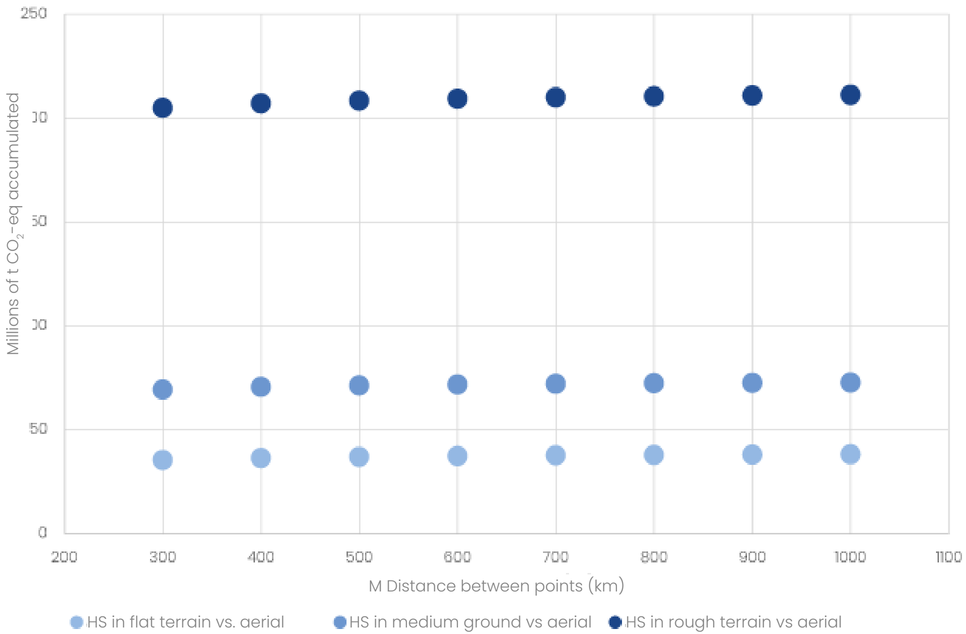
Source: Own elaboration

The type of terrain is indeed decisive in this efficiency threshold. In the example being analysed, if the land on which the railway line is built were flat, these emissions would be equivalent to transporting about 40 million passengers by air. In the case of rough terrain, it would be equivalent to transporting more than 200 million passengers. This is due to the significant difference in GHG emissions from the construction of high-speed rail infrastructure depending on the type of terrain, given the 6:1 ratio between construction emissions on rough terrain compared to flat terrain (next figure).

The focus of attention: the operation of the aerial mode and the construction of the railway.

Over a 50-year period of operation, with a demand of 1 million passengers annually, the accumulated GHG emissions generated by the air mode would be due 95% to operation, compared to 3% from construction and 2% from maintenance. In the case of high-speed rail, on the contrary, construction would have generated 94% of the GHG emissions. This analysis does not currently cover the stages of renewal and dismantling, nor the

EFFICIENCY THRESHOLD AS A FUNCTION OF DISTANCE AND TERRAIN CHARACTERISTICS



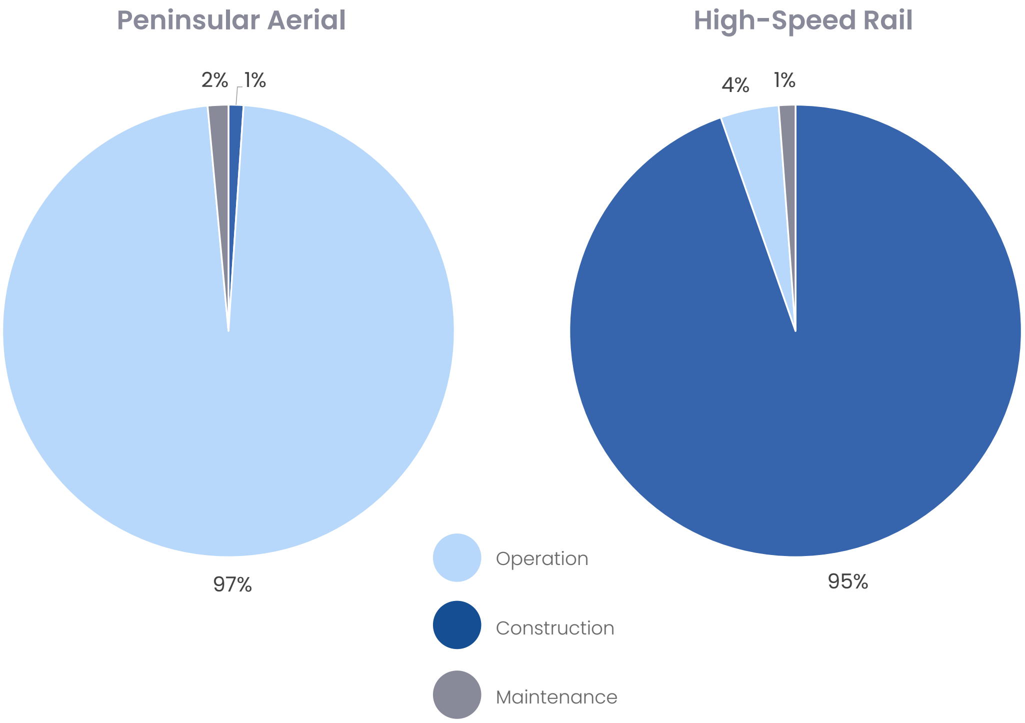
Source: Own elaboration

emissions associated with the manufacturing, maintenance, and scrapping of vehicles, but the decisiveness of the comparison allows for clear conclusions to be drawn.

