FMT. Final Master's Thesis

Market study of the Carbon Footprint in commercial aviation in comparison with another means of transport

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Contents

ACEA. European Automobile Manufacturers' Association
AOG. Aircraft On Ground
BBC. British Broadcast Corporation
CAA. Canadian Automobile Association
CC. Climate Change
CF. Carbon Footprint.
CFC. ChloroFluoroCarbon
EASA. European Aviation Safety Agency
EPA. Environmental Protection Agency
GDP. Gross Domestic Product
GHG. GreenHouse Gas
GM. Google Maps
GSE. Ground Service Equipment
HCH. HidroFluoroCarbons
IATA. International Air Transport Association
ICAO. International Civil Aviation Organization
ICCT. International Council on Clean Transportation
ICEV. Internal Combustion Engine Vehicle
LTAG. Long-Term Aspirational Goal
MITECO. Ministerio para la Transición ECOlógica y el reto demográfico
MMT. Million Metric Tonnes
MOT. Means Of Transport (not oficial, it has several meanings. Can be applied anyways
MTOW. Maximum Take-Off Weight
NGO. Non-Governmental Organization
OEM. Original-Equipment Manufacturers
PFC. PerFluororCarbons
SAF. Sustainable Aviation Fuel
TEU. Twenty-foot Equivalent Unit
UIC. International Union of Railways
UK. United Kingdom
US. United States

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Chapter 1

Introduction

Transportation is a critical aspect of modern society, enabling the movement of goods and people across the globe. However, the environmental impact of transportation has become a major concern in recent years, particularly with regard to greenhouse gas emissions and their contribution to climate change. As such, there is a growing need to understand and mitigate the impact of transportation on the environment.

This study aims to investigate the impact of the carbon footprint (CF) in different means of transport. Specifically, the study will examine the greenhouse gas emissions associated with various modes of transportation and their industries, including aviation, automotive, railway, and nautical industries. By analyzing the carbon footprint of each industry, this study seeks to provide a comprehensive understanding of them and identify opportunities for reducing their carbon footprint. By shedding light on the carbon footprint of different means of transport, this study will contribute to efforts to reduce emissions, promote sustainable transportation, and mitigate the impact of transportation on the environment.

1.1 Objective

The main goal of this document is to choose in average the cleanest mean of transport (MOT) and purpose improvements to reduce the CF in this and the other ones studied throughout these pages.

1.2 Scope

The scope determines how far the project is going to. Thus will be determined by which things will be self made, with the help of the bibliography; and the things that will be taken directly from the bibliography, without the need of developing them inside this document.
On one hand, the included things in this project will be:

- Current state of the art about general CF and the impact in different MOT
- Calculations and estimations of the CF in different MOT, numbers given by papers, current studies, own-employed methods…
- Testing on different routes the previous calculations to analyze the results and extract conclusions

- Conditions for the countries which will be the initial/ending points of the evaluated routes, to make them comparable in all the MOT:
  - Only European countries
  - The route evaluated must have a direct route by plane
  - All the countries of departure, arrival and the ones to cross on its way must be reachable in a direct non-scaled route by boat
  - All the countries of departure, arrival and the ones to cross on its way must be reachable by European highways (E-XX)
  - Maximum travel distance equal to 2000 km (taking the maximum value from the MOT whose distance travelled is higher)
  - The prototype for each MOT will have an averaged consumption of reference

On the other hand, non-included and out-of-scope things are:

- Scientific calculations of the CF (meaning scientific a CFD analysis, laboratory tests, run simulations and so on)
- Implantation of the proposed improvements
- Big data Analysis with a million of possible combinations regarding the routes, specifications for each mean of transport…

1.3 Requirements

Throughout this study (in the selection of routes and calculation of CF for each mode of transport) and as we encounter problems along the way, different requirements will be raised that will allow us to continue advancing in the study. Some of the most important and general requirements are listed below, while others will be revealed throughout this study:

- Routes analysed: reachable by plane, bus and boat in a route shorter than 4.000 km.
- CF aviation:
  - For the surface of the terminal and apron in many of the airports, and approximate method (by Google Maps) has been used.
  - Escalated values between the models studied with the data available for any of them.
  - The operation cost depend on the flight and the use of the airport. This use of the facility will be present in the rest of MOTs (motorways, train stations and rail and harbors)
- CF automotive:
  - Production cost is given as a % depending of the type of car.
  - Highways cost and emissions depends on the number of lanes
  - Economic cost is escalated with a formula.
- CF railway:
  - The production cost will be calculated from a self-made formula depending on the weight.

  - The infrastructure cost is related with the one in an airport due to the lack of real data.
  - Cost associated with the operation is escalated with a formula.

- CF nautical:
  - During the realization of the work, a normal boat and a cruise ship was analysed. The normal boat has worst values than cruise, being the cruise ship bad values also. That is why normal boats won't be analyzed and the cruise ship won't be included in the analysis.

- Scrapping contribution has been eliminated as it was a % of the production one and don't suppose a difference between the different MOTs.

1.4 Justification

Climate Change is one of the most important challenges that the humanity has to face within the next decades in order to avoid the 6th massive extinction in Earth's history. CF and GHG's values should become one of the main concern for all the human beings currently living in order to know the importance of the problem and the severity of the risks that we will have to withstand if no further, decisive and important actions are done now.

Chapter 2

State of the art

The first step for making a successful study is to learn, read and investigate about how far the topic has been studied and which data is available currently about it.

2.1 Carbon Footprint (CF)

As said in the introduction, CF is a new trend term which tries to relate the daily economic activities of the human beings with the total volume of GHG. In 2019 the GHG emissions set a new record and the current CO_2 levels are similar to the ones that Earth had more than 3 millions years ago, when the thermometer read 3ºC more and sea level measured between 10 and 20 meters more than currently. CF has multiplied by 11 since 1961 and, according to Global Footprint Network, it supposes the 60% of the total impact in the environment.
The CF is calculated adding the direct and indirect emissions of compounds like Methane (CH_4), Nitrous Oxid (NO_2), hidrofluorocarbons (HFC's), perfluorocarbons (PFC's), sulphur hexafluoride (SF_6) and the carbon dioxide (CO_2).
The CF can be calculated taken into account different actors and in different ways. Mainly, we have 2 kind of CF calculations:

1. By type. Where it's separated into personal, companies, products and events contributions. It's deeply explained in the annexes.
2. By kind of emissions, separated in direct and indirect. Same than above.

2.1.1 GHG worldwide emissions

Emissions by GHG gas

The US Environmental Protection Agency (EPA) is the institution in charge of evaluating the emissions produced by the US, propose mitigation measures, regulations and normative and they work in to make the American society aware about the importance of the CC. Currently the global GHG emissions by kind of gas emmited is as follows [2] :

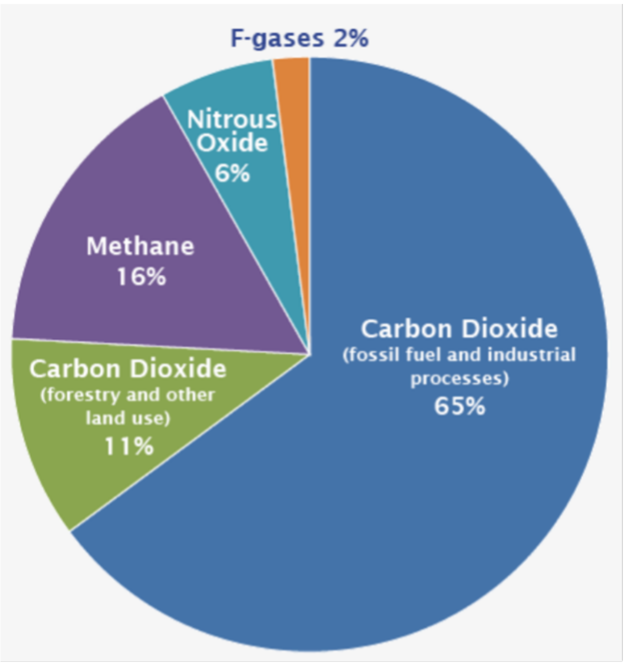


Figure 2.1: Origin from each of the gases of the GHG.

From the previous figure, in order of importance:

1. Carbon Dioxide (CO_2). Emmited by burning fossil fuels, solid waste, chemical relations, and emitted from direct human-induced impacts on forestry and other land use, such as through deforestation, land clearing for agriculture, and degradation of soils. It's absorbed by plans in his carbon cycle
2. Methane (CH_4). Agricultural activities, waste management, energy use, and biomass burning all contribute to CH_4 emissions.
3. Nitrous Oxid (N_2O). Agricultural activities, such as fertilizer use, are the primary source of N_2O emissions. Fossil fuel combustion also generates N_2O
4. Fluorinated gases (F-gases). Industrial processes, refrigeration, and the use of a variety of consumer products contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)

From each of them, in the Annex is more explained numbers and sources. Here are shown some graphics that will help to understand the levels of contamination and their sources[3]:

1. Carbon Dioxide (CO_2):

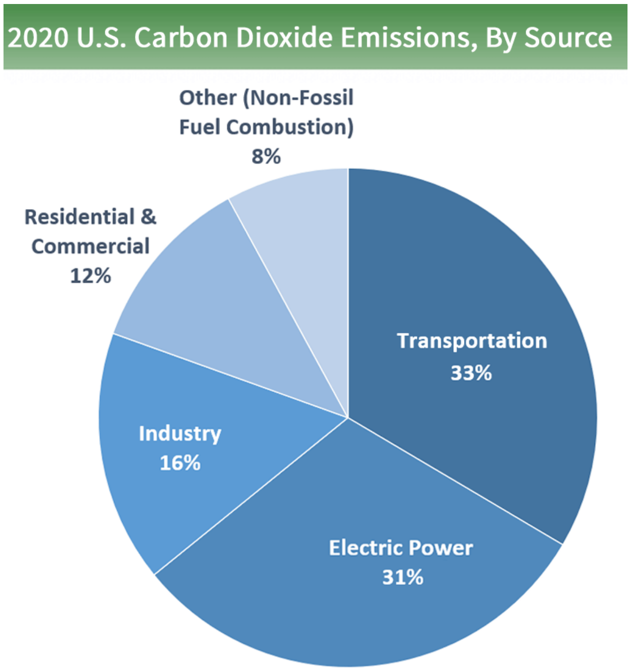


Figure 2.2: Origin of the CO_2 emissions in the USA

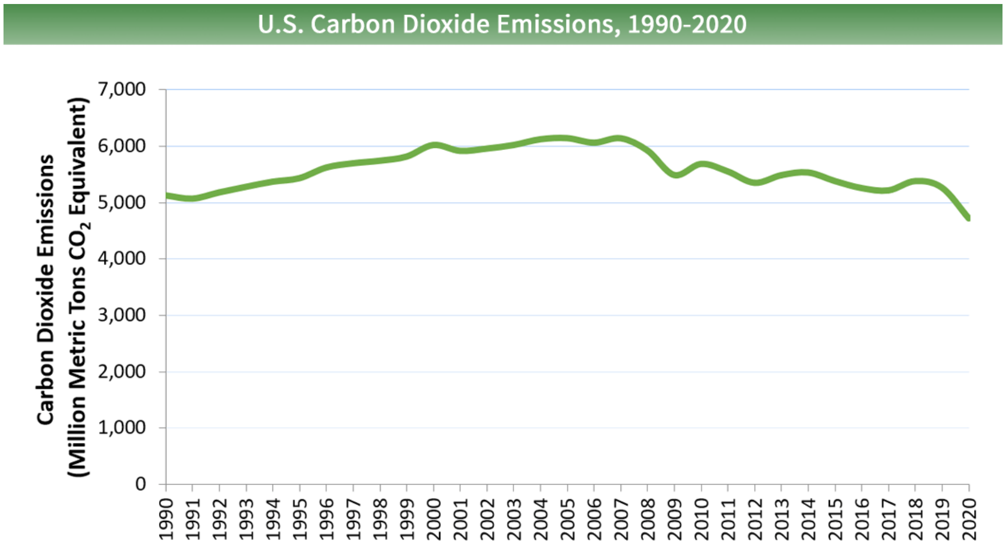


Figure 2.3: Predictions of the future CO_2 emissions in the USA.

2. Methane (CH_4):

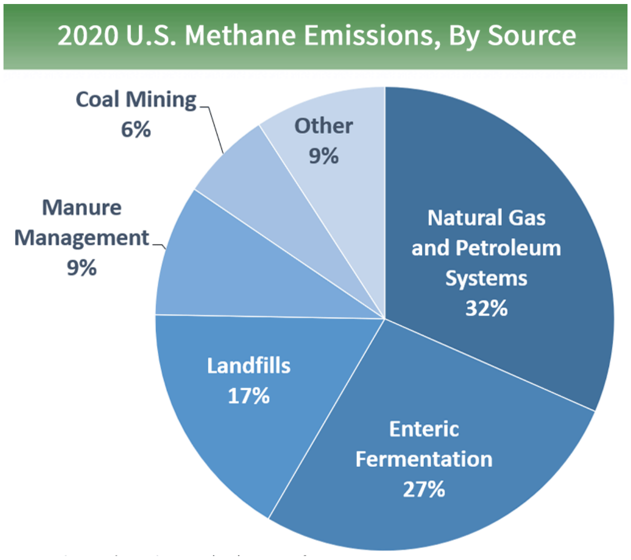


Figure 2.4: Origin of the of the CH_4 emissions in the USA.

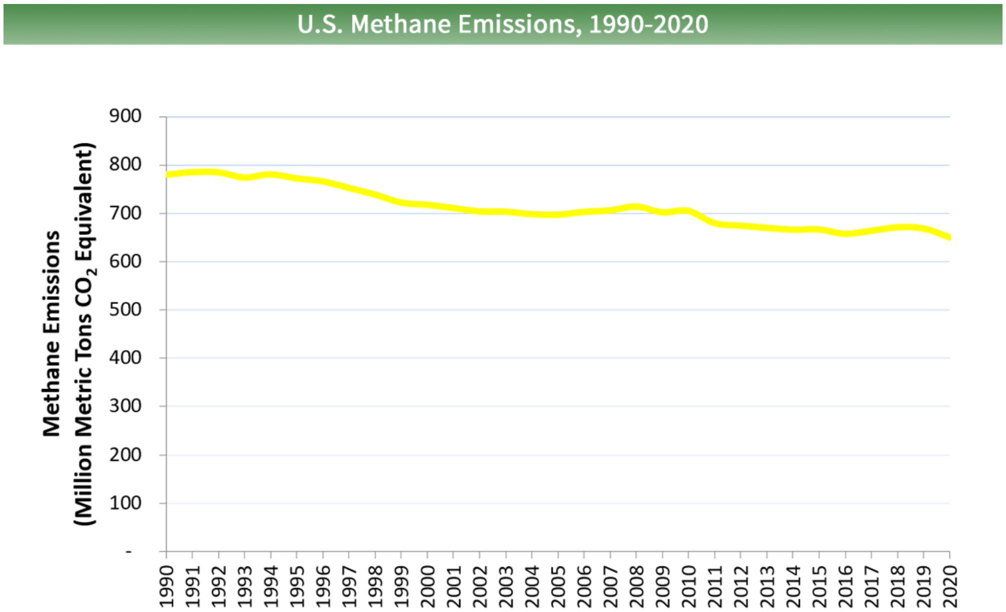


Figure 2.5: Future predictions of CH_4 emissions in the USA.

3. Nitrous Oxid (N_2O).

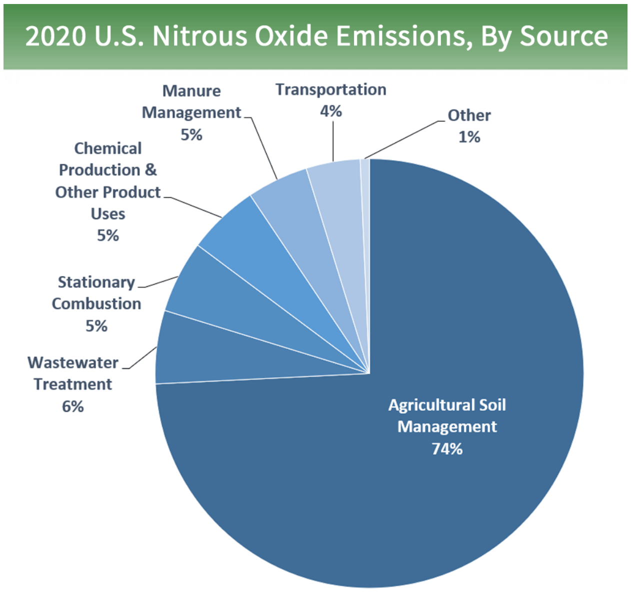


Figure 2.6: Origin of the N_2O emissions in the USA.

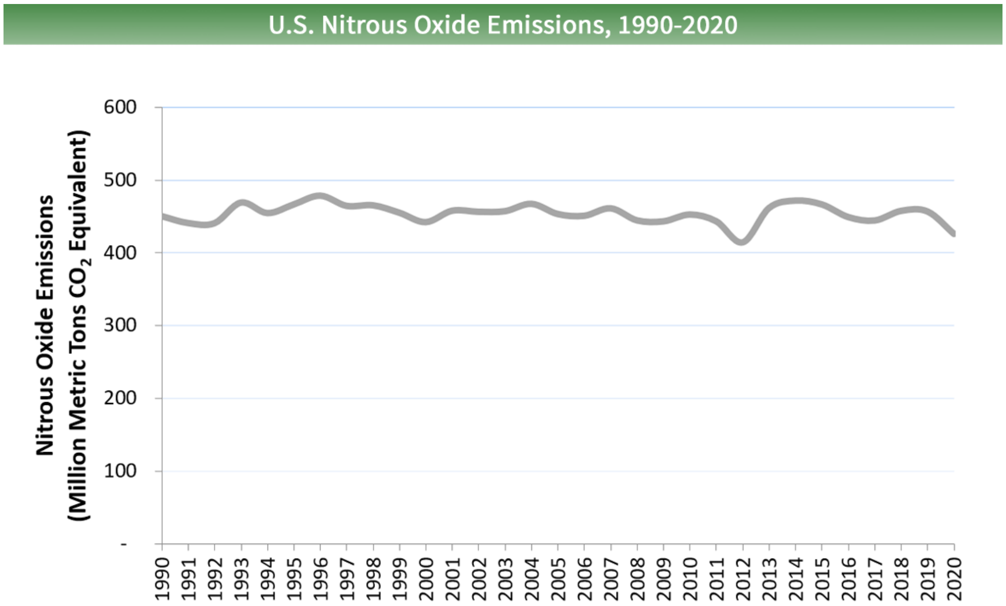
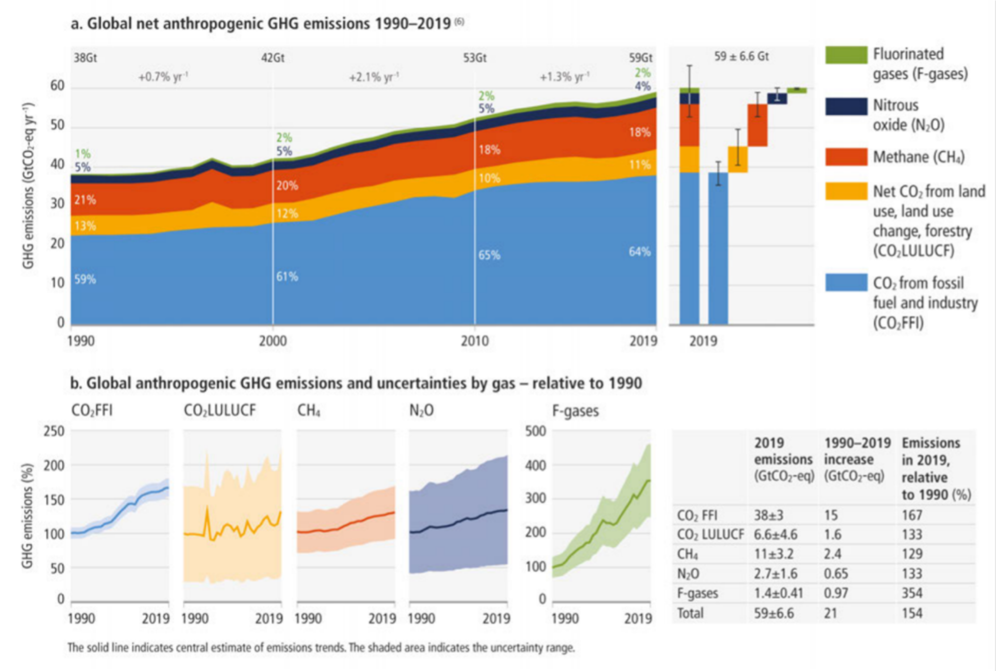


Figure 2.7: Future predictions of the N_2O emissions in the USA.