It is evident that the aviation sector must focus its efforts on reducing emissions during the operational phase, as this will have a greater impact on the overall efficiency of the system. The importance of emissions from the construction stage or the maintenance of airports is very small compared to the operation of the air mode itself or compared to railway construction.

In the railway mode, considering that the operational stage does not generate emissions (due to energy contracts with renewable GdO), the focus must be on construction and the optimisation of its emissions (fig. on the right).

DISTRIBUTION OF ACCUMULATED EMISSIONS BY STAGE AND MODE IN THE LIFE CYCLE



Source: Own elaboration

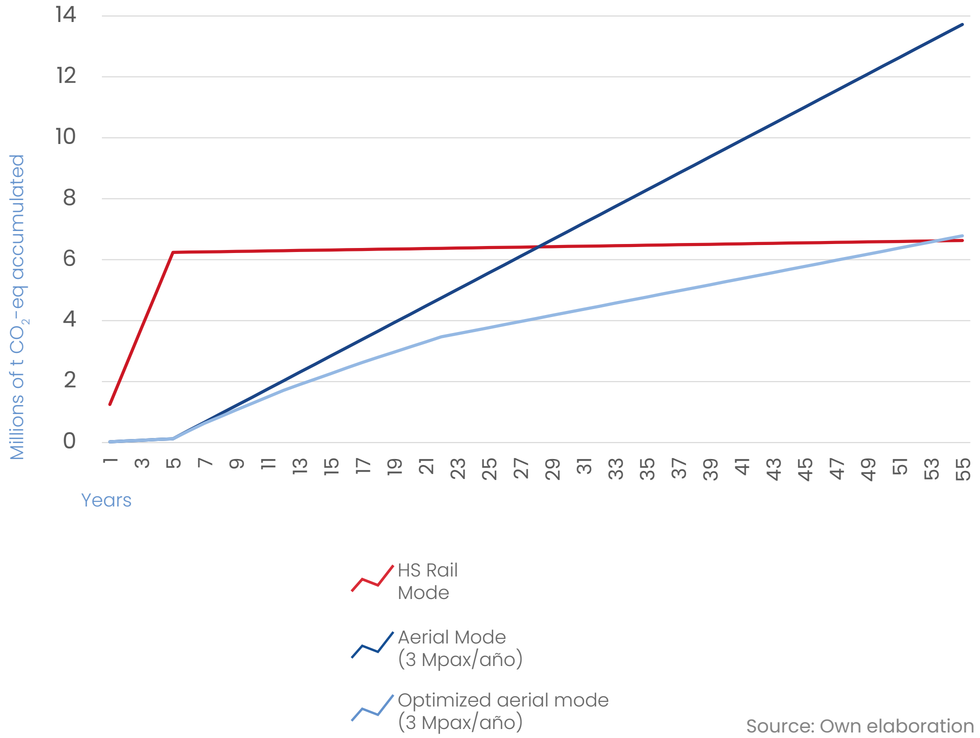
The reduction of emissions in air operations will transform the comparison between modes.

The aviation sector has been working for years on reducing its operational emissions, improving fuels, airspace management, and the aircraft themselves, and still has room for progress in the coming decades. The different proposals included in the Fit for 55 programme to reduce GHG emissions in the EU could reduce GHG emissions per unit of transport by up to 63%, in different stages.

Taking the previously analysed example, it can be seen how, for an annual demand of 3 million passengers, with the current GHG emission rates, the air mode, starting from year 22 of operation, would have emitted more than the rail mode. If we consider the emission reduction steps outlined in Fit for 55, this will occur in 50 years of operation.

The air mode has the opportunity to transform its climate impact and improve its positioning compared to other modes (next fig.)..

ACCUMULATED GHG EMISSIONS IN RAIL, AIR, AND OPTIMISED AIR MODES



Source: Own elaboration

A VISION OF THE SPANISH NETWORK

The entire network

In the last three decades, Spain has undergone an impressive process of modernising its transport infrastructure. The inauguration of **strategic airport terminals**, together with the development of **high-speed rail,** has consolidated a modern network that began its transformation with the construction of the motorway network that started in the 1980s.

This transformation has generated multiple benefits, but it also poses new challenges in terms of sustainability. Understanding its impact from a broad and rigorous perspective is essential for designing effective strategies towards a truly sustainable transport future.

This analysis focuses on the GHG emissions specifically generated by **mainland air transport and high-speed rail**, leaving aside other modes of transport and activity segments to obtain more precise and comparable results.

In **air transport**, all peninsular traffic is included, regardless of the existence of high-speed alternative connections (these pairs account for 63% of peninsular demand). Emissions from extra-peninsular and international air transport are not considered, as they cannot be replaced by rail and yet constitute the majority of air traffic in Spain.

In the case of rail transport, other uses of the constructed network have not been included, such as the AVANT Medium Distance services (24% of the passengers who used the high-speed network in 2023) or Alvia, Altaria, and Euromed services (14%).

Furthermore, the study does not consider the phase of **infrastructure renewal or its dismantling after the useful life** of its elements, due to the lack of verified information. This aspect is especially relevant in the case of High-Speed Rail, where construction accounts for a very high percentage of total emissions. Components such as the **manufacturing, maintenance, and dismantling of vehicles** have also not been considered, which also influences the global impact.

Therefore, this exercise does not aim to provide an exhaustive comparison or an absolute judgement on past or present policies. Rather, it seeks to provide clarity on the **orders of magnitude between modes of transport and demystify preconceived** ideas, facilitating a more informed and rigorous debate towards a more sustainable transport future.

Since 1989, key airport terminals have been constructed and expanded in Spain, such as **Madrid (1998 and 2006), Barcelona (2004 and 2009), and Málaga (2010 and 2012)**. In total, **2.4 million m² of terminals and 9.2 million m² of runways have been built.** These expansions have served the entirety of air traffic, and 11.5%[13] of the emissions resulting from the construction are attributed to domestic traffic.

On the other hand, the deployment of **high-speed rail** has resulted in nearly **4,000 km of lines being put into service** in the same period, on which simplified hypotheses have been made regarding the distribution over time of GHG emissions from their construction. In addition, maintenance emissions are accounted for and added as sections are put into service.

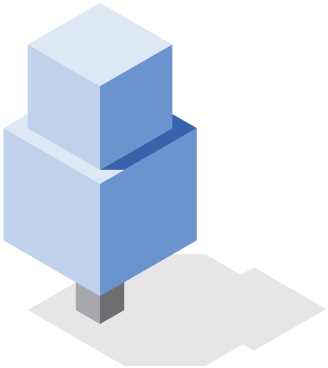
As a result, during these three decades, peninsular air transport has generated **45 Mt CO_2e**, while high-speed rail has emitted **50 Mt CO_2e**. Rail emissions have been stabilizing in recent years thanks to the completion of major projects and the exclusive use of renewable energy since 2019.

This analysis shows the importance of considering **the entire life cycle of infrastructures** and not just the operational phase, in order to truly understand the climate impact of each mode of transport.

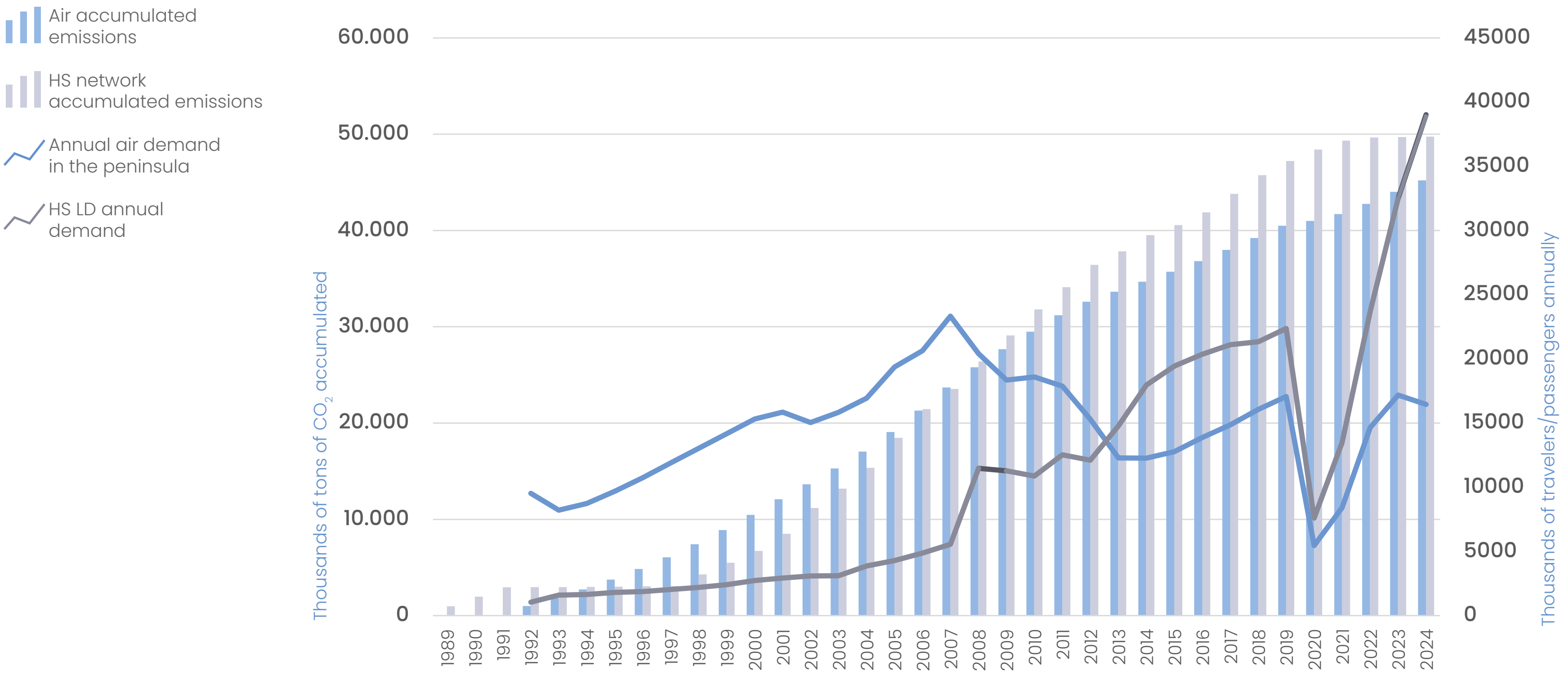
During this period, the demand in this segment of long-distance mainland travel has experienced strong growth (+162%), as well as a significant change in trend, as the high-speed network expanded, driven by the liberalisation of railway services in recent years. In 2024, the demand for Long-Distance High-Speed Rail nearly reached 40 million travellers, compared to 16 million passengers for domestic air transport, which has not surpassed the level reached in 2007 and has shown a declining trend since then.