Defined where they affect and the most important GHG gases, it's time to know about his emissions volume during the last years. From [4] we have the following figure:



	2019 emissions (GtCO₂-eq)	1990–2019 increase (GtCO₂-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

Figure 2.8: Global net anthropogenic GHG emissions (GtCO_{2eq} per year) 1990–2019.

Besides, in this report we can also find the graphics that will show the variation that must have all the important GHG emissions in order to avoid the raise of 1.5-2C in the upcoming years:

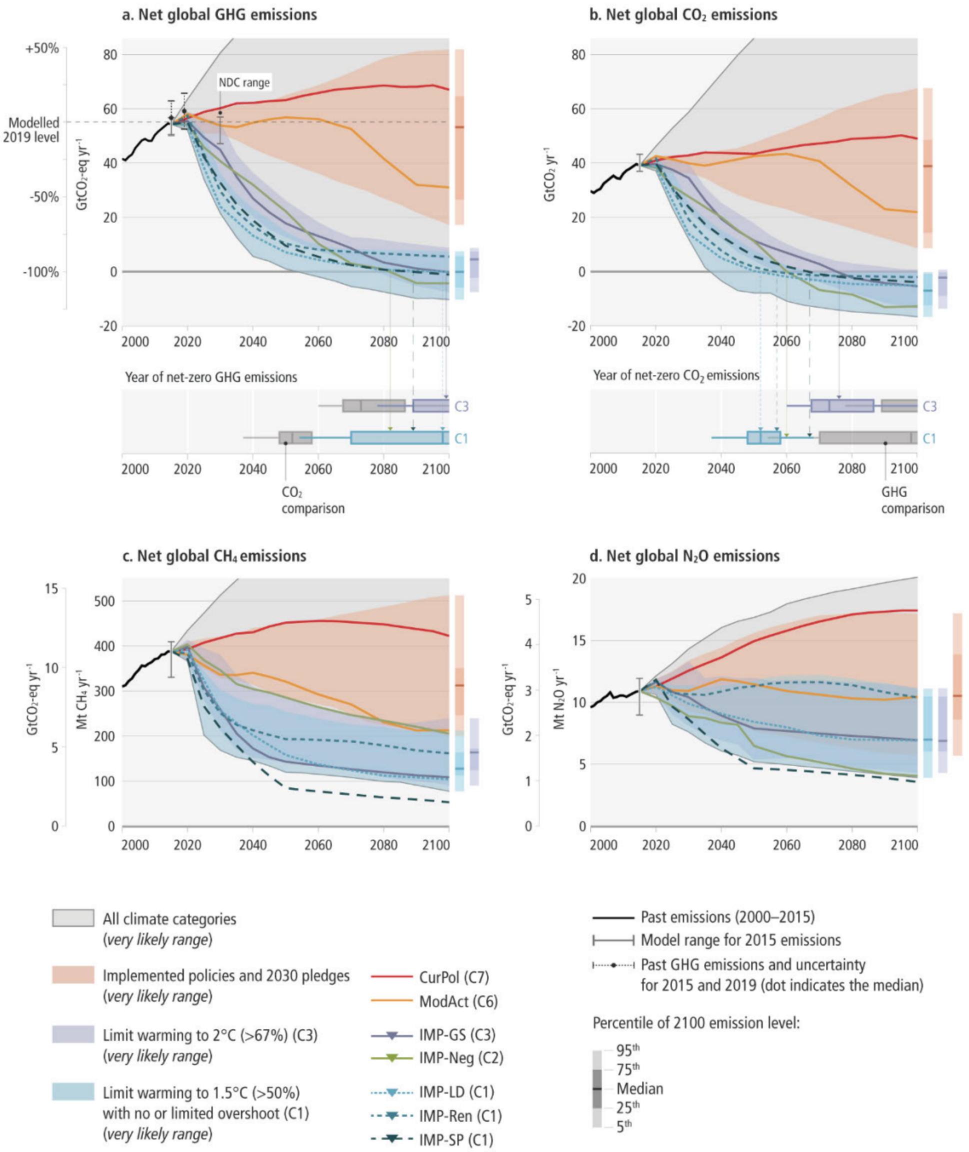


Figure 2.9: Reduction in the emissions in the upcoming years to not exceed 2 ºC.

From the last report done by the same organization, as 2022 new one is coming but still under development, [5], we can extract some figures and date interesting, like the GHG Emission Pathways, with different scenarios:

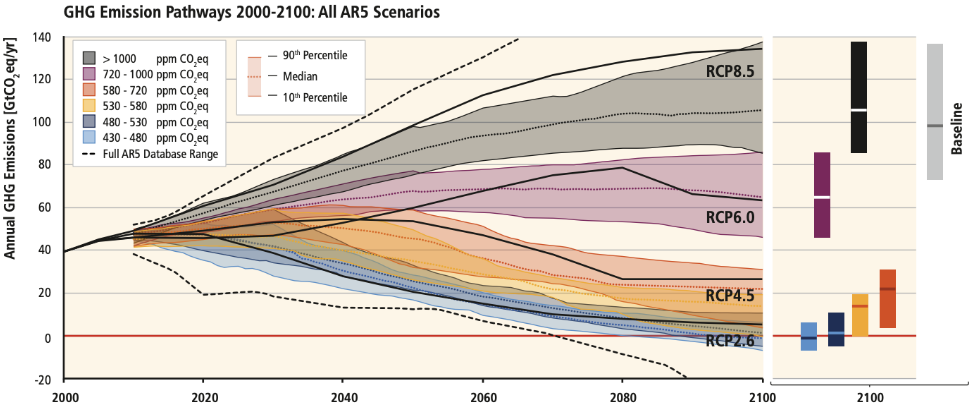


Figure 2.10: Different scenarios depending on the quantity of emissions produced in the upcoming years.

Emissions by country

To put in numbers, we are going to take a look on the CF that the most important countries of the world has produced annually until 2018 [?], ordered by the Gross Domestic Product (GDP) in 2022 [?].

In the page the data is given in 3 different ways, being the chosen one to show here is the 3rd one, Ecological Footprint (Number of Earths). This is the number or Earth, regarding the resources, that the worldwide population would need if all the inhabitants of the planet lived in the studied planet. For each of these countries, we are going to do a brief analysis of what we can see in the different graphics, and will talk about his future compromises regarding his neutrality in emissions. Before taking a general look on how the emissions are divided depending on the countries, we are going to introduce a new variable called CO_{2e} which will simplify a lot further calculations. The CO_{2e}, where e means equivalent, is the mass of CO_2 that would generate the same amount of emissions that the emissions produced by a combustion where there are more elements. It means that, for example, during the engine's combustion in a flight, if we give a value in CO_{2e} in tonnes, this quantity will be the addition of real CO_2 tonnes produced and adding to them the quantity of the tonnes produced by the rest of the different elements produced in the combustion: f-gases, N_2O, CH_4...and so on. The information regarding each country it's in the annex [6]. Taking a global point of view and extracting some conclusions about what can be seen in the annex, we can make several conclusions, like the following ones:

1. Most of the countries will be neutral by 2050, according to his policies. Would it be enough? I don't think so, since odds are against us, reaching the dangerous and point of no return of 1.5 $C^{\check{z}}$ before 2026 according to the last studies [7]

2. The country that contributes almost the third part of the GHG worldwide emissions, China, is one of the ones that will be neutral later. These are bad news since his emissions predictions are even worse and spiral upwards [8] [9]

2.2 CF in different Means of Transport (MOT)

In this section the current data, methodology and future forecasts about the CF of the different MOT's that will be analyzed in this document will be explained. As a first approximation and gathering the information for different ways of transport, here some graphics and figure will be shown [**?**]:

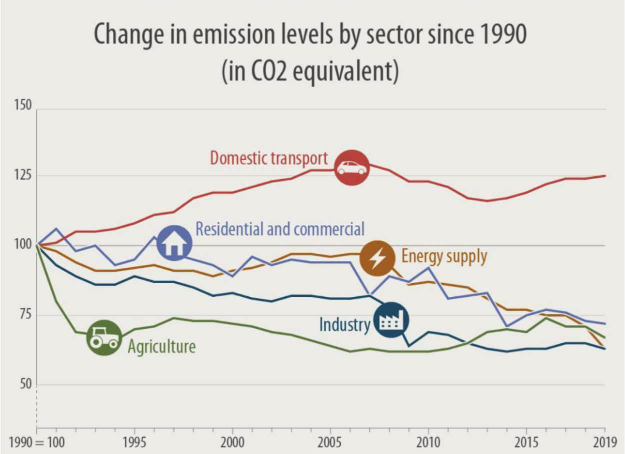


Figure 2.11: Different emissions by sector in the European Union.

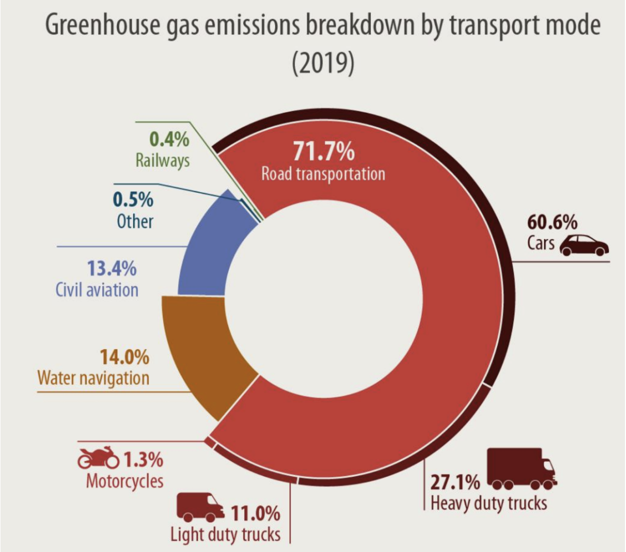


Figure 2.12: Emissions by MOT in the European Union.

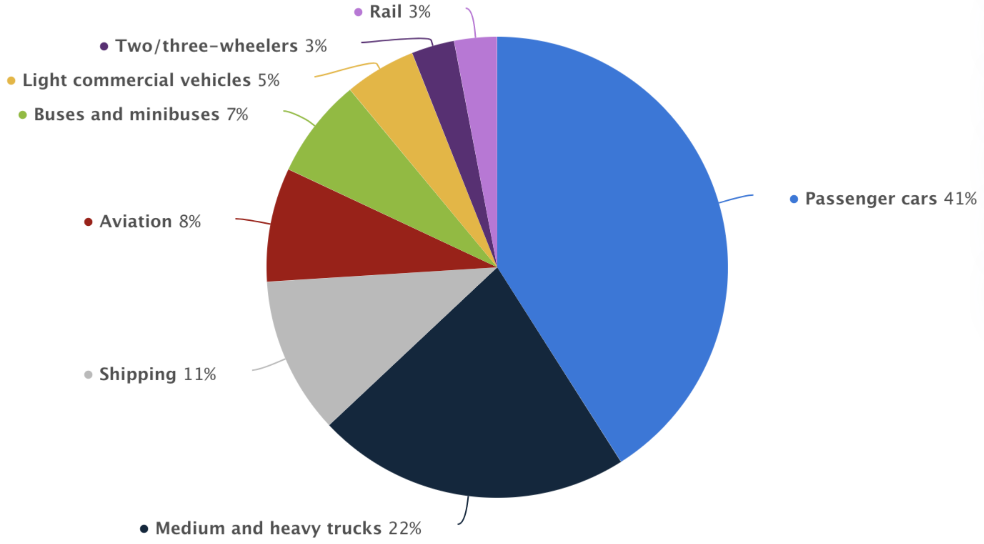


Figure 2.13: Carbon dioxide emissions produced by the transportation sector worldwide in 2020.

As we can see, most of the emissions come from domestic transport. Inside of it, more than 2/3 of the total emissions come from road transportation being 60 % from cars [10]. In the next images we can see the CF produced per PAX kilometer for every transport. It will be used later to compare with real results [**?**].

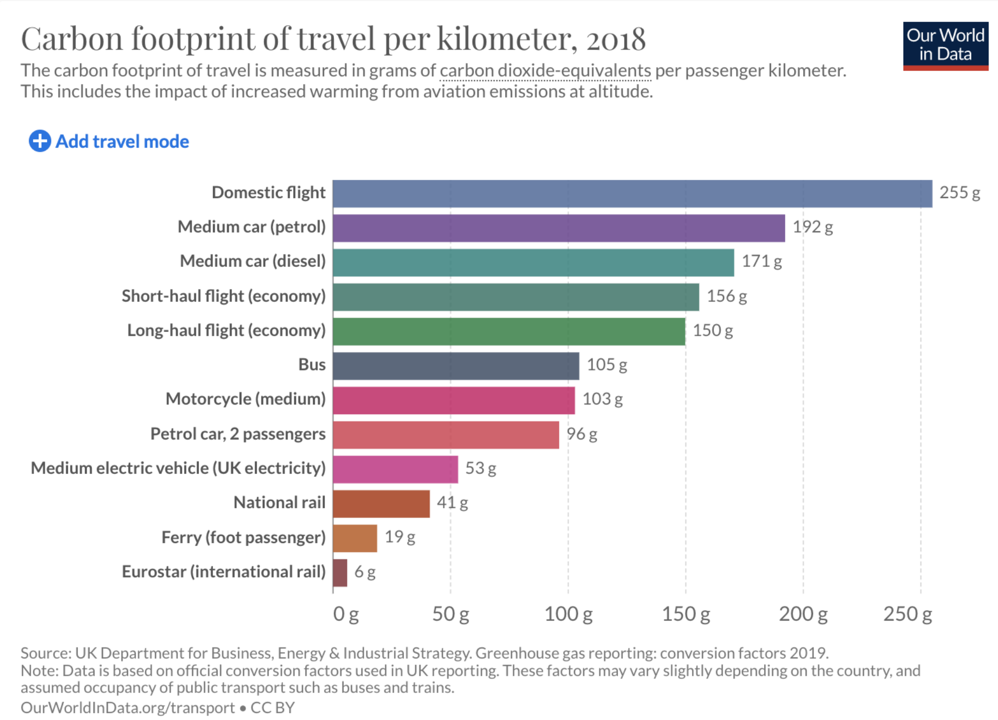


Figure 2.14: CF of travel per km (2018).

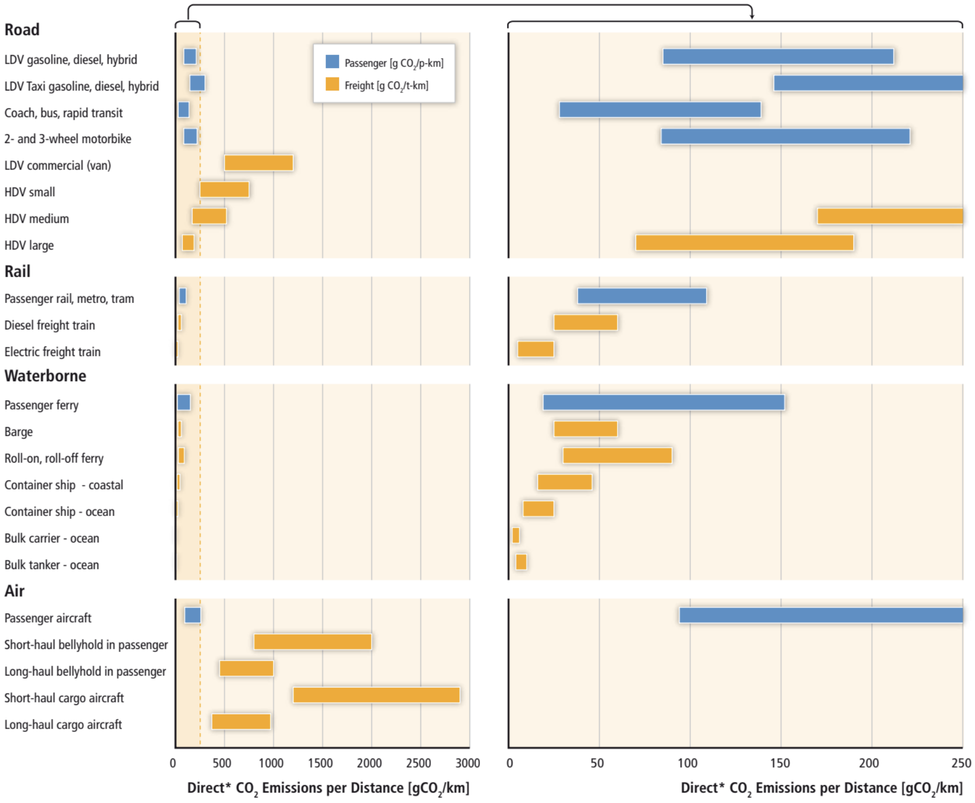
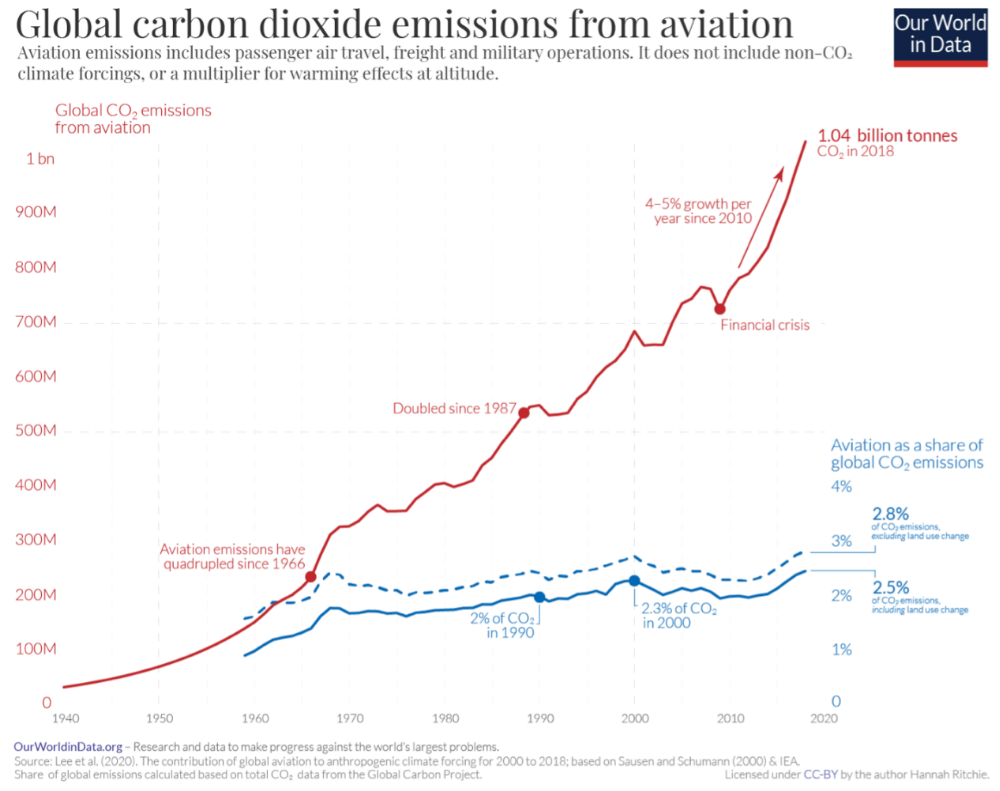


Figure 2.15: Emissions for different MOTs

2.2.1 Aviation Industry

It is well known that, although being the safest MOT, aviation produces a lot of GHG annually, and since air traffic is growing up and new commercial aviation routes are opened each year, the problem will get worse if no further actions are taken. Our World in Data is a page where several data regarding all the countries can be consulted. In this case, we are going to analyze the ones regarding at aviation's emissions [11]. In the next graphic we can confirm the statement previously said:



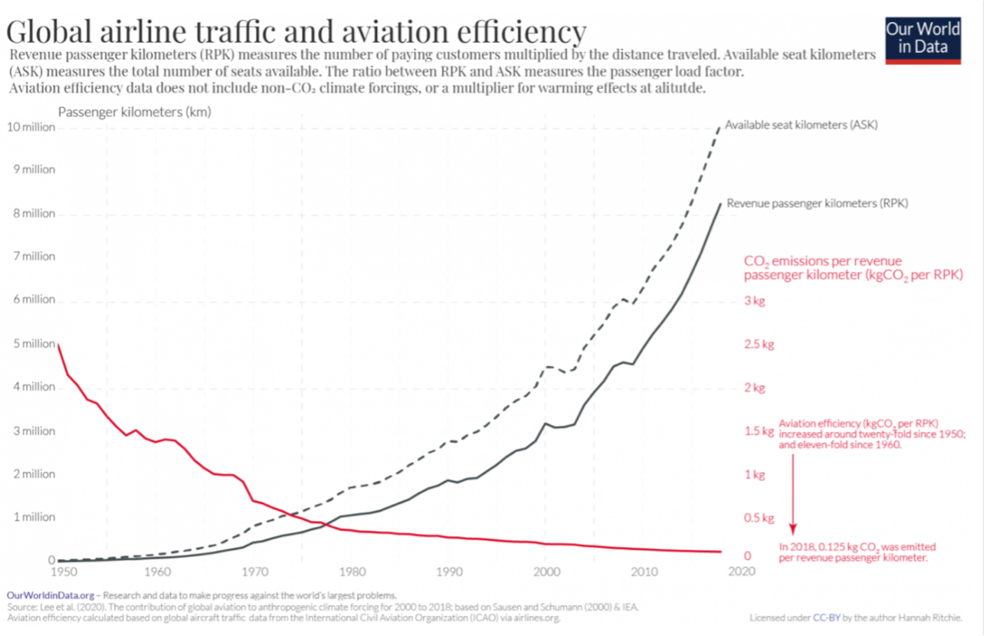
OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Lee et al. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018; based on Sausen and Schumann (2000) & IEA.
Share of global emissions calculated based on total CO₂ data from the Global Carbon Project.

Figure 2.16: Global CO_2 emissions from aviation.

Aviation's contribution in CO_2 emissions has been increasing his emissions since its creation, and in the last years has experience a huge exponential growth, surpassing the 1 billion tonnes of CO_2 before COVID arrived. Due to the pandemic, the levels start decreasing for the 1st time since the 2008 financial crysis, but now that the World has recovered again the normality and with the airlines explosion in this 2022, the exponential tendency has appeared again. global CO_2 from commercial aviation was 707 million tons in 2013. In 2019 that value reached 920 million tons, having increased approximately 30 percent in six years. The United States, with the world's largest commercial air traffic system, accounted for 200 million tons (23 percent) of the 2017 global CO_2 total [12]. And the future doesn't looks better, as by 2050, commercial aircraft emissions could triple given the projected growth of passenger air travel and freight. Here in the next graphic, we can see the effect of the pandemic in the world passenger traffic evolution [13].

Also, from the previous graphic we can see that it's one of the industries that more CO_2 produces annually, with 3% of the global emissions. Hopefully, the latest development in electrical and hybrid engines, as well as the apparition of Hydrogen as a combustible, will improve these values in the next years.

In the next graphic we will be able to see how the aircraft's efficiency is related with the CO_2 emissions, and the previous conclusion will be affirmed:



Global airline traffic and aviation efficiency

Revenue passenger kilometers (RPK) measures the number of paying customers multiplied by the distance traveled. Available seat kilometers (ASK) measures the total number of seats available. The ratio between RPK and ASK measures the passenger load factor. Aviation efficiency data does not include non-CO_2 climate forcings, or a multiplier for warming effects at alitutde.

Aviation efficiency (kgCO_2 per RPK) increased around twenty-fold since 1950; and eleven-fold since 1960.

In 2018, 0.125 kg CO_2 was emitted per revenue passenger kilometer.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Lee et al. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018; based on Sausen and Schumann (2000) & IEA.
Aviation efficiency calculated based on global aircraft traffic data from the International Civil Aviation Organization (ICAO) via airlines.org.

Figure 2.17: Aviation traffic vs the efficiency.

We have available some utile data for our calculations in the following figure, regarding 2018 data: [14]

- 918 million metric tonnes (MMT) of CO_2 from passenger and freight transport
- 32% increases since 2013
- 38 million passenger flights (67% domestic, 33% international)
- Top CO_2 emitters:
  1. United States. 182 MMT. 24% of the global total
  2. European Union. 142 MMT. 19% of the global total
  3. China. 95 MMT. 13% of the global total
- The emissions of CO_2, separated in types of passengers:
  1. Short-haul. Less than 1500 km. 33% of the global total
  2. Medium-haul. Between 1500 and 4000 km. 33% of the global total
  3. Long-haul. More than 4000 km. 33% of the global total
- Flights shorter than 500 km are the 5% of the CO_2, global total, nearly the double of CO_2 per passenger km as longer flights

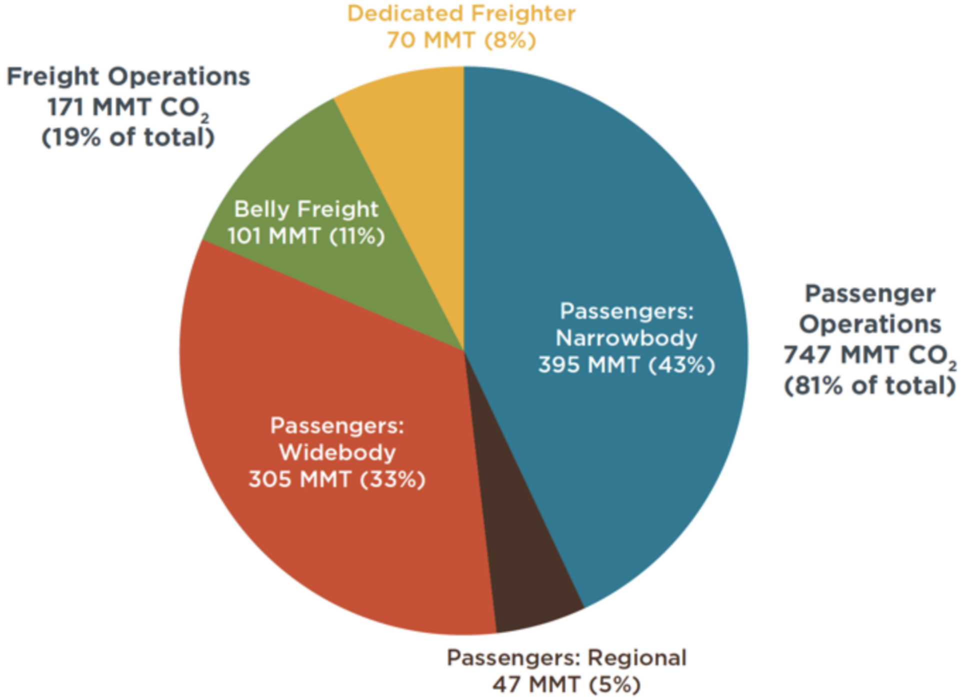
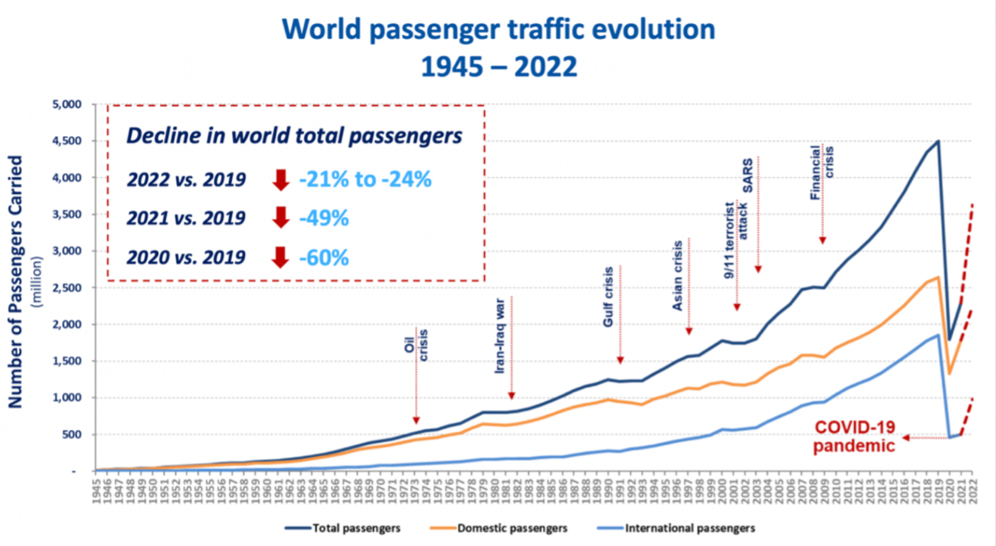


Figure 2.18: CO_2 emissions per kind of operation and flight.

Furthermore, some key findings from this document are:

- CO_2 emissions from all commercial operations in 2018 totaled 918 million metric tons—2.4% of global CO_2 emissions from fossil fuel use. Using aviation industry values, there has been a 32% increase in emissions over the past five years.
- Flights departing airports in the United States and its territories emitted about one-quarter (24%) of global passenger transport-related CO_2, two-thirds of which came from domestic flights. The top five countries for passenger aviation-related carbon emissions were rounded out by China, the United Kingdom, Japan, and Germany.
- 43% of CO_2 from commercial aviation was linked to passenger movement in narrowbody aircraft, followed by widebody jets (33%), and regional aircraft (5%). The remaining aviation emissions were driven by freight carriage.

Once the current emissions levels and acknowledge has been discussed, it's time to see how the development of the aviation industry has been. Looking at the world passenger traffic evolution, in the past and the upcoming years we can see that:



Used with permission from the International Civil Aviation Organization (ICAO).

Figure 2.19: Passenger evolution of the aviation traffic.

With a highly pronounced recovery after COVID's crysis. The expected growth after the COVID (from 21). And the future expectations, from ICAO's predictions:

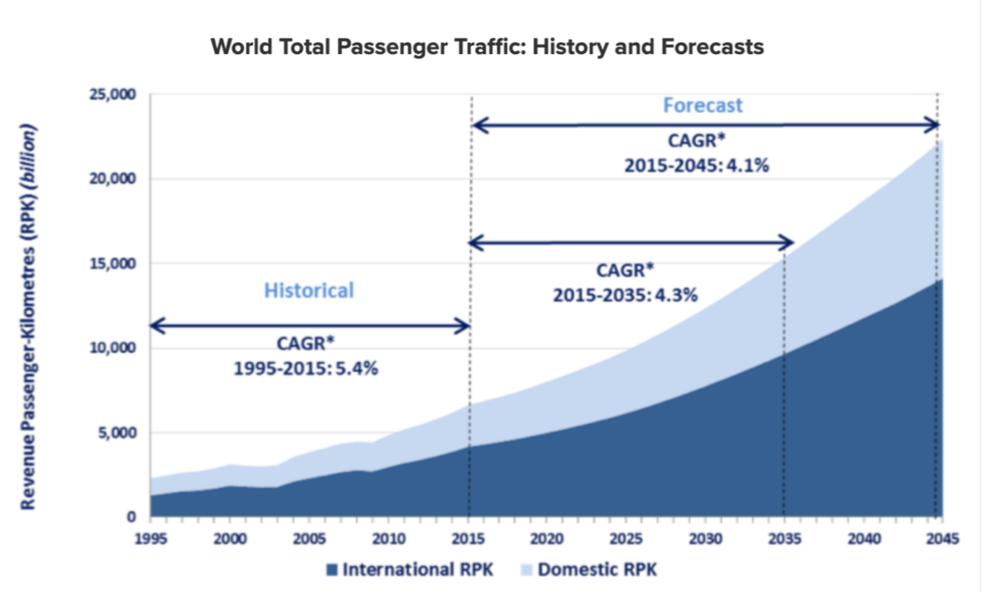


Figure 2.20: ICAO prediction of the aviation PAX.

2.2.2 Automotive Industry

About the automotive industry, values for his emissions and different things will be shown [15]. In the annex are other's less important.

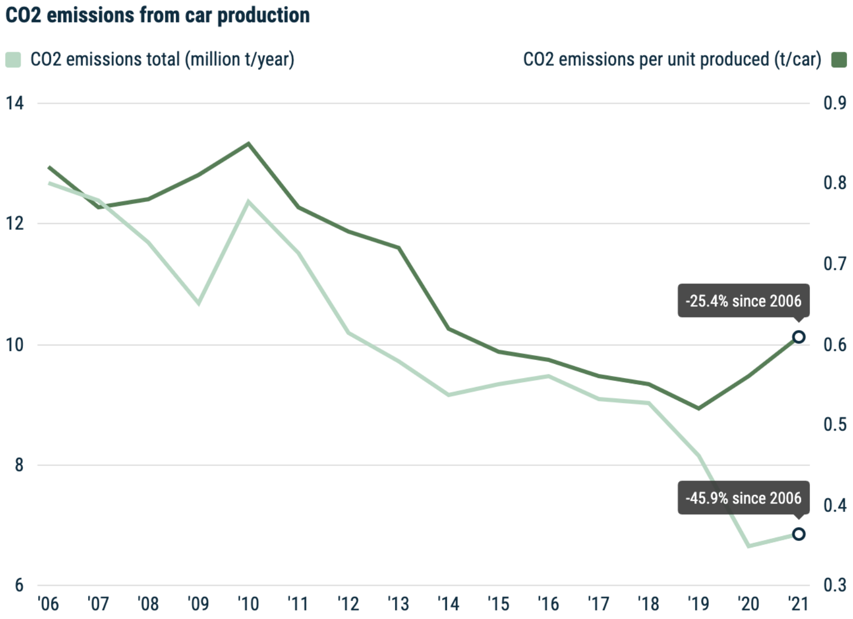


Figure 2.21: CO_2 emissions from car production in the EU

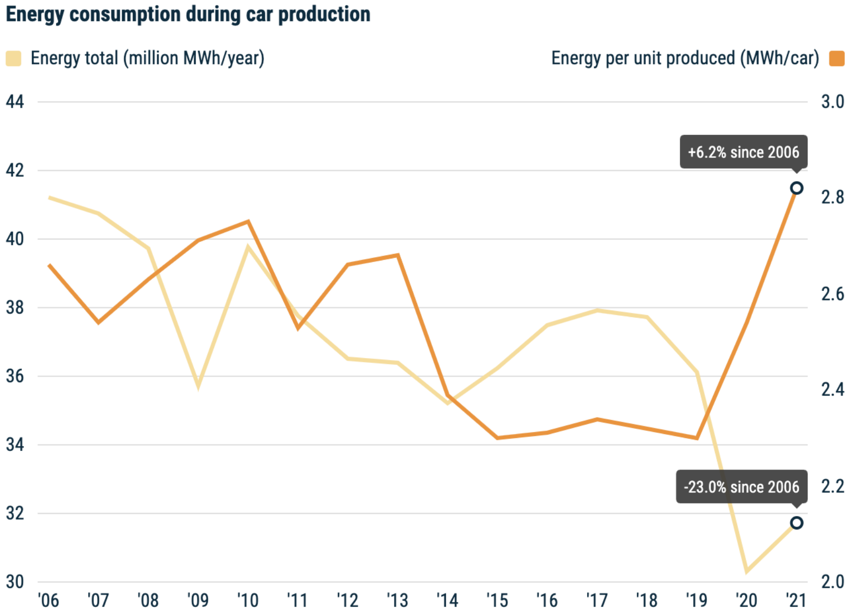
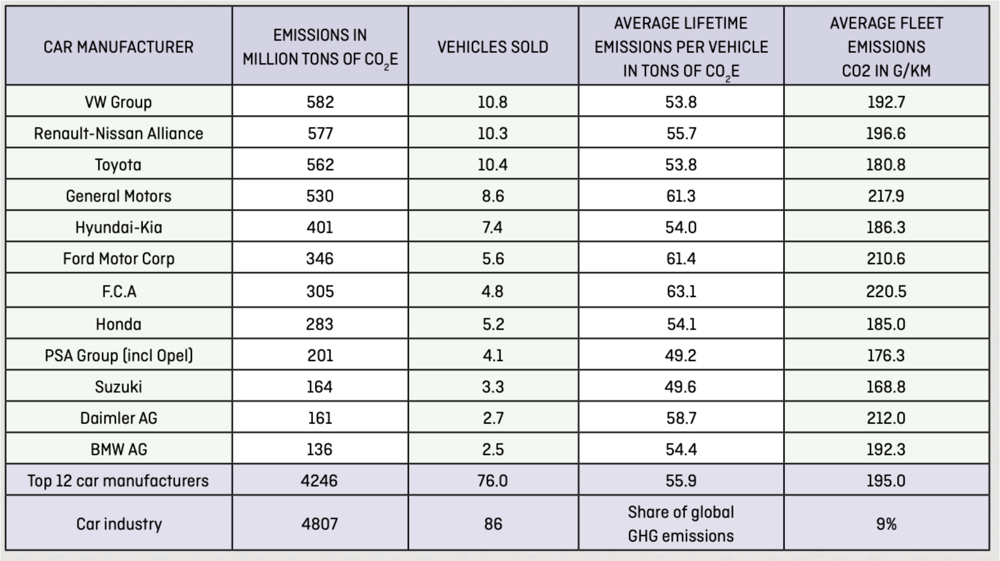


Figure 2.22: Energy consumption during car production in the EU [1]

About the emissions from different companies, regarding [16]:



CAR MANUFACTURER	EMISSIONS IN MILLION TONS OF CO$_2$E	VEHICLES SOLD	AVERAGE LIFETIME EMISSIONS PER VEHICLE IN TONS OF CO$_2$E	AVERAGE FLEET EMISSIONS CO2 IN G/KM
VW Group	582	10.8	53.8	192.7
Renault-Nissan Alliance	577	10.3	55.7	196.6
Toyota	562	10.4	53.8	180.8
General Motors	530	8.6	61.3	217.9
Hyundai-Kia	401	7.4	54.0	186.3
Ford Motor Corp	346	5.6	61.4	210.6
F.C.A	305	4.8	63.1	220.5
Honda	283	5.2	54.1	185.0
PSA Group (incl Opel)	201	4.1	49.2	176.3
Suzuki	164	3.3	49.6	168.8
Daimler AG	161	2.7	58.7	212.0
BMW AG	136	2.5	54.4	192.3
Top 12 car manufacturers	4246	76.0	55.9	195.0
Car industry	4807	86	Share of global GHG emissions	9%

Figure 2.23: CF of different car companies in 2018

About the % related to each part of the lifecycle in a car: [17]

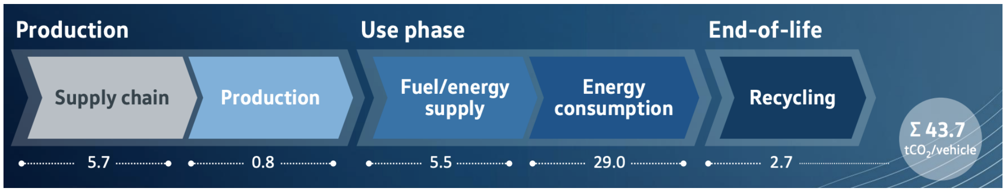


Figure 2.24: CO_2 emissions during the lifecycle of a car.

About how much each part of the process takes all the %: [18]

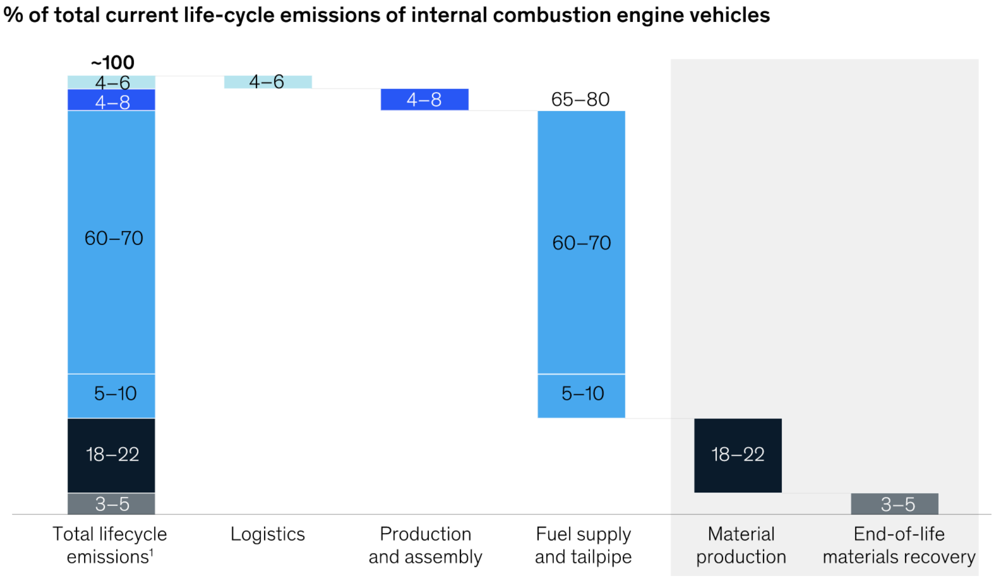


Figure 2.25: Total emissions during the lifecycle of a car.