The construction of the High-Speed network has involved a significant effort in investments and emissions. However, the success in demand means that the accumulated emissions per high-speed traveller have drastically reduced in recent years, reaching 139 kg CO_2e per accumulated traveller by 2024.

The aviation sector has already achieved significant reductions in its greenhouse gas emissions due to improvements in aircraft and engines, resulting in emissions of 94 kg CO_2e per accumulated passenger (next fig.).



CUMULATIVE EMISSIONS FROM THE MAINLAND AIR TRANSPORT VS. HIGH-SPEED RAIL NETWORK

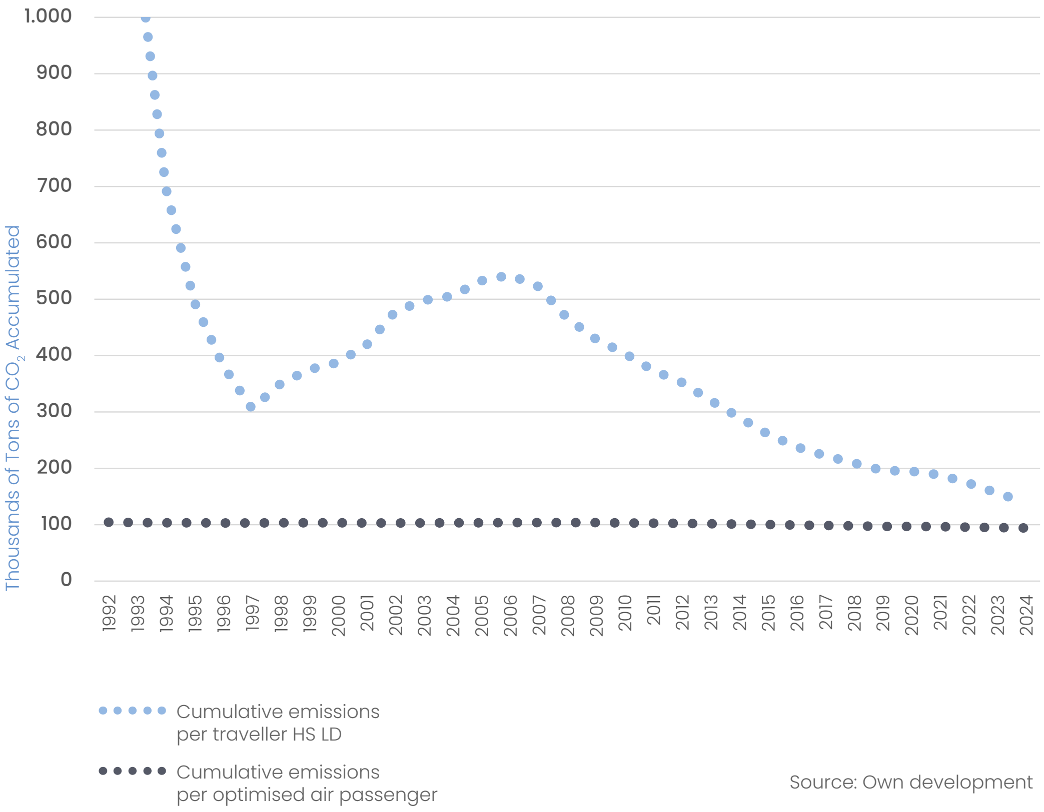


Source: Own development

This graph (next fig.) allows us to appreciate the different temporal profile of emissions in both modes. The railway emits practically all of its emissions at the beginning and must "amortise" them over time, whereas the air mode emits them as flights occur.

A key result of the analysis is that the emissions from each mode of transport are generated in very different phases. In the case of **air transport, 97% of emissions** come from the operational phase, whereas, in **high-speed rail, an** overwhelming **95% of emissions are attributed to infrastructure** construction.