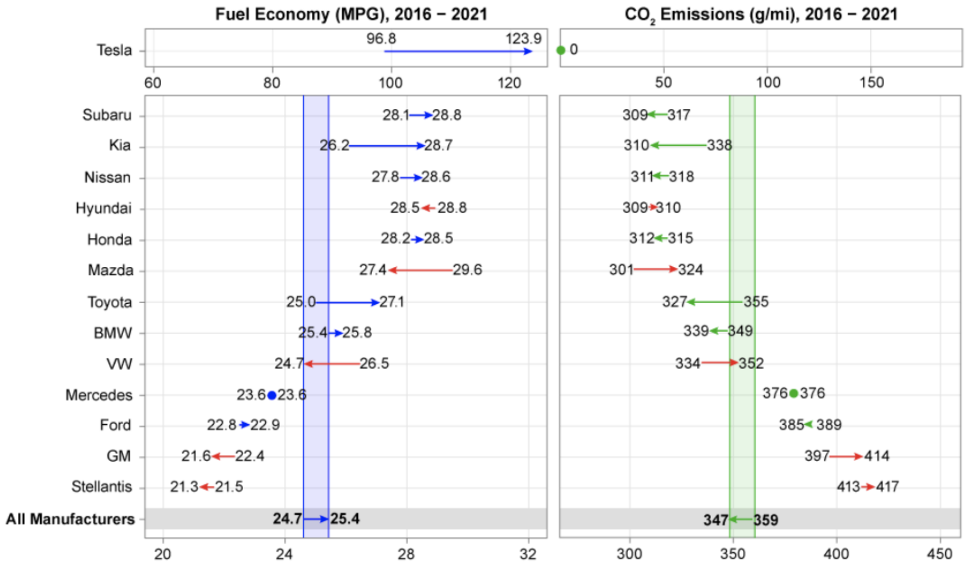


Figure 2.26: Changes in estimated world fuel usage.

2.2.3 Railway Industry

As a first approach and being already commented the aircraft and automotive influence, a comparison between the emissions produced by each one: [19]

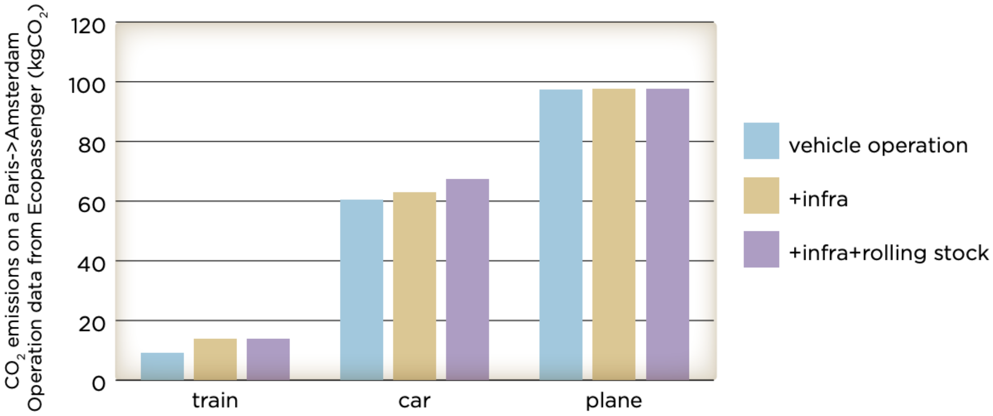


Figure 2.27: Emissions comparison between different MOTs.

About the worldwide emissions by country: [20]

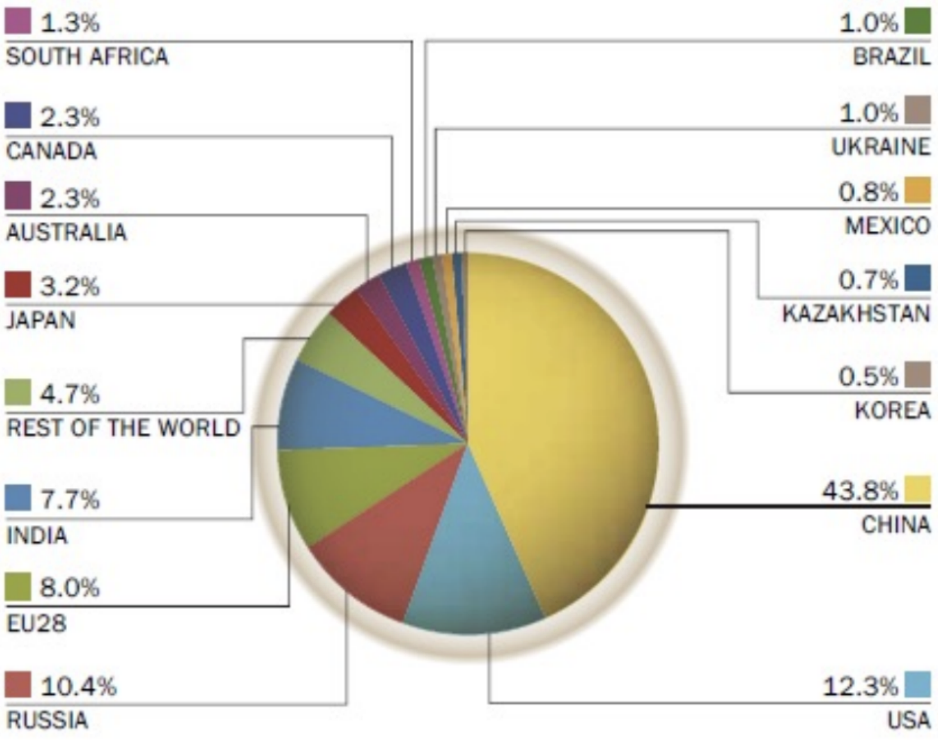
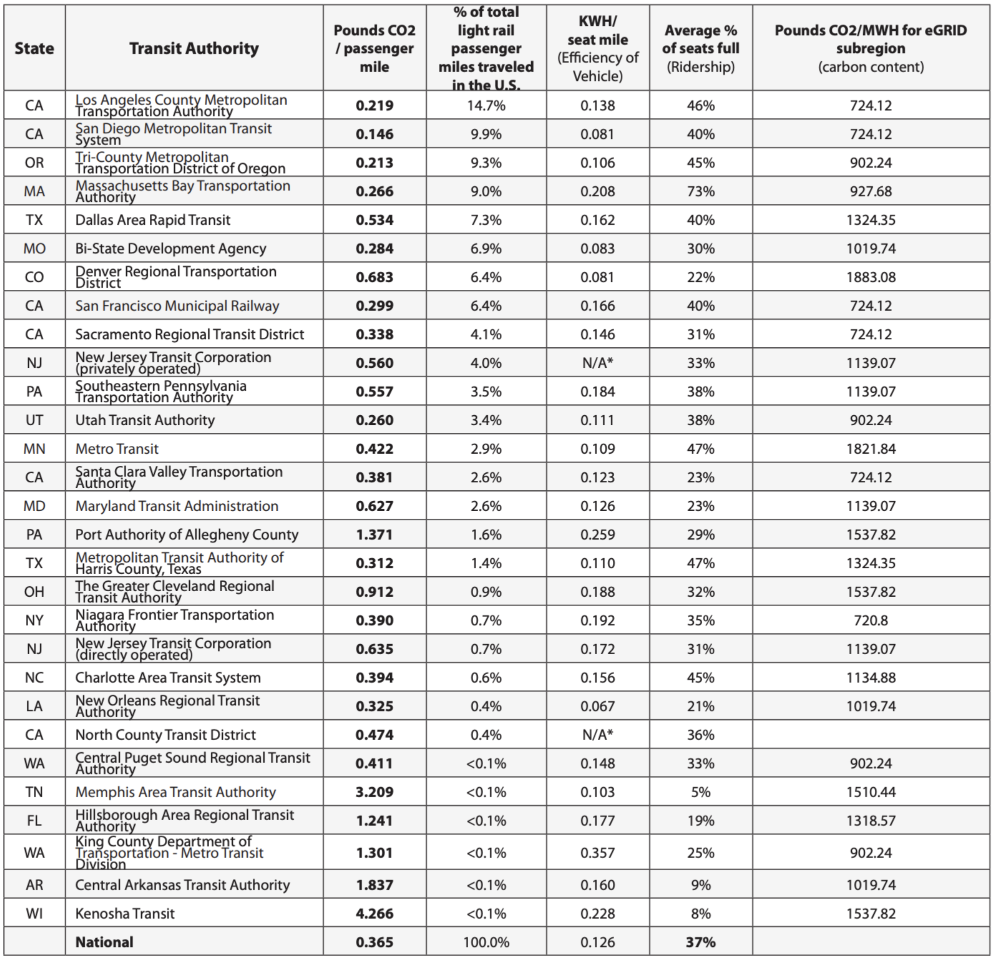


Figure 2.28: CO_2 emissions from rail transport by country in 2015.

And the data for the USA to be able to compare later with our numbers obtained: [21]



State	Transit Authority	Pounds CO2 / passenger mile	% of total light rail passenger miles traveled in the U.S.	KWH/ seat mile (Efficiency of Vehicle)	Average % of seats full (Ridership)	Pounds CO2/MWH for eGRID subregion (carbon content)
CA	Los Angeles County Metropolitan Transportation Authority	**0.219**	14.7%	0.138	46%	724.12
CA	San Diego Metropolitan Transit System	**0.146**	9.9%	0.081	40%	724.12
OR	Tri-County Metropolitan Transportation District of Oregon	**0.213**	9.3%	0.106	45%	902.24
MA	Massachusetts Bay Transportation Authority	**0.266**	9.0%	0.208	73%	927.68
TX	Dallas Area Rapid Transit	**0.534**	7.3%	0.162	40%	1324.35
MO	Bi-State Development Agency	**0.284**	6.9%	0.083	30%	1019.74
CO	Denver Regional Transportation District	**0.683**	6.4%	0.081	22%	1883.08
CA	San Francisco Municipal Railway	**0.299**	6.4%	0.166	40%	724.12
CA	Sacramento Regional Transit District	**0.338**	4.1%	0.146	31%	724.12
NJ	New Jersey Transit Corporation (privately operated)	**0.560**	4.0%	N/A*	33%	1139.07
PA	Southeastern Pennsylvania Transportation Authority	**0.557**	3.5%	0.184	38%	1139.07
UT	Utah Transit Authority	**0.260**	3.4%	0.111	38%	902.24
MN	Metro Transit	**0.422**	2.9%	0.109	47%	1821.84
CA	Santa Clara Valley Transportation Authority	**0.381**	2.6%	0.123	23%	724.12
MD	Maryland Transit Administration	**0.627**	2.6%	0.126	23%	1139.07
PA	Port Authority of Allegheny County	**1.371**	1.6%	0.259	29%	1537.82
TX	Metropolitan Transit Authority of Harris County, Texas	**0.312**	1.4%	0.110	47%	1324.35
OH	The Greater Cleveland Regional Transit Authority	**0.912**	0.9%	0.188	32%	1537.82
NY	Niagara Frontier Transportation Authority	**0.390**	0.7%	0.192	35%	720.8
NJ	New Jersey Transit Corporation (directly operated)	**0.635**	0.7%	0.172	31%	1139.07
NC	Charlotte Area Transit System	**0.394**	0.6%	0.156	45%	1134.88
LA	New Orleans Regional Transit Authority	**0.325**	0.4%	0.067	21%	1019.74
CA	North County Transit District	**0.474**	0.4%	N/A*	36%	
WA	Central Puget Sound Regional Transit Authority	**0.411**	<0.1%	0.148	33%	902.24
TN	Memphis Area Transit Authority	**3.209**	<0.1%	0.103	5%	1510.44
FL	Hillsborough Area Regional Transit Authority	**1.241**	<0.1%	0.177	19%	1318.57
WA	King County Department of Transportation - Metro Transit Division	**1.301**	<0.1%	0.357	25%	902.24
AR	Central Arkansas Transit Authority	**1.837**	<0.1%	0.160	9%	1019.74
WI	Kenosha Transit	**4.266**	<0.1%	0.228	8%	1537.82
	National	**0.365**	100.0%	0.126	**37%**	

Figure 2.29: CO_2 emissions from rail transport in USA.

2.2.4 Nautical Industry

The emissions produced by a normal cruise can vary depending on several factors, such as the size and age of the ship, the type of fuel used, the distance and speed of the cruise, and the number of passengers and crew on board. However, according to a study conducted by the International Council on Clean Transportation (ICCT), the average emissions produced by a typical cruise ship are approximately 0.2 to 0.5 kilograms of carbon dioxide (CO_2) per passenger mile traveled.

In addition to CO_2, cruise ships also emit other harmful pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM). The ICCT study estimated that in 2017, the global cruise industry emitted approximately 14 million metric tons of CO_2, 700,000 metric tons of SOx, 150,000 metric tons of NOx, and 10,000 metric tons of PM. These emissions contribute to air pollution, acid rain, and other environmental problems, as well as climate change.

To address these issues, the cruise industry has implemented a range of measures to reduce emissions, such as using cleaner fuels, optimizing ship routes and speeds, and installing emissions control technologies. However, more work is needed to achieve truly sustainable and responsible cruising practices.

And finally some general data about the different kind of ships: [22]

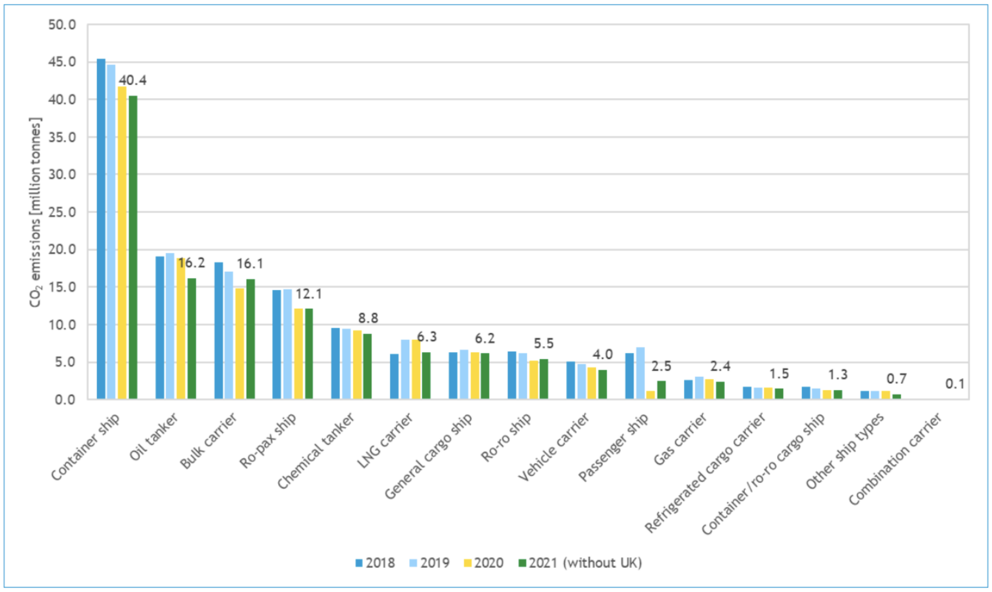


Figure 2.30: Total emissions per ship type.

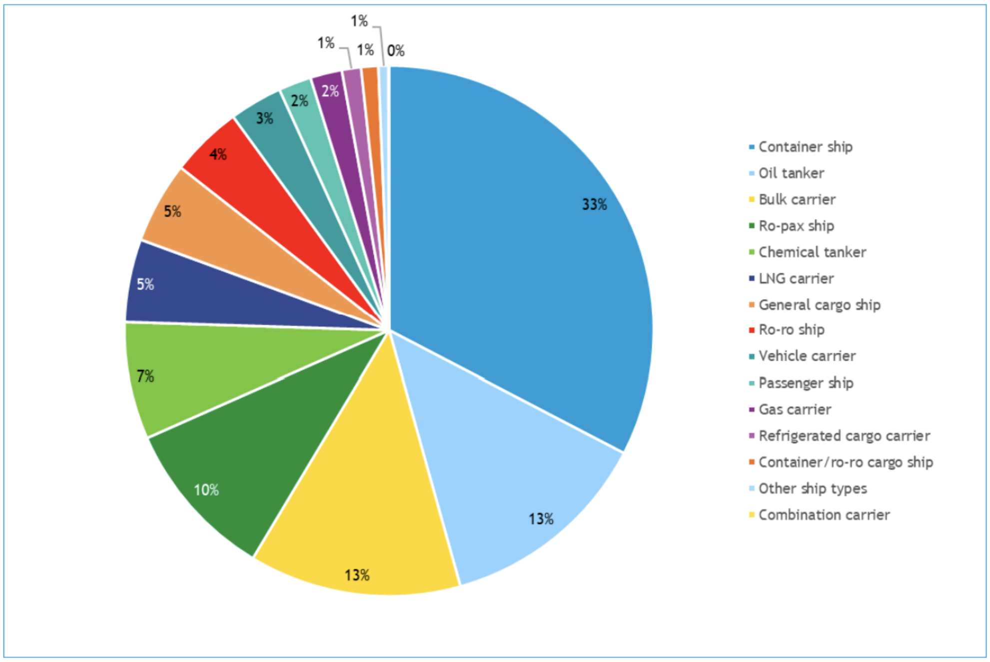


Figure 2.31: Share of CO_2 emissions in 2021 per ship type.

2.2.5 CF existing calculation methods

Finally, here we can find some of the calculation methods that you can currently find in internet done by some of the most importants organisms of the world. They could be important as a way to compare if our calculations makes sense and our conclusions are in the line of what these calculators can tell us. It's also remarkable to thing that probably the quantitiy of emissions obtained here will be higher as some of the requirements and limitations established for doing the current project requires avoid some calculations, meaning it in a minor quantity of GHG emissions calculated. Here are different calculation methods and calculations done:

- Several university studies, like these ones [23]
- ONU calculator, for home and transport. You have to introduce the number of people, country, surface, times, kind of different things...and it calculates your CF impact. [24]
- ICAO calculator. Introducing a departure and arrival airport, it calculates your CF impact in the flight. [25]

Chapter 3

Election of the analysed routes

Once a brief introduction about CF has been done it's time to choose the routes that will be analysed in this document.
In order to make the used routes comparable in equalised conditions, some requirements previously seen in the introduction are imposed:

- Only European countries
- The city chosen for each country will be the one that has one of the biggest harbours and airports (within the city or near).
- All the countries must be reachable by boat.
- Maximum travel distance equal to 4000 km (taking the maximum value from the MOT whose distance travelled is higher).
- Only one departure or destination arrival per country can be used.
- The model chosen for each MOT will be the model most commonly used by the airlines, country or companies for this route. If more or less a couple of models are chosen the same amount of times, then the used one will be the one whose flight has a higher weekly frequency is higher from [26].
- Neither an airline or aircraft couldn't be the same one for more than 1 route.
- The route evaluated must have a direct route by plane. The aircraft model will be the one used by the airline with the shortest flight duration.
- The length of the flight will be calculated linking with an straight line both airports in Google Maps.
- All the countries of departure, arrival and the ones to cross on its way must be reachable by highways.
- The route by car, bus and train will be the shortest in time. Scales time will not be included in the bus or train.
- Both countries must have available railway infrastructure enough to connect both cities.
- The distance travelled by train will be calculated using straight lines during along the route with Google Maps.

- If the time by Google Maps is given with a minimum and maximum, the average time will be chosen.
- The distance travelled by car and bus will be the same.

Since there are not so many countries that meet all the requirements, the available countries are shown in the following table in alphabetical order, separated in the following 2 tables depending on the coast:

1. Cities reachable by the Mediterranean Sea

Country	City
Albania	Durrës
Croatia	Split
Cyprus	Larnaca
France	Marseille
Greece	Athens
Italy	Naples
Malta	La Valletta
Montenegro	Bar
Portugal	Lisboa
Spain	Barcelona
Turkey	Antalya

Table 3.1: Cities selected for each country with mediterranean coast in Europe

2. Cities reachable by the Atlantic Ocean / North Sea

Country	City
Belgium	Antwerp
Denmark	Copenhagen
Estonia	Tallinn
Finland	Helsinki
Germany	Hamburg
Letonia	Riga
Lithuania	Klaipėda
Netherlands	Rotterdam
Norway	Oslo
Poland	Gdańsk
Sweden	Stockholm

Table 3.2: Cities selected for each country with Atlantic or North's sea coast in Europe

As we are going to analyse 4 routes, we will choose 2 routes per table. The method to choose the 4 routes will be simple: for each of the cities that appear on it, we are going to do match cities linked by a direct flight, with the nearest possible route, with direct train connection and well connected with motorways. The final election has been:

(a) Route 1. Naples-Marseille
(b) Route 2. Barcelona-Lisboa
(c) Route 3. Hamburg-Copenhagen
(d) Route 4. Stockholm-Oslo

Once the routes to analyse are known and before taking a deeper look on it, we are going to set several specifications for the manner that the duration and lenght of the travel will be taken: [27] [28]

3.1 Route 1. Naples-Marseille

Naples-Marseille will be the 1st route that we will study in this document. This Mediterranean route is relatively short and it sails along the edge of the Mediterranean sea, from the French Riviera to the Amalfi Coast. As the routes taken by car, taxi, bus and boat (non-direct) are very similar, we will take for thesed MOT the same travel distance: 1090 km.

- Route by plane

  Both cities are connected in a direct route, which the main operator is Ryanair, whose fleet is composed by Boeing 737 Max.

  The duration of the flight is 01h 30min. The distance travelled by plane is around 780 km, flying over the Mediterranean Sea.

- Route by car

  The distance travelled by car is 1090 km. The travel by car or taxi has a duration of 12:10h.

- Route by bus

  The travel by bus needs to do an scale in Genoa. The distance travelled is similar to the one by car, so this value will be taken (1090 km). The total duration of the travel is 18:20h.

- Route by train

  The route by train needs to do several scales in Lyon, Milan and Rome. More or less the distance travelled is the same, as we will again take 1.570 km. Nevertheless, the duration of this travel purely in movement will be 10:30h approximately

- Route by boat

  The only way to reach Naples from Marseille by train is taking a cruise that will make an stop in Ajaccio. Using [29] the distance traveled is 817 km and it takes 22:00 at a speed of 20 kt.

To sum up:

MOT	Distance (km)	Duration (hh:mm)
Plane	780	01:30
Car	1090	12:10
Bus	1090	18:20
Train	1.570	10:30
Boat	817	22:00

Table 3.3: Specifications of route 1

3.2 Route 2. Barcelona-Lisbon

This route crosses the Iberican peninsula from one side to the other, joining the biggest city in Portugal with the 2nd largest in Spain. It will be the larger route studied.

- Route by plane

  Both cities are connected in a direct route, which several operators like TAP Portugal, Easyjet, Ryanair or Vueling. Due to the frequency and the lenght, the chosen one is the first one. The flag airline of Portugal operates mostly with Airbus A320-200 and A321neo, the model chosen.

  The length of the flight is 02:00h and the distance travelled by plane is around 1000 km,

- Route by car

  The distance travelled by car is 1245 km. The travel by car has a duration of 12:00h.

- Route by bus

  The travel by bus has a direct route. The duration of the travel is 15h 15 min. The distance travelled is more or less the same than by car, 1245 km.

- Route by train

  The route by train makes scale in Madrid, Badajoz and Entroncamento. More or less the distance travelled is 1760 km, according to the operators (Renfe and Comboios do Portugal). Nevertheless, the duration of this travel purely in movement will be 11h 30min approximately

- Route by boat

  Both cities doesn't have a direct route by boat, as Lisbon isn't a city where big ferries commonly stop. Through the website [29] we have that the distance between harbours is approximately 1478 km. Taking the maximum speed of a common boat (20 knots), that means 39h to travel between both cities

To sum up:

MOT	Distance (km)	Duration (hh:mm)
Plane	1000	02:00
Car	1245	12:00
Bus	1245	15:15
Train	1760	11:30
Boat	1478	39:00

Table 3.4: Specifications of route 2

3.3 Route 3. Hamburg-Copenhagen

This route joins the 2nd more important city in Europe in terms of maritime traffic and one of the most importants in Germany with Denmark.

- Route by plane

  Both cities are connected in a direct route, which only operator is Xfly, being again the aircraft used is the ATR-72-600.

  The distance travelled by plane is around 280 km and the duration of the flight is 01:00

- Route by car

  The distance travelled by car is 465 km. The travel by car has a duration of 04:40h.

- Route by bus

  The duration of the travel is 07:00 h. The distance travelled is 340 km

- Route by train

  Several trains have to be taken. The duration of the travel is 05:00 km approximately and the distance travelled is more or less 520 km

- Route by boat

  The distance travelled is around 847 km and the duration of the travel 22 hours.

To sum up:

MOT	Distance (km)	Duration (hh:mm)
Plane	280	01:00
Car	465	04:40
Bus	465	07:00
Train	520	05:00
Boat	847	22:00

Table 3.5: Specifications of route 3

3.4 Route 4. Stockholm-Oslo

This route will be the shortest and will gather the Sweden's capital with the Norway's one.

- Route by plane

  Both cities are connected in a direct route, which main operators are Norwegian and SAS. The second one has slightly more frequency than the other. His main aircraft is the Airbus A320neo.

  The distance travelled by plane is around 385 km and the duration of the flight is 1 hour

- Route by car

  The distance travelled by car is 530 km. The travel by car has a duration of 06:00h.

- Route by bus

  The travel by bus is a direct route. The duration of the travel is 07h and 20 min. The distance travelled is the same than in the car, 530 km

- Route by train

  The route by train is a direct one. The duration of the travel is 5h 15 min and the distance travelled is more or less 600 km

- Route by boat

  To do the travel by boat between these 2 cities, you have to sail along the edge of the scandinavian coast. The distance travelled is around 1100 km and the duration of the travel 23 hours.

To sum up:

MOT	Distance (km)	Duration (hh:mm)
Plane	385	01:00
Car	530	06:00
Bus	530	07:20
Train	600	05:15
Boat	1100	23:00

Table 3.6: Specifications of route 4

Chapter 4

CF Aviation

The 1st CF impact measured will be the one produced by the aviation. First of all, the methodology used will be explained as it will apply to all the upcoming sections and will be common. However, specific comments can be considered for each of the routes. In this section the calculations needed to find the values for the first route will be done. Once all the phases have been calculated, it all will be added and gathered as a final results and shown together. From now on, when high numbers or numbers with decimals are used, to separate the number and the decimal the comma will be used (,), while the (.) will mean thousand, million...

4.1 Methodology used

For calculating the total aviation CF, the calculations developed will be divided into the following steps. The methodology used for each step is explained in this section. Here the common process to follow for each of the routes will be briefly explained. Later on, for each of the cases, it may vary a little bit and incorporate some new things. All of them will be further discussed.

4.1.1 Production

.

This comment is a general one for the production and infrastructure cost and emissions produced for each of the MOTs. The production cost and emissions produced are an initial figure, but the aircraft amortizes this throughout its entire lifespan. This is why it is also necessary to obtain an approximate value for the total number of hours that an aircraft usually flies annually, as well as the average age of the fleet of the airlines that will be using it, in order to calculate the cost associated with production per flight hour. In this case, [30] the average duration of the operation time in a Boeing 737 or Airbus A320 is around 25-30 years, so it will be taken a value of 27.5 years. To simplify, the aircraft will only operate the route chosen in a whole round trip, so twice the duration of a single flight during all this time. Considering 4 leap years, these are 10045 days.

Economic cost

Producing an airplane it's approximately proportional to the market price of the airplane and the MTOW (Maximum Take-Off Weight) [31]. Obtaining official data from each of the MTOW for for each of the airplanes used , and being the data taken the maximum possible value of each model, if more than one value is found, MTOWs are:

- Boeing 737-MAX. 82.6 tonnes = 182.101,612 lb
- Airbus A321neo. 129.5 tonnes = 285.498,29 lb
- ATR-72-600. 23 tonnes = 61.729 lb
- Airbus A320neo. 79 tonnes = 174.165 lb

Mainly, the production of an aircraft is separated into development and manufacturing [32]. In the tables that appear in the annex we can see the price per pounds [33]. Multiplying the different MTOW by the prices of the tables and adding the development and manufacturing, we will obtain the total cost of producing each of the models studied.

Emissions produced

The amount of emissions produced during the manufacturing of an aircraft can vary widely depending on the size and type of aircraft, as well as the materials and manufacturing processes used. However, as a rough estimate, a study by the International Council on Clean Transportation (ICCT) estimated that the production of a mid-size commercial aircraft (such as the Airbus A320 or the Boeing 737) results in approximately 4.500 to 6.000 kilograms of CO_2 emissions per kilogram of aircraft weight. An average value of 5.250 kilograms of CO_2 per kilogram will be taken for the calculations. [34]

4.1.2 Infrastructure. Airport

Most of economical information about the construction of the airports is also confidential so it's difficult to obtain real numbers for each of the airports, so certain values have been found and by proportions the rest of the data will be obtained. In order to obtain some data, for example the size of apron or terminal building, an information commonly hidden and not found easily in internet, Google Maps (GM from now on) will be also used to extract some values. For all of them the indication about where the data comes from will be given.

In that case and as happened with the total production cost of an airplane, the construction cost of the airport is something paid for a long time, so it will be also needed the total lifetime of the airport, as well as the annually operations in each of them. The 1st one, the value taken as an standard will be 30 years. Firstly the one taken was the construction, but due to huge differences, the criteria has been changed. For the second one and to simplify, the number of operations will be the ones in 2022 or with available published data. The values used for both economic and emissions will be the average between the values obtained for each of the airports.

Economic cost

For the economic cost of building an airport, an estimation will be done following the numbers and values given by the previous document. The value taken for doing the calculations will be always the average of both values (in case it has a range not only a single value). [35]. Both figures can be found in the Annex.

Emissions produced

Estimating the exact amount of carbon dioxide (CO_2) emissions produced during the construction of a new airport per square meter can be challenging, as it depends on numerous variables, including the construction materials used, construction methods, energy sources, transportation of materials, and other factors.

However, a general estimate of the CO_2 emissions associated with the construction of a new airport from the previous links gives a range from 200 to 600 kilograms of CO_2 per square meter, based on various studies and reports. This estimate includes the emissions associated with the production and transportation of construction materials, on-site construction activities, and energy use during construction. The value used will be the average, 400 kg per m^2.

As it depends on the whole surface, for that case from GM the data taken will be the surface of all the airport (including non-pavement zones). Once the total surface is calculated and with the data of kg per m^2, 30 years of lifetime for the airport and the number of operations, the part proportional to the flight will be taken.

4.1.3 Operation

.

In this section the costs associated to operate aircraft's and airports'.

Economic cost

The cost associated to operate an aircraft will be taken from [36]. In the tables in the Annex we will able to see hte prices of operating an airplane. As a summary, we can extract that the cost to operate an aircraft for a company like the ones in this case (more than 100 milion $ in revenues, is 8.916 $ per block hour. In this case, the block hour per flight will be the flight time + the scale time (1 hour).

The cost to operate an airport can vary widely depending on the airport's size and level of activity. As exact data has been impossible to be found, on average, the operating cost per square meter for a large international airport can range from $200 to $400 USD per year, 300 $ will be taken as an average value. For obtaining the exact value for each flight, we will divide it into airport's operations.

Emissions produced

Flight time. These are the expenses and consumption associated to an airplane during the time that he is operating a single flight. Data obtained will be taken from ICAO's calculator introducing the airports used: [25]. About emissions associated to the operation of the airport, from [37] we can extract some useful information to calculate GHG emissions associated to operating an airport. For the Hong Kong International Airport, we can take the following picture:

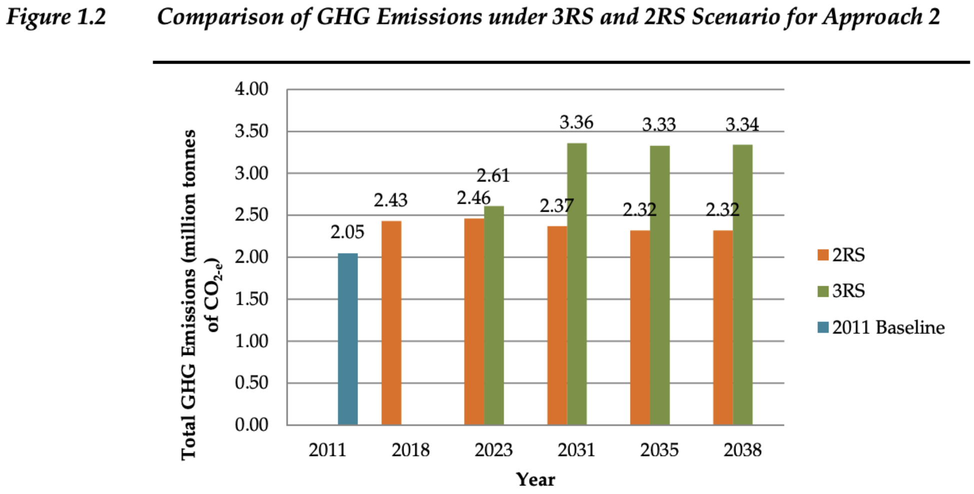


Figure 1.2 Comparison of GHG Emissions under 3RS and 2RS Scenario for Approach 2

Figure 4.1: Airport emissions

Under his current 2 runway system and taking the last available information before making predictions, in 2018, in a year where they had a total traffic of 74.672.000 million passengers (PAX from now on)[38] operating this airport produced 2.43 million tonnes of CO_{2e} (2430 million kg). We will take as an standard values for the rest of the airports a ratio between the contamination and the volume of PAXs, which value will represent the CF that an airport produces yearly per PAX:

$$CF_{PAX1} = \frac{CO_{2e}}{PAX} = \frac{2.430.000.000}{74.672.000}\frac{kg}{PAX} = 32,5423\frac{kgCO_{2e}}{PAX} \tag{4.1}$$

In order to compare this data with another airport, from [39] we will extract available information about the emissions produced by the Paris Charles de Gaulle airport during 2018. In this case, the data obtained is in CO_2, so its value should be fewer that the one we got in the previous calculation. Using the same formula and taking the data for the PAXs traffic volume from [40]

$$CF_{PAX2} = \frac{CO_2}{PAX} = \frac{1.526.298.000}{72.229.723}\frac{kg}{PAX} = 21,1312\frac{kgCO_2}{PAX} \tag{4.2}$$

In both cases the kilograms of CO_2 per passenger will be the same, varying only the one per kilometer.

4.2 Calculations

For each of the routes the total cost and emissions produced will be calculated. To remember the general data, first of all the distance and duration of the flight will be shown. All the calculations has been included in the annexes.

4.3 Final results

If we put together all the information for the different calculated phases for all the routes, converting $ into €:

Production

- Economic cost

	PAX	**km**
Route 1	9,2269	2,3306
Route 2	14,7064	3,178
Route 3	6,5572	1,6391
Route 4	7,1883	3,3645
Average	**9,4164**	**2,6253**

Table 4.1: Economic cost in € related to production associated cost

- Emissions produced

	PAX	**km**
Route 1	147,0945	37,1764
Route 2	313,3469	67,683
Route 3	85,8636	21,466
Route 4	114,6922	53,6223
Average	**165,2494**	**44,9869**

Table 4.2: Emissions produced in kg of CO_2 related to production associated cost

Infrastructure

- Economic cost

	PAX	**km**
Route 1	0,8668	0,2190
Route 2	1,4827	0,3204
Route 3	2,2445	0,5617
Route 4	1,4725	0,6899
Average	**1,5167**	**0,4471**

Table 4.3: Economic cost in $ related to infrastructure associated cost

- Emissions produced

	PAX	**km**
Route 1	2,7076	0,6838
Route 2	1,6964	0,3664237
Route 3	7,8848	1,9712
Route 4	4,365	2,0408
Average	**4,1635**	**5,0622**

Table 4.4: Emissions produced in kg of CO_2 related to infrastructures associated cost

Operation

- Economic cost

	PAX	**km**
Route 1	78,8255	19,8966
Route 2	128,3965	27,6931
Route 3	277,4746	67,1272
Route 4	111,8658	52,3237
Average	**146,7570**	**41,7759**

Table 4.5: Economic cost in € related to operation associated cost

- Emissions produced

	PAX	**km**
Route 1	76,1312	19,228
Route 2	134,23	31
Route 3	54,8312	13,708
Route 4	76,1312	35,5938
Average	**85,3311**	**24,8824**

Table 4.6: Emissions produced in kg of CO_2 related to operation associated cost

Total

- Economic cost

	PAX	**km**
Route 1	88,9906	22,4672
Route 2	144,2839	31,1548
Route 3	277,058	69,39
Route 4	120,4926	56,3463
Average	**157,4501**	**44,7687**

Table 4.7: Total economic cost in €

- Emissions produced

  To convert values of CO_2 into CO_2 equivalent [41]:

	PAX	**km**
Route 1	225,9333	57,09
Route 2	449,2733	99,0494
Route 3	148,5796	37,1452
Route 4	195,1884	91,2569
Average	**254,7436**	**71,1354**

Table 4.8: Total of emissions produced in kg of CO_2

Chapter 5

CF Automotive

The 2nd CF impact measured will be the one produced by the automotive industry. The same procedure that in Chapter 4 will be developed here. The requirements from the previous chapter applies to all the following chapters, so won't be developed again in here.

5.1 Methodology used

For calculating the total automotive impact in the CF, the calculations developed will be divided into the following steps. The methodology used for each step is explained in this section. Here the common process to follow for each of the routes will be briefly explained. Later on, for each of the cases, it may vary a little bit and incorporate some new things. All of them will be further discussed.
For all the cases, the afection of a single one-way trip respect to the volume of emissions and cost will be done. The information needed includes the lifespan of the vehicle, in km and as average, as well as the traffic volume in the infrastructures used.

5.1.1 Production

.
To choose each car that will be used in each case, the best common car in the countries involved will be taken as a reference [42]. For each of the cars, the model chosen has been the one whose fact sheet about GHG emissions has been found (explained in production - emissions).

Economic cost

Nowadays we can find different kind of vehicles regarding how the engine is feed. There are [43]:

- Gasoline. Toyota – Toyota is probably the most popular car brand globally. Forbes magazine has also listed the Toyota Corolla as the best selling car globally. Toyota relies on huge production volumes to lower their costs. For a car that sells for $15,000, the manufacturer can make about $2,500 in profits, leaving the cost of manufacturing at about $12,500. That means that the production car can be estimated as 12500/15000=125/150=0.833333333*selling price is the manufacturing cost, the 83,3% of the car's cost.
- Hybrid. Around the production cost, with no concrete data available, the average between the above and below ratio is taken: 0,756 (75,6%).

- Electrical. The leader in electric vehicles, Tesla, allegedly spends about \$28,000 on every Tesla Model 3. That leaves a mere \$9,000 in profit for the EV manufacturer's low end model. Making the same percentage than in the previous cases, 9000/28000=0,3214% of profit, that is, the production ratio is 0,6786 (67,86%).
- Public bus. From [44] as an average, a public bus costs 500.000 € to be produced.

Emissions produced

From [45] the available data in a form of a life cycle assesment fact sheet of the emissions produced producing different car models are available. The information for the model used or similar will be taken from there. There you can find the emissions associated to the whole lifetime of the car, so in this case, the emissions produced for producing the car will be directly added in the operation chapter.

5.1.2 Infraestructure. Highways and roads

. Economic cost and GHG consumption produced for the construction and maintenance of the highways.

Economic cost

For calculating the economic cost associated to build roads and highways, we will differentiate between these 2 cases. In order to take 2 different values adjusting them to what has been found on internet: roads of 1-2 lanes and highways (3-4). Out of the highways or main roads calculations are avoided, as well as considering tunnels or mountainous highways, which are more expensive and are out of the scope [46].
For the construction depending on the kind of surface:

- Motorways (3-4 lanes): the average cost per kilometer of a motorway in Europe is 10.941.402 € [47]
- Express road (2 lanes): 6.225.187 €
- 2 lane (one each way): 4.159.281 €

About the maintenance costs, the data calculated for Switzerland has been taken [48]. The conversion from CHF [49] to € has been made with the currency status of 2003:

- The average price for a highway (3-4 lanes) is 203.000 CHF per km, which corresponds to 133.552,632 € per km.
- The average price for a road (1-2 lanes) is 59.300 CHF per km, which corresponds to 39.013,1579 € per km.

If we add the construction and maintenance costs, we have:

- 3-4 lanes. 11.074.954,632 € per km.
- 2 lanes. 6.264.200,1579 € per km.
- 1 lane. 4.198.294,16 € per km

With these data and from Google Maps, an estimation of what kind of surface and the kilometers of each one has each of the cases will be done to extract the real numbers. Highways, motorways and roads will be considered in the km account, not the cities' streets or anothers, considered despreciable, so it could be possible that the total addition of km between the different kind of lanes differ from the total distance traveled.