CUMULATIVE EMISSIONS PER PASSENGER/TRAVELER FOR EACH MODE

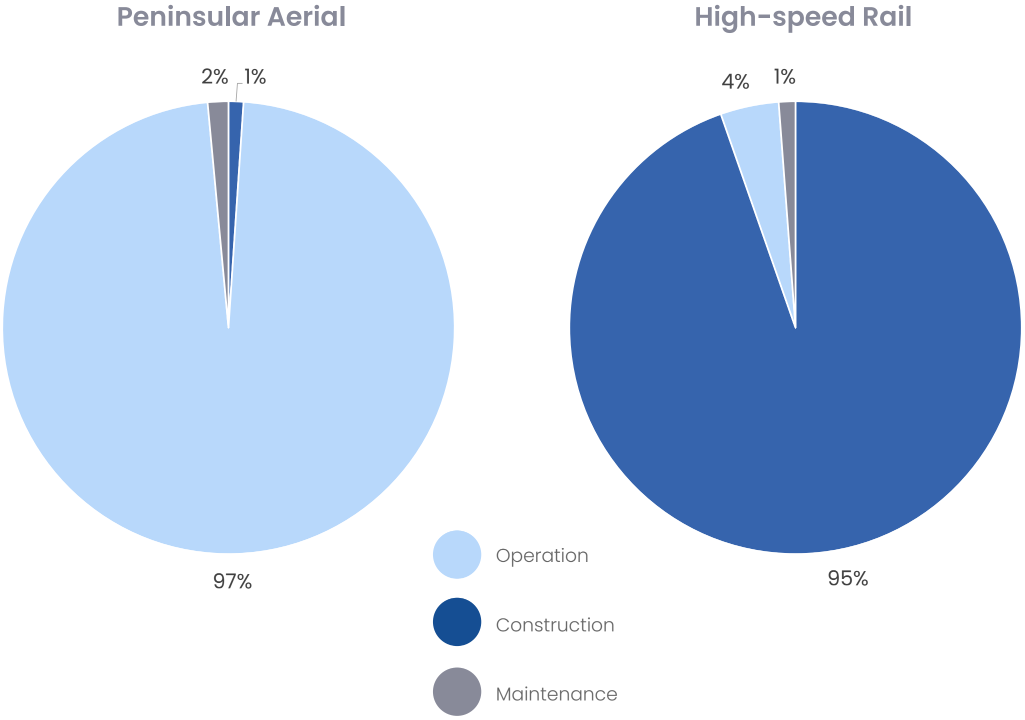


Source: Own development

This data is revealing because it clearly shows **where each mode should focus its efforts** to reduce emissions in the future: air transport, by continuing to optimise its operations; rail transport, by focusing on efficient and sustainable construction, especially in future renovations and expansions of the network.

Identifying these priorities is essential to ensure that decarbonisation strategies are effective and can have a real and lasting impact on the reduction of GHGs.

DISTRIBUTION OF ACCUMULATED EMISSIONS BY STAGE IN EACH MODE



Source: Own elaboration

Some Corridors

Adopting a corridor vision allows for refining the results obtained for the entire network, by specifying the main long-distance connections. This approach incorporates both the emissions generated during the construction of infrastructure and those arising from the operational stage.

In the case of the **railway mode**, however, this analysis loses the valuable **"network effect":** the ability of the same infrastructure to offer multiple additional connections within the peninsula. Furthermore, the circulation of Alvia trains, which partially use the High-Speed network, is excluded, as well as the AVANT services between intermediate points, which have no equivalent in air travel.

Understanding these differences is essential for formulating effective strategies that maximise the efficiency and sustainability of the transport system.

Three corridors are included in the analysis:

Madrid – Córdoba – Sevilla / Málaga

This corridor is the one that allows for a longer period of analysis. The construction of the high-speed infrastructure is estimated to have generated 5.2 million t CO_2e, and in total, 6.1 million t CO_2e are reached, which include 11% of operational emissions (up to 2019).

The air mode accumulates 3.4 million t CO_2e during the period. The accumulated volume of railway demand, bolstered by the growth of recent years, means that the accumulated emissions per railway traveller (48 kg CO_2e) are lower than those of each air passenger (90 kg CO_2e).

Madrid – Zaragoza – Barcelona

In the case of the Madrid – Barcelona route, the emissions from the construction of the high-speed line (estimated at around 8 million t CO_2e) together with those from operation (up to 2019) and infrastructure maintenance, total 8.7 million t CO_2e in total. For its part, the air mode in the same period has emitted 5 million t CO_2e, 97% of which during the operation phase.

In this case, the accumulated emissions per air passenger (80 kg of CO_2e/pax) are still lower than those of rail travellers (88 kg of CO_2e/pax).

Madrid – Valencia / Alicante - Murcia

The Madrid – Levante corridor is the most recent of the three analysed, with estimated construction emissions of 6.9 million t CO_2e, and a total of railway mode emissions of 7.1 million t CO_2e in the analysed period.

Air demand has drastically reduced since the high-speed connection was put into service, having accumulated only 0.8 million tonnes of CO_2e during the period.

For the moment, the accumulated emissions per air passenger (85 kg of CO_2e/pax) remain lower than those of rail travellers (112 kg of CO_2e/pax).

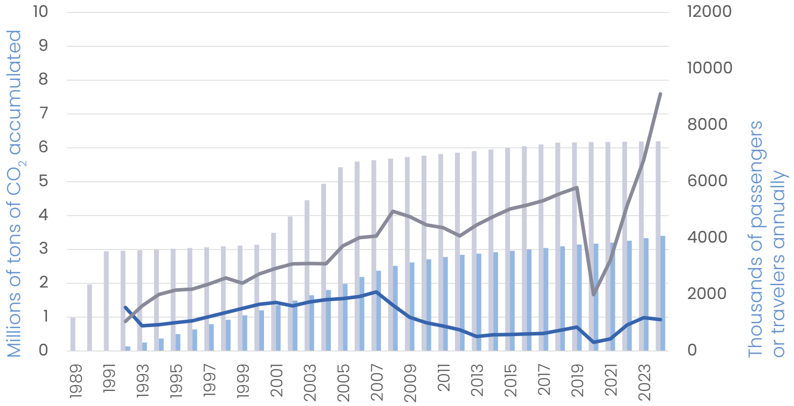
Total accumulated emissions in each mode by corridors