Emissions produced

From [50] it can be seen that approximately for building, maintenance and so on, during the life-cycle of 50 years of a highway, the total tonnes of CO_2 associated are (proportion between the minimum and maximum values given has been done):

- 1 lane. 72.390 tonnes of CO_2 per km.
- 2 lanes. 86.890 tonnes of CO_2 per km.
- 3 lanes. 101.390 tonnes of CO_2 per km.
- 4 lanes. 115.886 tonnes of CO_2 per km.

To obtain the specific number, we also need the average quantity of cars that circulates per each kind of highway every day. From [51] this number is 14.820 million vehicles / year per kilometer.

5.1.3 Operation

. Expenses and GHG consumption generated by a single car during his average lifetime.

Economic cost

To properly calculate the production cost and the emissions, the most common car used in each of the countries involved in both airports will be taken, with the average of both value and consumption.

For calculate the fuel cost, the average consumption in L/100 km of each car will be taken. Making a proportion between this data and the km of the route, we will obtained the needed L to complete it. Once done, with the price of the fuel per litres, the total cost will be found. The price per fuel used has been taken from [52] for each of the countries.

About the maintenance cost of the car, per kilometer is estimated to be between 4,5 to 9 cents$ per kilometer, escalating from 4,5 to the cheapest car (Fiat Panda with a cost of 10.360 €) to 9 for the most expensive (Volvo XC40 with a cost of 57.779 €). With a lineal regression, being X the price of the car and Y the maintenance cost per kilometer, the equation to be used will be in:

$$y = \frac{9x + 333.531}{9,483,800€} \tag{5.1}$$

The average rest of the operating costs (except the fuel and maintenance) of a car per kilometer can include expenses such as insurance, taxes, and depreciation. According to estimates by the Canadian Automobile Association (CAA), [53] these costs can average around 21 cents per kilometer for a small sedan (Fiat Panda considered), 24 cents per kilometer for a medium-sized sedan, and

28 cents per kilometer for a large sedan or SUV (Volvo XC40 considered). Again, doing a lineal regression and being Y the remaining operating costs, the equation used will be:

$$y = \frac{7x + 923.279}{4.741.900€} \tag{5.2}$$

For the buses, the value taken is 1.39 €/km directly from [54].

Emissions produced

From [55] we have the total emissions of one car during all his lifecycle and its production. If we take as an average of 100.000 km/car until he is scrapped, that means that per kilometer:

1. Gasoline or diesel vehicle. Direct emissions between 85-215 [gCO_2, /km].
2. Hybrid vehicle. Direct emissions between 85-215 [gCO_2, /km].
3. Plug-in vehicle. Direct emissions between 170-190 [gCO_2, /km].
4. Battery electric vehicle. Direct emissions between 170-190 [gCO_2, /km].

If the model is available, the exact consumption will be taken from [45]. For the buses an average consumption for a diesel bus is 24 L/100 km. Taking per L of diesel burned 2,7 kg of CO_2 eq , that means 0,648 kg of CO_2 equivalent burned per kilometer. [56].

5.2 Calculations

Section included in the Annex

5.3 Final results

If we put together all the information for the different calculated phases for all the routes:

Production

- Economic cost

	PAX (car)	**PAX (bus)**	**km (car)**	**km (bus)**
Route 1	31,6536	99,0909	0,1452	5
Route 2	48,14	113,1818	0,1933	5
Route 3	24,5269	42,2727	0,2637	5
Route 4	38,1162	48,1818	0,3596	5
Average	**35,6092**	**75,6818**	**0,2405**	**5**

Table 5.1: Economic cost in € related to production associated cost

Infrastructure

- Economic cost

	PAX (car)	**PAX (bus)**	**km (car/bus)**
Route 1	3,0669	0,2788	0,0141
Route 2	2,8389	0,258	0,0114
Route 3	0,3715	0,0338	0,004
Route 4	0,444	0,0404	0,0042
Average	**1,6803**	**0,1527**	**0,0084**

Table 5.2: Economic cost in € related to infrastructure associated cost

- Emissions produced

	PAX (car)	**PAX (bus)**	**km (car/bus)**
Route 1	31,649	2,8772	0,1452
Route 2	38,5348	3,5032	0,1547
Route 3	5,1495	0,4681	0,0554
Route 4	6,6277	0,6025	0,0625
Average	**20,4902**	**1,7121**	**0,1044**

Table 5.3: Emissions produced in kg of CO_2 related to infrastructure associated cost

Operation

- Economic cost

	PAX (car)	**PAX (bus)**	**km (car)**	**km (bus)**
Route 1	80,5074	27,5473	0,3693	1,39
Route 2	92,3402	31,4645	0,3708	1,39
Route 3	40,2853	11,7518	0,4332	1,39
Route 4	84,6783	13,3945	0,7988	1,39
Average	**74,4528**	**21,0395**	**0,4930**	**1,39**

Table 5.4: Emissions produced in € related to operations associated cost

- Emissions produced

	PAX (car)	**PAX (bus)**	**km (car)**	**km (bus)**
Route 1	42,2252	12,7138	0,1937	0,6415
Route 2	48,9569	14,5217	0,1966	0,6415
Route 3	20,5086	5,4238	0,2205	0,6415
Route 4	12,1798	2,4866	0,1149	0,2580
Average	**30,9676**	**8,7864**	**0,1814**	**0,5456**

Table 5.5: Emissions produced in kg of CO_2 related to operations associated cost

Total

- Economic cost

	PAX (car)	**PAX (bus)**	**km (car)**	**km (bus)**
Route 1	113,8252	126,917	0,5286	6,5352
Route 2	143,3192	144,9043	0,5755	6,4014
Route 3	65,1837	54,0583	0,7009	6,394
Route 4	123,2385	61,6167	1,1626	6,3942
Average	**111,3916**	**96,8741**	**0,7419**	**6,4303**

Table 5.6: Total economic cost in €

- Emissions produced

	PAX (car)	**PAX (bus)**	**km (car)**	**km (bus)**
Route 1	73,8742	15,591	0,3389	0,7867
Route 2	87,4916	18,0248	0,3514	0,7963
Route 3	25,6581	5,8919	0,2759	0,6969
Route 4	18,8075	3,0891	0,1774	0,7040
Average	**51,4579**	**10,6492**	**0,2859**	**0,746**

Table 5.7: Total emissions produced in kg of CO_2

Chapter 6

CF Railway Transport

6.1 Methodology used

6.1.1 Production

The trains used are going to be electrical as from [57] it can be seen that most of the fleet of the studied countries has more electrical than diesel trains. Besides, in the kind of trains that our routes takes (high-speed trains), almost all of them are electric.
In this case about the amortization of every train, the assumption made is also a round trip with it, in this case taken into account only the displacement time. According to a report by the Federal Railroad Administration (FRA) in the United States, the typical lifespan of a passenger train ranges from 25 to 35 years, so 30 years will be the value taken. [58]

Economic cost

The exact cost of producing the different train models that will be analysed is not publicly available information, as it likely involves a complex calculation that takes into account various factors such as material costs, labor costs, research and development expenses, and other related expenses. The production cost of similar trains have been found and will be related with the different models used in the different routes making some proportions regarding their specifications. The data available is:

- Siemens Velaro: The production cost of a Siemens Velaro high-speed train is estimated to be around €35-40 million per trainset, according to industry experts. [59]
- Alstom Euroduplex: The production cost of an Alstom Euroduplex trainset is estimated to be around €30-35 million per trainset, according to industry sources. [60]
- Bombardier Zefiro 350: The production cost of a Bombardier Zefiro high-speed train is estimated to be around €30-35 million per trainset, according to industry sources. [61]

With this information we can see that a train costs approximately between 30 and 40 million €. Similar to the case of an airplane, supposing a production cost proportional to his MTOW, in this case the weight of each of those trains will be taken in order to make a regression:

- Siemens Velaro. 667 tonnes.
- Alstom Euroduplex. 385 tonnes.

- Bombardier Zefiro 350. 462 tonnes.

With this data a weight of 385 tonnes means a cost of 30 million €, while a weight of 667 tonnes means a cost of 40 million €. Highest or lowest values will be taken proportionally, while the ones in the range will follow the next equation:

$$y = \frac{5x + 2305}{141} \tag{6.1}$$

where x will be the weight of the train. We will also need the passengers capacity. It will always be taken the one more similar between the 2 or more trains used.

Emissions produced

For the emissions, a study published in the Journal of Cleaner Production estimated that the production of a Siemens Velaro high-speed electric train is estimated to emit around 19 tonnes of CO_2 per kW of power output.

6.1.2 Infrastructure. Railways and train facilities

Economic cost

For the economic cost of constructing a high-speed rail infrastructure is expensive [62]. From the previous study and taking the final construction cost per kilometer, taken lines of the countries studied, we have the following averages for the different routes (price in million € per kilometer):

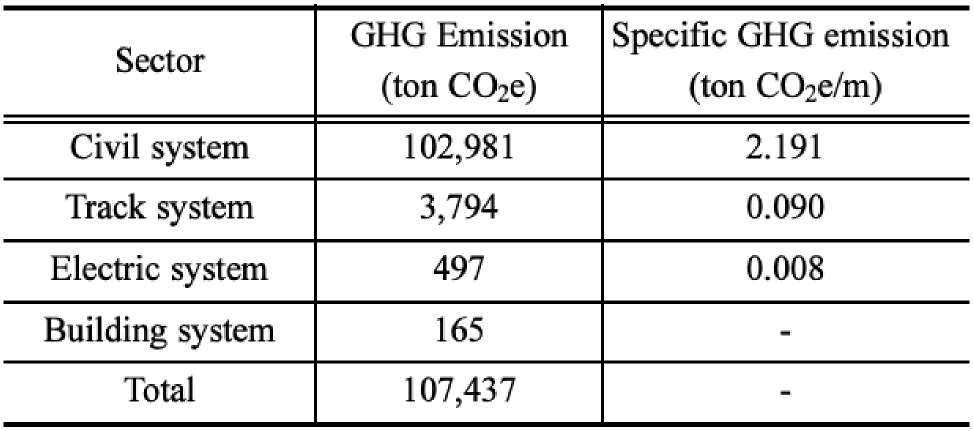
- Route 1. Naples - Marseille. Lines per Italy/France: 18,8; 16,5;15,7;31,9;43. On average: 25,18 million €.
- Route 2. Barcelona - Lisbon. Lines per Spain/Portugal: 15,2;15,7;13,7. On average: 14,8666 million €.
- Route 3. Hamburg - Copenhagen. Lines per Germany/Denmark: 21,9;49,7;18,8. On average: 23,4667 million €.
- Route 4. Stockholm - Oslo. As there is any data for lines per Sweden or Norway, the average of previous averages is done, giving a number of 21,1711 million €.

Having the total km of the line, we will be able to calculate the total cost. With the total cost, we will calculate the daily cost. [63] Taking as a reference that Hamburg Hauptbahnhof,the busiest railway station in Germany, it's estimated to have around 550 trains pass through the station every day, with 480.000 daily passengers and 550 trains, the average is 872,7273 PAX/train (if not information is found). The information for the 2 stations will have to be added with the total PAX of both.

About the cost of building a railway station can vary greatly depending on its size. It will depend on the surface (if not found taken from GM) and daily operations/passengers and it will be seen in each route. As no relationship has been found in €/m2 or similar particularly for the stations, as the data in general is done of the full construction of the lanes per km, generally including what is purely railways, tunnels and so on, the value taken will be the one chosen for the airports' terminals, 4576 $ per m2 converted into € 4.170,2 € per m_2, as the kind of facilities, installations needed are the same. Also as in the airports', 30 years of lifespan will be taken. It will be needed to know also the PAX per year.

Emissions produced

About the emissions, in this article you can find the CO_2 equivalent emissions of building the railway infrastructure. Adding the 3 kind of systems they mention (civil, track and electric), the cost is 2,289 tonnes CO_2e/m. [64]



Sector	GHG Emission (ton CO_2e)	Specific GHG emission (ton CO_2e/m)
Civil system	102,981	2.191
Track system	3,794	0.090
Electric system	497	0.008
Building system	165	-
Total	107,437	-

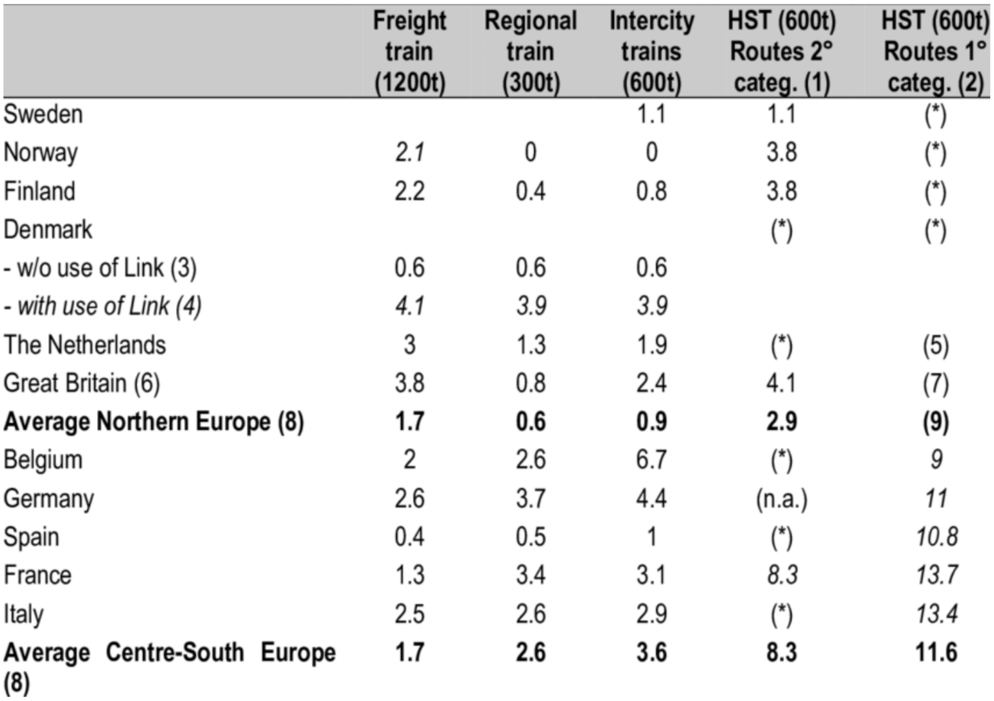
Figure 6.1: Railroad cost per meter

Besides, we have to add the approximate emissions produced when constructing a train station. While the exact amount of emissions associated with the construction of a train station will vary depending on a range of factors, from [65] is estimated that the construction of a typical railway station in the UK produces around 300-500 tonnes of CO_2. An average value of 400 tonnes of CO_2 will be taken.

6.1.3 Operation

Economic cost

About the economic cost to operate a train, from this source it will be obtained the average cost per kilometer of different countries in Europe. There is only one country of the ones where the trains will pass who isn't in the list (Portugal), so its value will be the last one (Average South Europe) [66] . The value taken will be the ones of the column Intercity trains:



	Freight train (1200t)	Regional train (300t)	Intercity trains (600t)	HST (600t) Routes 2° categ. (1)	HST (600t) Routes 1° categ. (2)
Sweden			1.1	1.1	(*)
Norway	*2.1*	0	0	3.8	(*)
Finland	2.2	0.4	0.8	3.8	(*)
Denmark				(*)	(*)
- w/o use of Link (3)	0.6	0.6	0.6		
- with use of Link (4)	*4.1*	*3.9*	*3.9*		
The Netherlands	3	1.3	1.9	(*)	(5)
Great Britain (6)	3.8	0.8	2.4	4.1	(7)
Average Northern Europe (8)	**1.7**	**0.6**	**0.9**	**2.9**	**(9)**
Belgium	2	2.6	6.7	(*)	*9*
Germany	2.6	3.7	4.4	(n.a.)	*11*
Spain	0.4	0.5	1	(*)	*10.8*
France	1.3	3.4	3.1	*8.3*	*13.7*
Italy	2.5	2.6	2.9	(*)	*13.4*
Average Centre-South Europe (8)	**1.7**	**2.6**	**3.6**	**8.3**	**11.6**

Figure 6.2: Average cost per km of the use of the train network

The cost per kilometer to maintain a train can vary widely depending on a number of factors, such as the type of train, the age of the train, the frequency of maintenance, and the specific maintenance activities required. However, as a rough estimate, the maintenance cost per kilometer for a passenger train is typically between 0,045 € and 0,18 €. As in this case intercity trains have very similar specifications, a common average value will be taken, 0,1112 € per kilometer.

About the cost of operating a train station daily can vary widely depending on a number of factors. However, as a rough estimate, the daily operating cost for a medium-sized train station it's about 4.500 €, while larger stations may have operating costs of 10.000 € per day. Each of the stations will be qualified as a smallest one (16.720) or largest one (77.000) and, in comparison with all, some or other values will be given to them. The equation used is:

$$y = \frac{25x}{274} + \frac{407500}{137} \tag{6.2}$$

being x the size of the station in m2.

Emissions produced

About the emissions to operate a train, from here [67] we can take a value of 358 grams of CO_2 equivalent per km for electric trains and 1400 grams for diesel ones. It won't depend on any factor and will be the same in all the cases, but no data has been found.

About the emissions to operate a train station, the CO_2 equivalent emissions per square meter could range from approximately 0.1 to 1 kilogram of CO_2 equivalent per square meter per day. A value of 0.55 kg CO_2 equivalent per square meter per day will be taken.

6.2 Calculations

Included in the Annex

6.3 Final results

6.3.1 Production

Economic cost

	PAX	**km**
Route 1	4,1358	1,0563
Route 2	6,8458	0,6807
Route 3	4,926	1,9325
Route 4	3,4455	1,6883
Average	**4,8383**	**1,3395**

Table 6.1: Economic cost in € related to production associated cost

Emissions produced

	PAX	**km**
Route 1	0,019	0,0049
Route 2	0,0205	0,002
Route 3	0,0095	0,0037
Route 4	0,0062	0,0031
Average	**0,0138**	**0,0034**

Table 6.2: Emissions produced in kg of CO_2 related to production associated cost

6.3.2 Infrastructre

Economic cost

	PAX	**km**
Route 1	45,7204	11,674
Route 2	33,1129	3,2941
Route 3	16,4529	6,4546
Route 4	19,7444	9,6748
Average	**28,7576**	**7,7744**

Table 6.3: Economic cost in € related to operations associated cost

Emissions produced

	PAX	**km**
Route 1	4,1244	1,0534
Route 2	5,0774	0,5049
Route 3	1,5947	0,6256
Route 4	2,1246	1,0411
Average	**3,2607**	**0,8062**

Table 6.4: Emissions produced in kg of CO_2 equivalent related to infrastructures associated cost

6.3.3 Operation

Economic cost

	PAX	**km**
Route 1	12,2852	3,1378
Route 2	25,3478	2,5204
Route 3	10,6401	4,1742
Route 4	2,4647	1,2077
Average	**12,6845**	**2,76**

Table 6.5: Economic cost in € related to operations associated cost

Emissions produced

	PAX	**km**
Route 1	1,7922	0,3969
Route 2	3,8309	0,3809
Route 3	0,9896	0,3882
Route 4	0,8771	0,4298
Average	**1,8724**	**0,3989**

Table 6.6: Emissions produced in kg of CO_2 equivalent related to operations associated cost

6.3.4 Total

Economic cost

	PAX	**km**
Route 1	62,1431	15,8682
Route 2	65,3065	6,2253
Route 3	32,019	12,5613
Route 4	25,6547	12,5708
Average	**46,2808**	**11,8064**

Table 6.7: Total economic cost in €

Emissions produced

In CO_2 equivalent due to the few influence that production's associated emissions have.

	PAX	**km**
Route 1	5,9356	1,4552
Route 2	8,9288	0,8878
Route 3	2,5939	1,0176
Route 4	3,008	1,4739
Average	**5,1166**	**1,2086**

Table 6.8: Total emissions produced cost in kg of CO_2 equivalent

Chapter 7

CF Nautical

The last MOT and CF calculated, following the same structure than before, will be presented here. Calculations for recreational/private boats or yachts and cruise ships will be done. According to a report by the Cruise Lines International Association (CLIA), many of the newest and largest cruise ships in operation today are expected to have a lifespan of around 25 to 30 years or more, thanks to advancements in shipbuilding technology and ongoing maintenance and refurbishment efforts. This last value is the taken one, the same that for airplanes and trains [68]

7.1 Methodology used

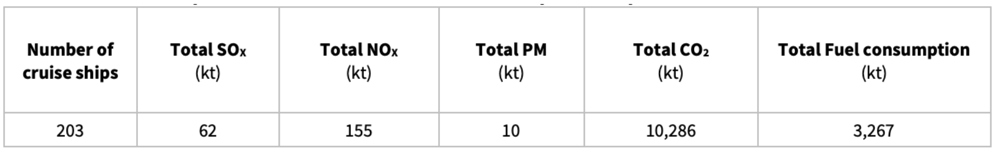
7.1.1 Production

Economic cost

For the cruise ship used, the chosen vessel will be a cruise ship for which weight, and passenger capacity data are available, and which has a stop at least one of the harbours associated with the studied routes. [69] The specifications will be found here [70].

Emissions produced

From here and being this value usable for future calculations [71] the conversion between CO_2 and CO_2 equivalent in boats will be done taken into account this data:



Number of cruise ships	Total SO_x (kt)	Total NO_x (kt)	Total PM (kt)	Total CO_2 (kt)	Total Fuel consumption (kt)
203	62	155	10	10,286	3,267

Figure 7.1: Conversion to CO_2 equivalent for ships

Using the formula of the CO_2 equivalent, the ponderation of each gas, and with the GWP of NOx being 41.075, 1 gram of CO_2 will be 5 g of CO_2 [72]. For the emissions of a boat from [73] a 152.407.036,5 kg boat emits 101.097 tonnes of CO_2 equivalent, which is 0,6633 kg of CO_2 equivalent per kg.

7.1.2 Infrastructure. Harbours

Economic cost

Although TEus (Twenty-foot Equivalent Unit) is a unit from the mercaderies transportation, it will be the reference unit to obtain the total cost of the port. From some of the projects in the [74]. For the Sorong, Seget district, West Papua, Indonesia, whose project involves the construction of a new port with 2.950.000 million TEUs with a cost of 1.630.000.000 €, the following proportion is done: 552,5424 € / TEU. If any of the ports has no available data about the annually capacity of TEUs, a proportion with the PAX of another port will be done (the other of the route for example).

Emissions produced

From this link, we can have an average of 1.000 kg of CO_2e per each m2 of floor area of the airport. [75]

7.1.3 Operation

Economic cost

Operating costs can be calculated regarding the initial production prace. Normally, operating costs are around 10 to 15% of the initial price of the boat, while maintenance moves between 5 to 15% annually. It means that from 15 to 30 % is the total value to operating a costs per year. A value of 20 % will be taken.

For the cost for harbors, the operating cost of a commercial harbor will depend on various factors, such as labor costs, maintenance costs, and energy costs, among others. According to a report by PwC, the average operating cost per container for a typical terminal ranges between 20-60 euros per TEU, depending on the size and location of the harbor. A price of 40 € will be taken.

Emissions produced

Although a large cruise ship can use almost 250 tons of fuel per day, on average it is 150 tons. It is 6,25 tonnes per hour. With the conversion between L and kg is 1 kg = 1.15 L it is 7.187,5 L per hour. With the average data of diesel maritime burned of 20 lb CO_2/gallon, which is the same that 5,28 kg of CO_2 per each liter burned. [76]

For the emissions emited by the port, from [77] we will obtain the total emissions in the port. With the TEUs or directly the PAX, the ratio will be obtained and later on converted to the one in km.

7.2 Calculations

Shown in the Annex

7.3 Final results

7.3.1 Production

Economic cost

	PAX	**km**
Route 1	14,691	101,2726
Route 2	26,4185	122,798
Route 3	18,7892	92,7259
Route 4	18,7892	71,3989
Average	**19,672**	**97,0488**

Table 7.1: Total economic cost associated to the production in €

Emissions produced

	PAX	**km**
Route 1	1,8524	12,7697
Route 2	3,3486	15,5645
Route 3	2,4591	12,1357
Route 4	2,4591	9,3445
Average	**2,5298**	**12,4536**

Table 7.2: Total emissions produced related to production in kg of CO_2e

7.3.2 Infrastructure

Economic cost

	PAX	**km**
Route 1	12,0229	82,8801
Route 2	8,8271	41,0298
Route 3	152,929	754,7101
Route 4	0,3118	1,185
Average	**43,5227**	**219,9512**

Table 7.3: Total economic cost associated to the infrastructure in €

Emissions produced

	PAX	**km**
Route 1	5,4185	37,3526
Route 2	37,5879	174,7149
Route 3	****	****
Route 4	34,7436	132,0256
Average	**25,9166**	**114,6977**

Table 7.4: Total emissions produced related to infrastructure in kg of CO_2e

7.3.3 Operation

Economic cost

	PAX	**km**
Route 1	105,9828	730,5936
Route 2	217,1325	1.009,2696
Route 3	161,9618	782,4739
Route 4	111,25	422,7523
Average	**149,0818**	**736,2724**

Table 7.5: Total economic cost associated to the operation in €

Emissions produced

	PAX	**km**
Route 1	1.008,1421	6.949,6275
Route 2	364,5143	1.694,3255
Route 3	****	****
Route 4	43,1249	163,8748
Average	**471,9271**	**2.935,9426**

Table 7.6: Total emissions produced related to operation in kg of CO_2e

7.3.4 Total

Economic cost

	PAX	**km**
Route 1	132,6967	914,7463
Route 2	252,3781	1.173,0974
Route 3	333,68	1.629,91
Route 4	130,3510	495,3362
Average	**212,2764**	**1.053,2725**

Table 7.7: Total economic in €

Emissions produced

	PAX	**km**
Route 1	1015,4131	6999,7498
Route 2	405,4507	1884,6050
Route 3	***	***
Route 4	80,3276	305,245
Average	**500,3971**	**3063,1999**

Table 7.8: Total emissions produced in kg of CO_2e

Chapter 8

Comparison of the previous calculations and election of the cleanest MOT

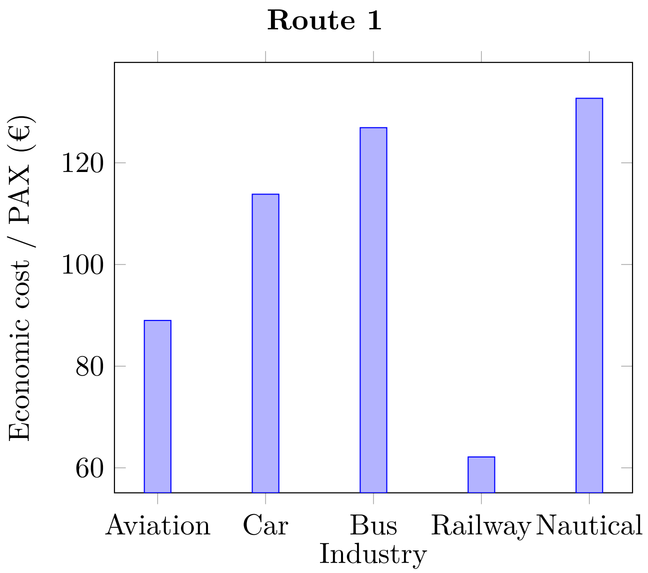
In the previous section, the economic and environmental impact of the production, infrastructure construction, and operation of different MOTs was studied. In this section, we delve deeper into comparing the results obtained according to the MOT and the evaluated part of the process. Different industries, such as aviation, automotive, railway and maritime transportation, will be examined, and their impact on economic and environmental terms will be evaluated.

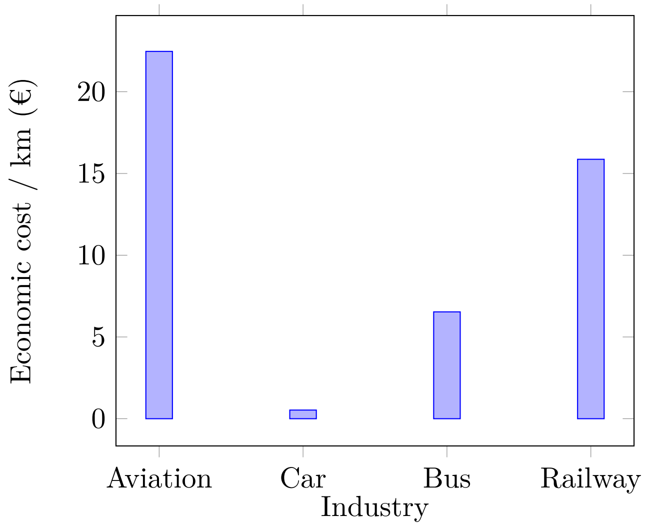
Additionally, the results obtained in different parts of the process, such as production, infrastructure construction, and operation, will be compared. The aim of this section is to provide a detailed insight into how different modes of transportation affect the economy and the environment, which can be useful for decision-making in transportation planning and management.

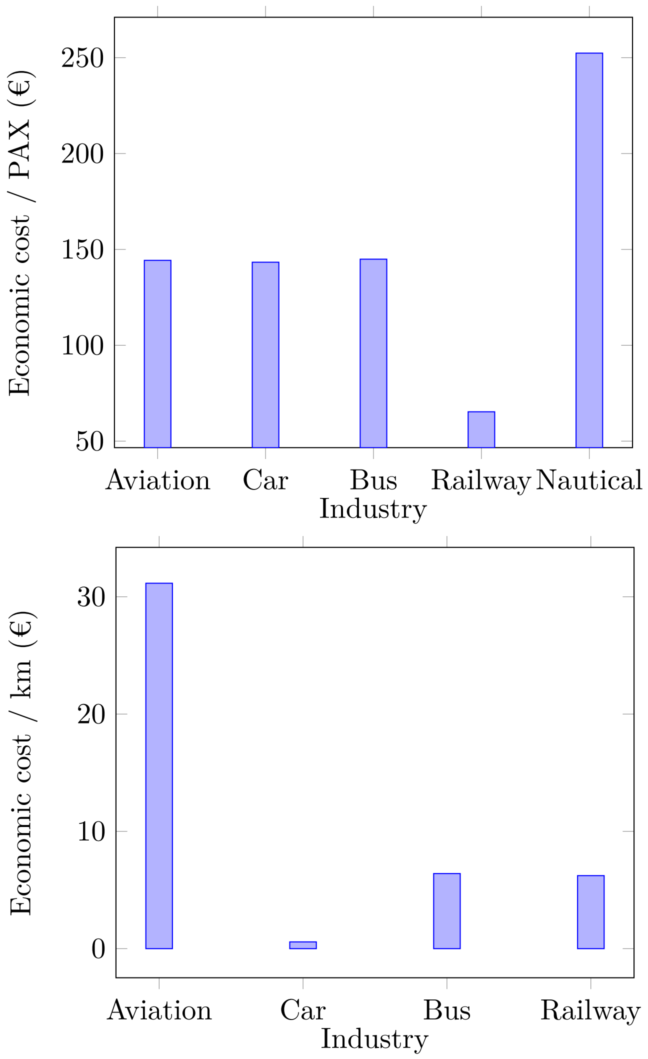
8.1 Comparison by route

In this section for every route we will see 2 graphics. The 1st of them is the comparison between the different industries of the cost per PAX & km for each of them. The 2nd one, about the emissions produced.

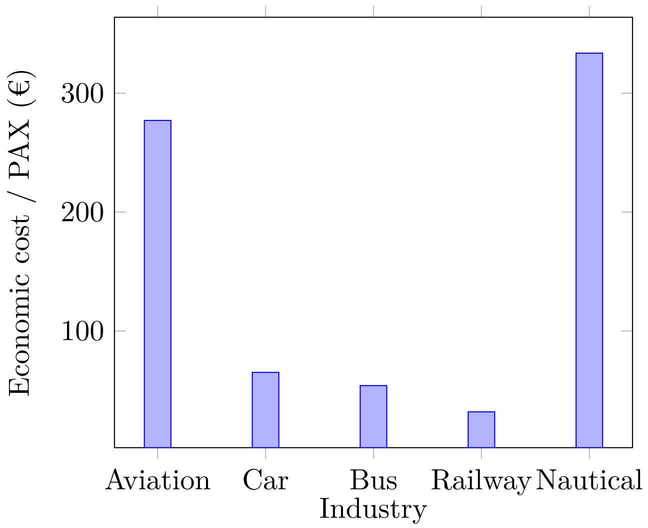
8.1.1 Economic cost

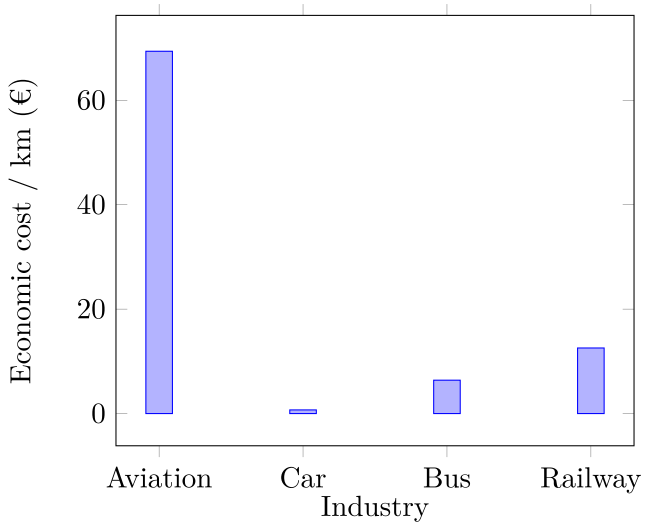




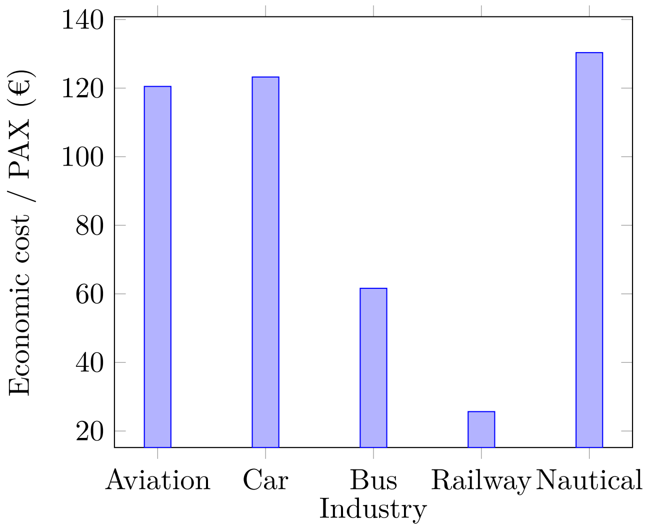

Route 2
Economic cost / PAX (€)
250
200
150
100
50
Aviation
Car
Bus
Railway
Nautical
Industry
Economic cost / km (€)
30
20
10
0
Aviation
Car
Bus
Railway
Industry

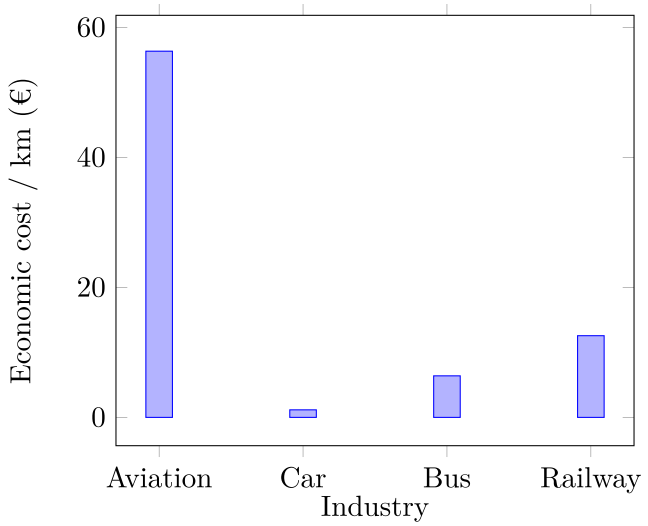
Route 3


Economic cost / PAX (€)
300
200
100
Aviation
Car
Bus
Railway
Nautical
Industry


Economic cost / km (€)
60
40
20
0
Aviation
Car
Bus
Railway
Industry

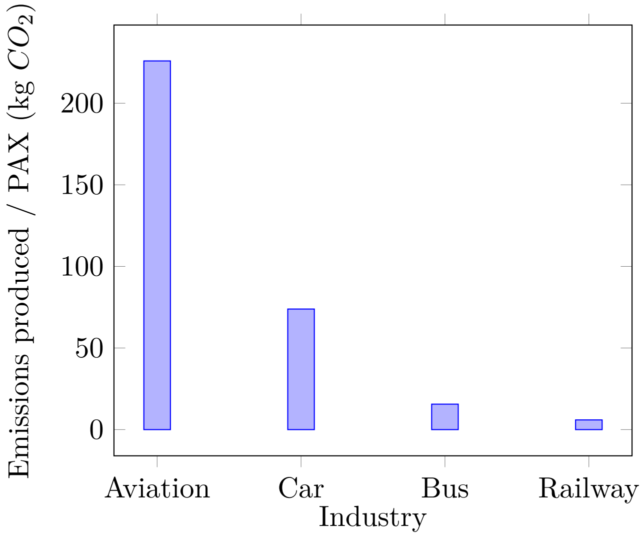
Route 4

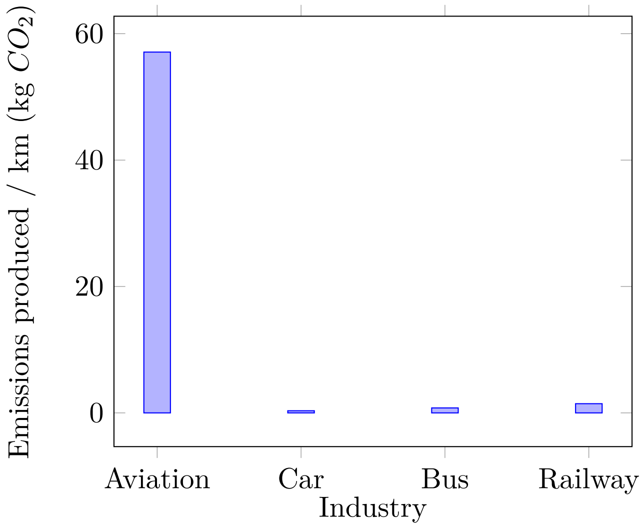

Economic cost / PAX (€)
140
120
100
80
60
40
20
Aviation
Car
Bus
Railway
Nautical
Industry