Cumulative Air Emissions

Cumulative Rail Network Emissions

Annual Air Corridor Demand

Annual HS Demand

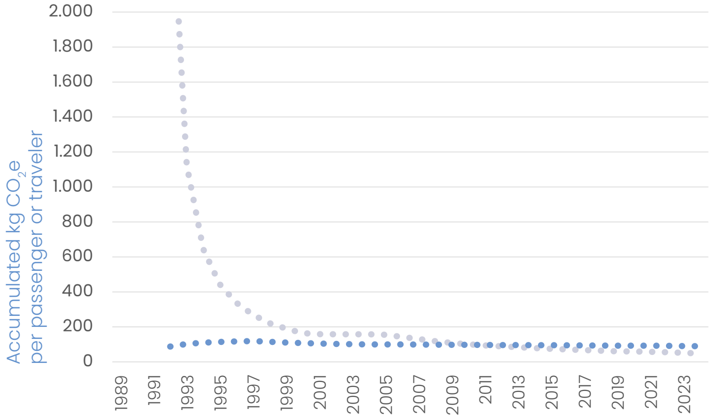


Madrid - Córdoba - Sevilla / Málaga

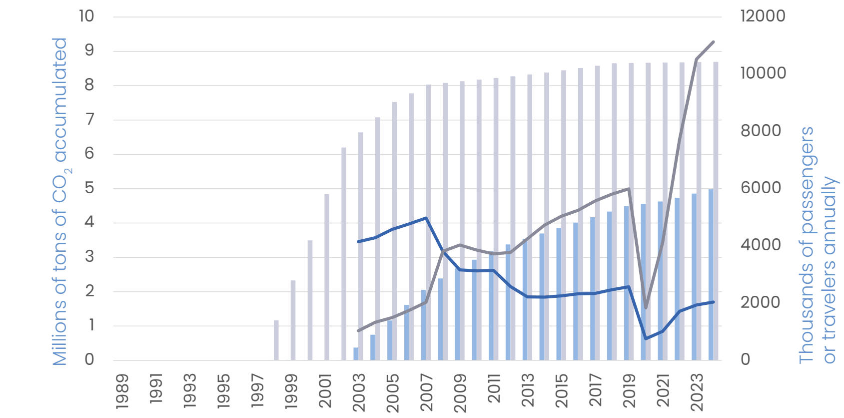
Total accumulated emissions and per passenger/traveler emissions accumulated in each mode by corridors

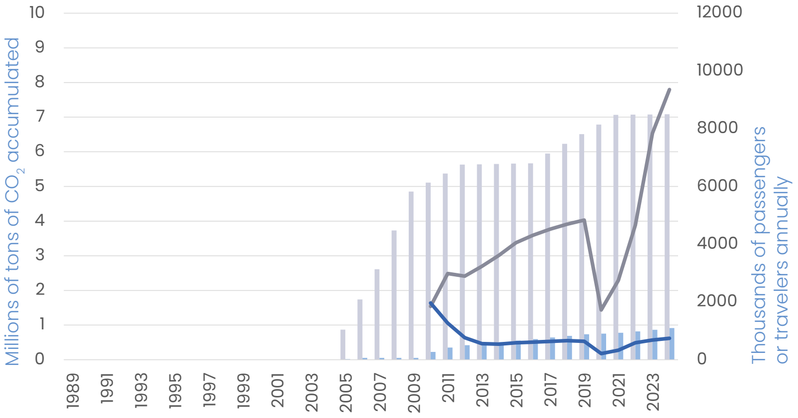
Accumulated emissions per air passenger

Accumulated emissions per rail traveler



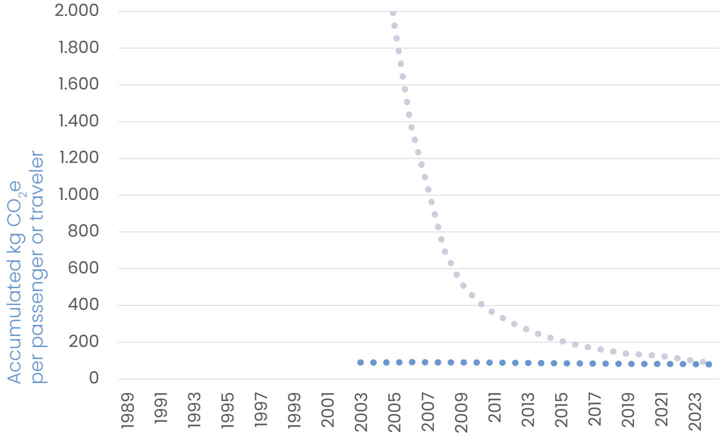
Source: Own development

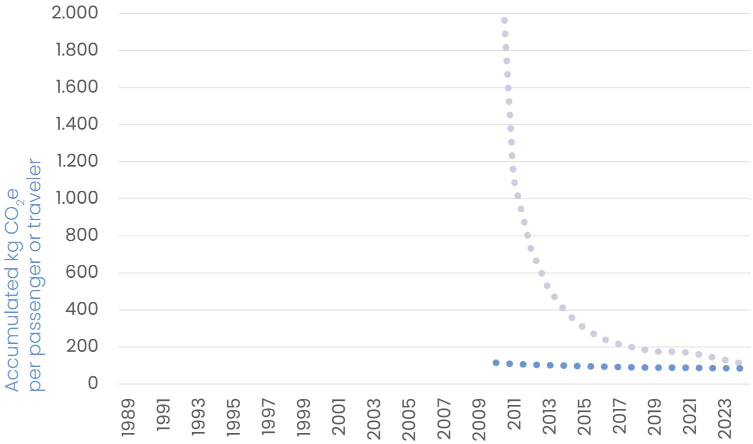




Madrid – Zaragoza - Barcelona

Madrid – Valencia / Alicante - Murcia





A 360º LOOK AT THE IMPACT OF TRANSPORT

In a context of global climate emergency, rethinking the transport system from an environmental perspective is a necessity. This report and the CarbonTrack360 tool that supports it, are created precisely with that purpose: to offer a complete, rigorous, and comprehensible view of the climate impact of transport, beyond traditional data.

For years, the debate on transport emissions has focused almost exclusively on the operational stage: how much a train or a plane pollutes while it is running. However, this partial view can lead to misleading conclusions. What happens with the emissions generated when constructing a high-speed rail line or an airport? And what about those produced during the maintenance or renovation of these infrastructures? How does the balance change if we consider the entire life cycle?

CarbonTrack360 answers these questions with a clear methodology: analysing the accumulated emissions over time, considering the different stages of the life cycle of the modes of transport. And results are revealing.

On the one hand, **air transport** concentrates the vast majority of its emissions during the operational phase. This means that any improvement at this stage (such as the use of sustainable fuels (SAF), air traffic optimisation or fleet renewal) has a direct and significant impact on the reduction of greenhouse gases. Despite the fact that the construction and maintenance of airports generate emissions, their impact on the total is very small.

On the other hand, **the high-speed railway**, which has been operating with 100% renewable energy in Spain since 2019, presents a very different profile: its emissions are concentrated in the construction phase. This includes the intensive use of materials such as concrete and steel, and the machinery necessary to build complex infrastructures, especially on rugged terrain. Although its operation is clean, the initial effort in emissions is considerable, and therefore, its climate efficiency largely depends on the demand it is able to absorb over time.

This is where CarbonTrack360 provides a key tool: it allows the identification of **so-called climate efficiency thresholds**. That is to say, the point from which one mode of transport starts to be more efficient than another in terms of accumulated emissions. For example, a high-speed line can surpass the aeroplane in efficiency if it carries enough passengers over a certain number of years. However, if the demand is low or the terrain very complex, that threshold may never be reached.

The analysis of actual corridors in Spain (such as Madrid-Seville, Madrid-Barcelona or Madrid-Levante) confirms this logic. In some cases, the railway has already surpassed the aeroplane in efficiency per passenger. In others, it has not yet done so, but it could achieve it if the growth in demand continues, and construction processes are optimised.

Beyond the numbers, this report sends a clear message: each mode of transport has its role, its strengths, and its challenges. It's not about choosing between train or plane, but about understanding in which context each is more efficient and how they can complement each other to build a more sustainable transport system.

The future lies in acting where the most impact can be achieved:

In the **air mode**, reducing operational emissions through technological innovation, new fuels, and more efficient airspace management.

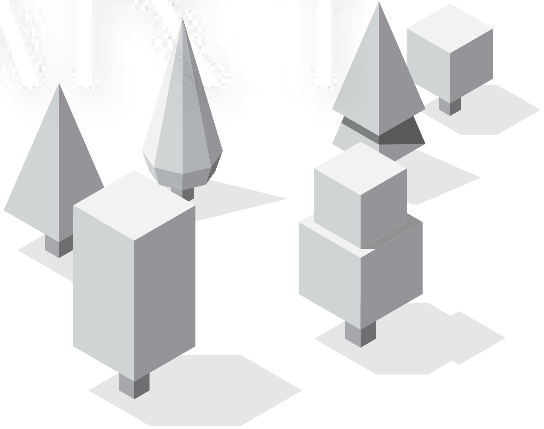
In the **railway mode**, focusing on more sustainable construction, with low-carbon materials and optimised processes, especially with a view to future renovations.

CarbonTrack360 is not a closed tool, but a starting point. Its value lies in providing a solid foundation for analysis, comparison, and informed decision-making. As new variables are incorporated (such as the manufacturing and scrapping of vehicles, or the renewal of infrastructures) their ability to anticipate impacts and guide policies will be even greater.

Ultimately, if we want to achieve climate goals realistically and effectively, we need tools like this: ones that not only measure, but also help to **understand, plan, and transform**. Because only with a complete vision of the life cycle can we build truly sustainable transport.

We hope that CarbonTrack360 will be a useful tool for advancing climate analysis in transport, contributing to a more comprehensive and rigorous reflection on its impact, and serving as a basis for more informed decisions. Our intention is for it to continue evolving, progressively incorporating those aspects that have not yet been considered. We will continue to listen attentively to the reactions, contributions, and suggestions of the various stakeholders involved, with the aim of improving and enriching this tool.

GLOSSARY



LCA: Life Cycle Assessment

SAF: Sustainable Aviation Fuels.

UNFCCC: United Nations Framework Convention on Climate Change

CNMC: National Competition Commission (Spain)

CORES: Corporation of Strategic Reserves of Petroleum Products

EASA: European Union Aviation Safety Agency

EEE: European Economic Area: an economic zone comprising the countries of the European Union (EU) and the three countries of the European Free Trade Association (EFTA) that are not members of the EU: Iceland, Liechtenstein, and Norway.

REGO: Renewable Energy Guarantee of Origin

GHG: Greenhouse Gases

ICEC: ICAO Carbon Emissions Calculator

ICAO: International Civil Aviation Organisation

ETS: Emissions Trading System

Refuel EU: Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport

SES2+: Single European Sky. Regulation (EU) 2024/2803 of the European Parliament and of the Council, of 23 October 2024, on the implementation of the Single European Sky.

NOTES

1 Regulated under Circular 2/2021 of the CNMC
https://www.boe.es/buscar/act.php?id=BOE-A-2021-2570

2 Spanish System for Inventory of Emissions.
https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/sistema-espanol-de-inventario-sei-.html

3 Eurostat
https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_16784757/default/table?lang=en

4 Refuel Aviation
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023AP0319&qid=1747737438824

5 Aviation biofuels produced from food and fodder crops, including biofuels with high risk of indirect land-use change, are not admissible.

6 European Aviation Environmental Report 2025
https://www.easa.europa.eu/sites/default/files/eaer-downloads/EASA_EAER_2025_BROCHURE_WEB_es_v2.pdf

7 Biofuel statistics
https://www.miteco.gob.es/es/energia/hidrocarburos-nuevos-combustibles/biocarburantes/estadisticas.html

8 SES2+
https://eur-lex.europa.eu/legal-content/es/ALL/?uri=CELEX:32024R2803

9 SESAR Master Plan 2025
https://www.sesarju.eu/sites/default/files/documents/reports/SESAR%20Master%20Plan%202025.pdf

10 RCDE-UE
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20240301

11 European Aviation Environmental Report 2025
https://www.easa.europa.eu/sites/default/files/eaer-downloads/EASA_EAER_2025_BROCHURE_WEB_es_v2.pdf

12 ICAO Carbon Emissions Calculator (ICEC)
https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

13 The percentage has been taken as the share of peninsular passengers relative to the total number of passengers in Spain; however, in a minimum-investment approach to meet this demand, the emissions would probably be higher

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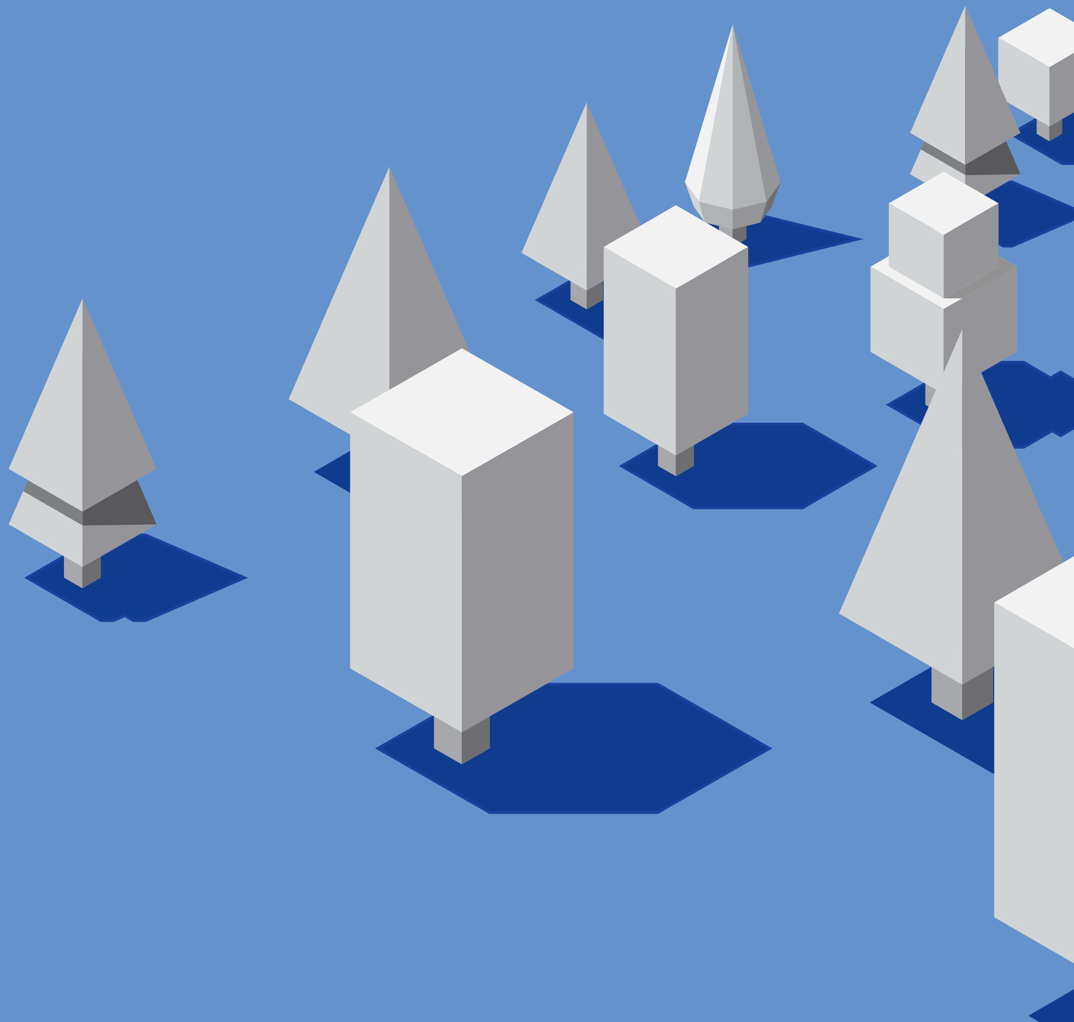


Ineco
Impulsa
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