Economic cost / km (€)
60
40
20
0
Aviation
Car
Bus
Railway
Industry

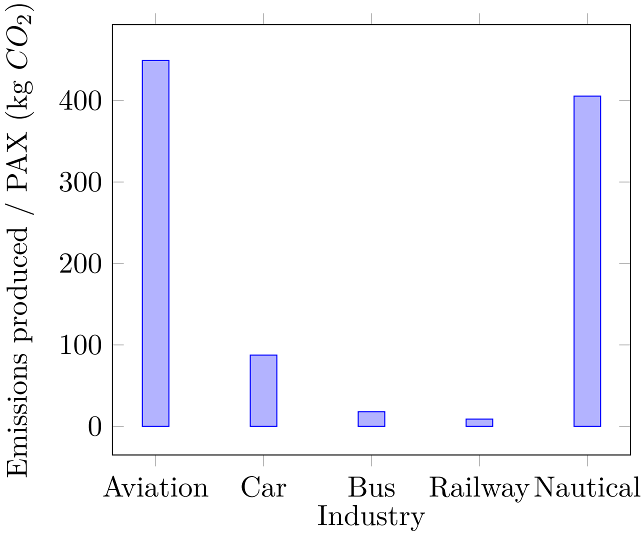
8.1.2 Emissions produced

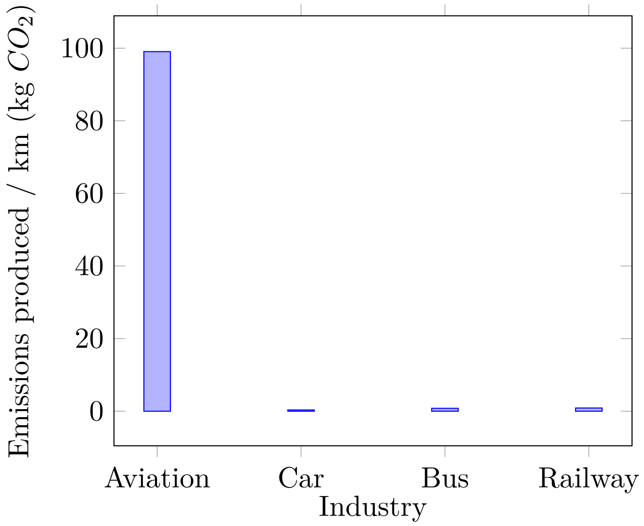
Route 1



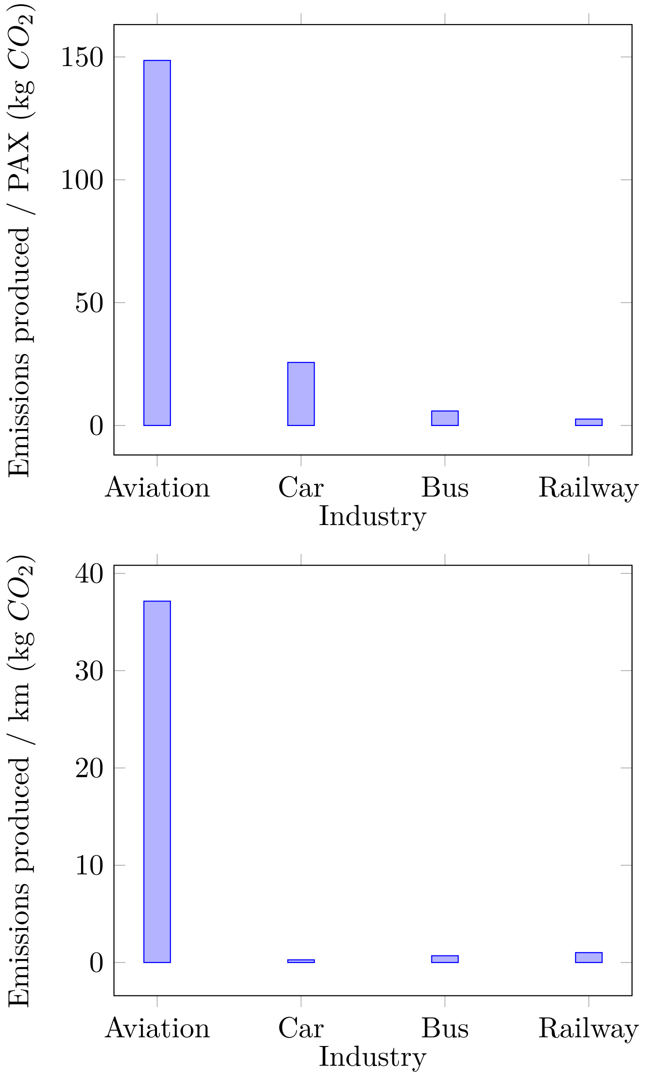


Route 2

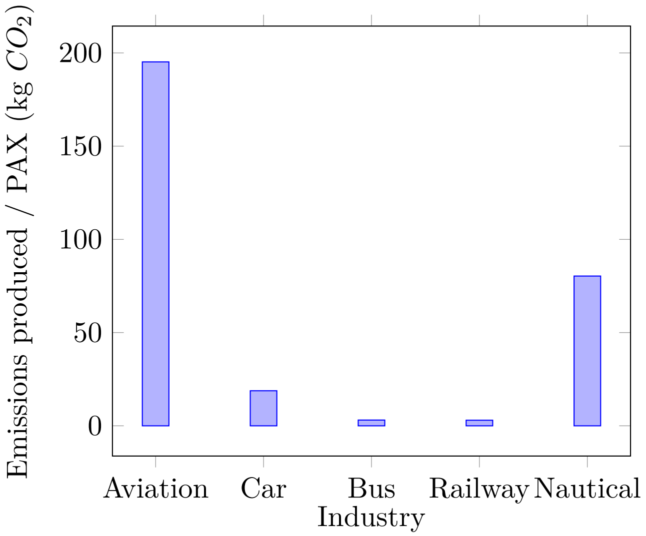

Emissions produced / PAX (kg CO_2)
0
100
200
300
400
Aviation
Car
Bus
Railway
Nautical
Industry

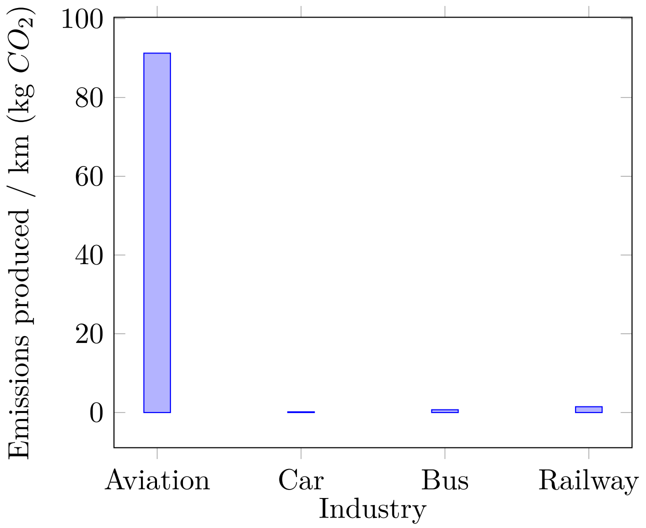

Emissions produced / km (kg CO_2)
0
20
40
60
80
100
Aviation
Car
Bus
Railway
Industry

Route 3


Emissions produced / PAX (kg CO_2)
150
100
50
0
Aviation
Car
Bus
Railway
Industry
Emissions produced / km (kg CO_2)
40
30
20
10
0
Aviation
Car
Bus
Railway
Industry

Route 4


Emissions produced / PAX (kg CO_2)
200
150
100
50
0
Aviation
Car
Bus
Railway
Nautical
Industry


Emissions produced / km (kg CO_2)
100
80
60
40
20
0
Aviation
Car
Bus
Railway
Industry

8.1.3 Conclusions

From all the graphics seen before we can see several tendencies

- Economic cost
    1. The economic cost per PAX in a train is the lowest compared to the others. In all the routes, being the one with the closes difference to the public tranport (bus) the route 3, which is one of the shortest in time.
    2. The economic cost per km in a car is the lowest compared to the others. This is mainly because the cost in production, it will be seen in the next section.
    3. In the graphics where the nautical industry appears, the ones who is not there is because its numbers make the others being meaningless, it can be seen that with the aviation is the one whose economic cost per PAX is higher.
    4. In all the graphs, we can see that aviation is the industry that has the highest economic cost per km, by far. In most of the cases the cost per PAX is paired with others' one.
- Emissions produced
    1. In all the cases aviation is by far the one who produces more emissions than the others.
    2. In all the cases, the lowest emissions produced by PAX are from the railway industry.
    3. For the emissions produced per km, the car is the one with the lowest ones, followed by the bus and railway

8.2 Comparison by part of the process

8.2.1 Production

Economic cost

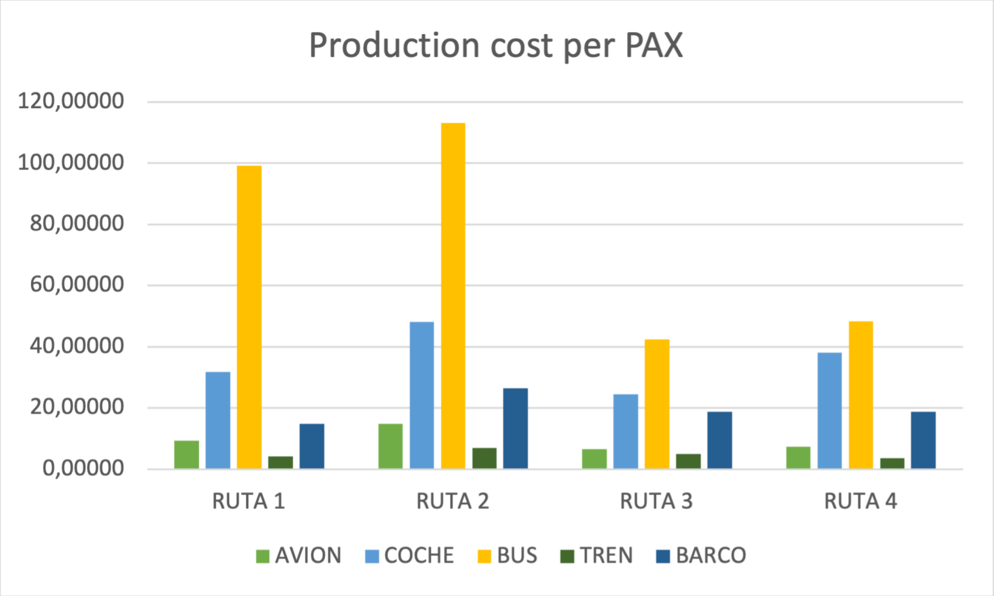


Figure 8.1: Production cost per PAX in each of the routes.

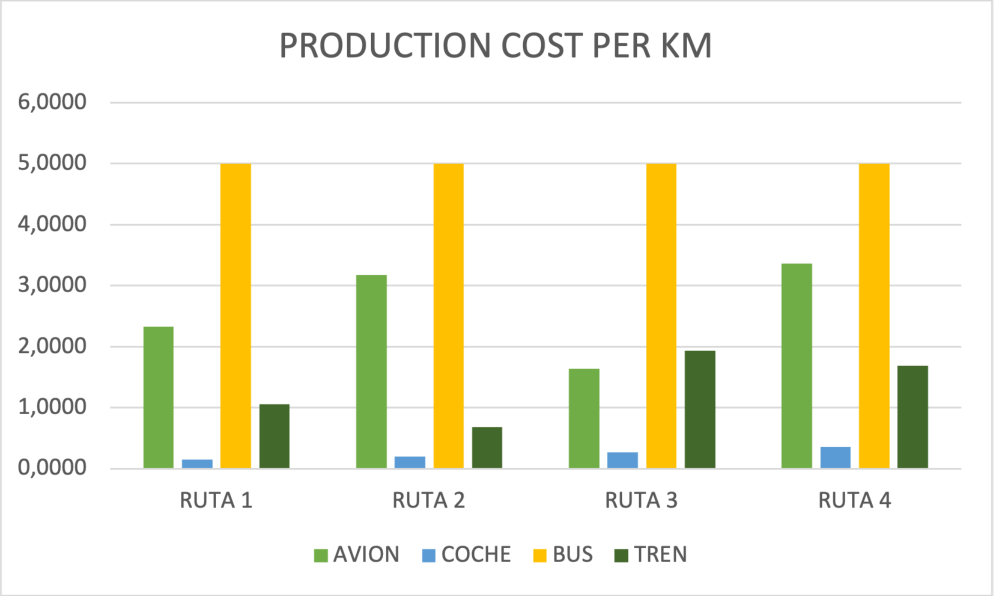


Figure 8.2: Production cost per km in each of the routes.

Emissions produced

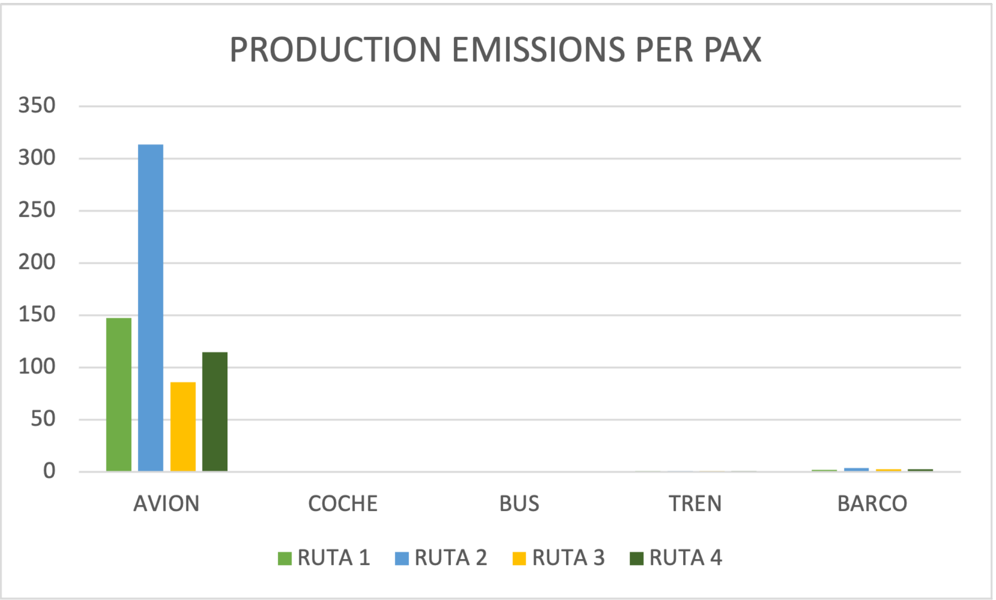


Figure 8.3: Emissions produced for production per PAX in each of the routes.

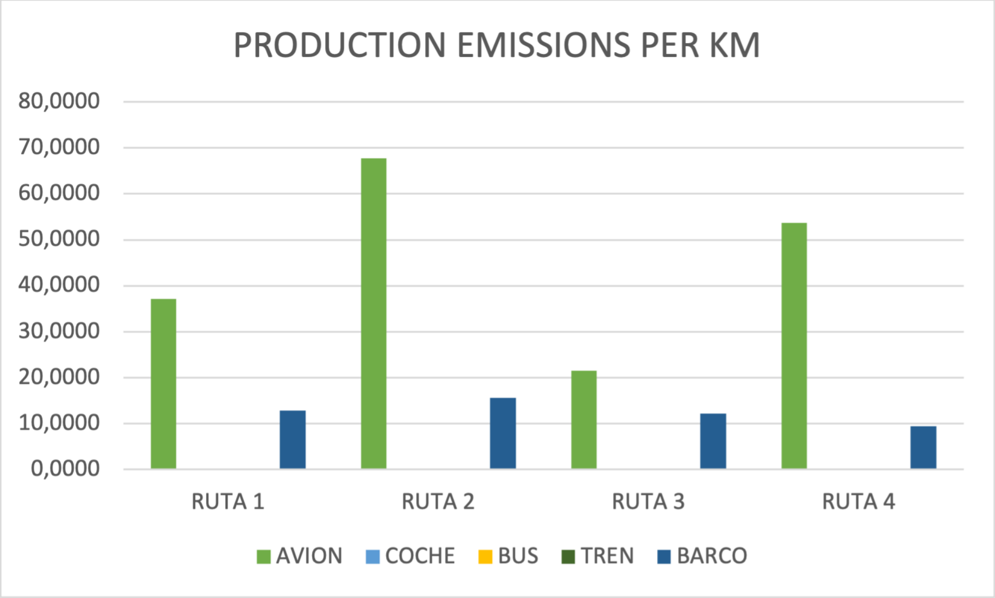


Figure 8.4: Emissions produced for production per km in each of the routes.

8.2.2 Infrastructure

Economic cost

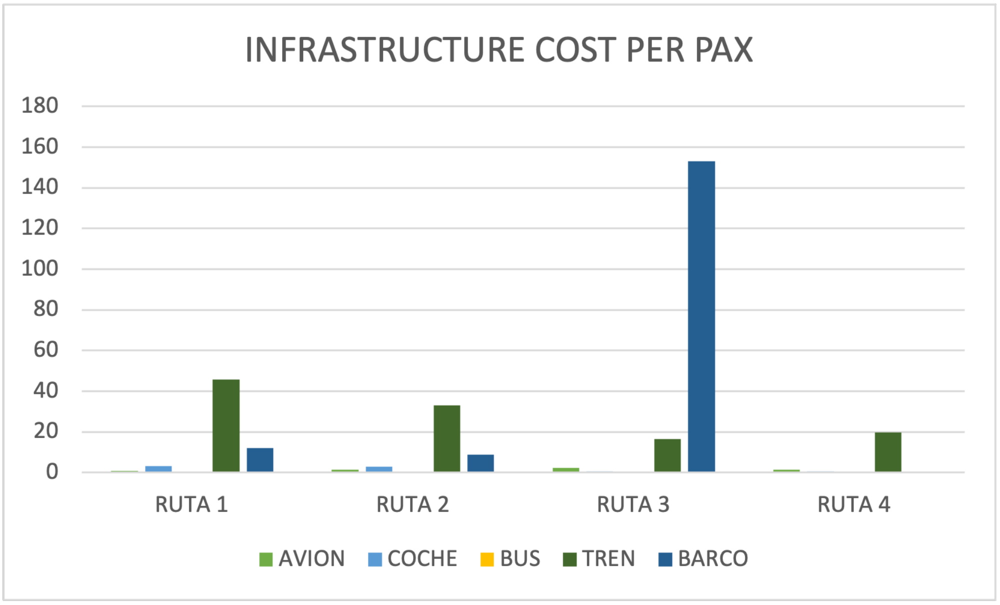


Figure 8.5: Infrastructure cost per PAX in each of the routes.

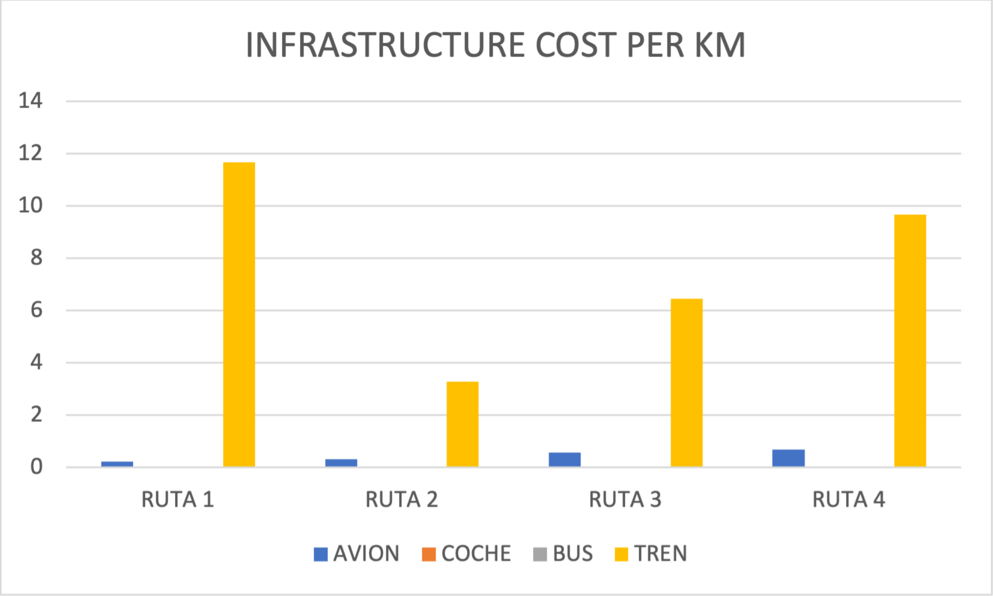


Figure 8.6: Infrastructure cost per km in each of the routes.

Emissions produced

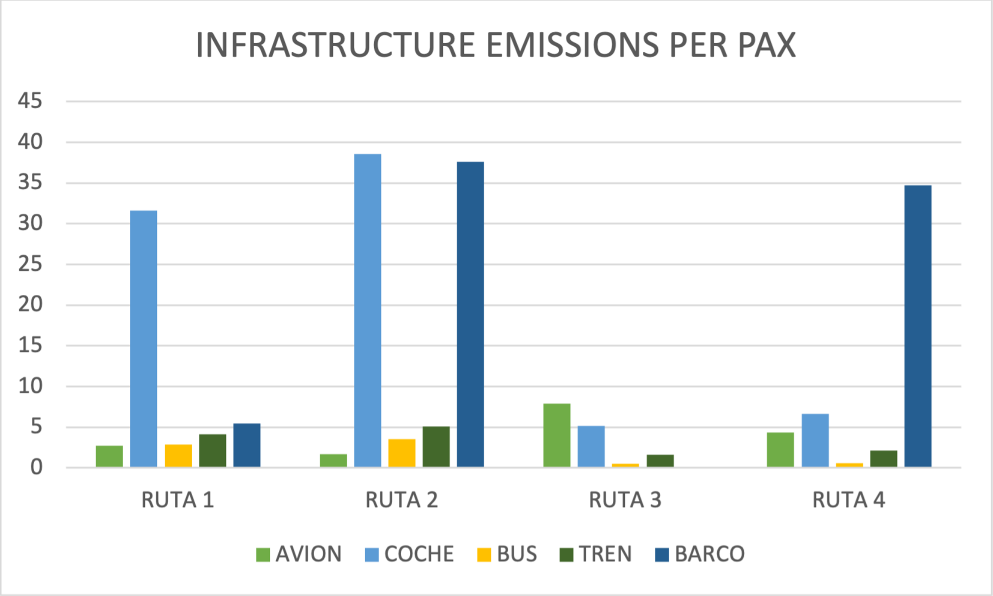


Figure 8.7: Emissions produced for infrastructure per PAX in each of the routes.

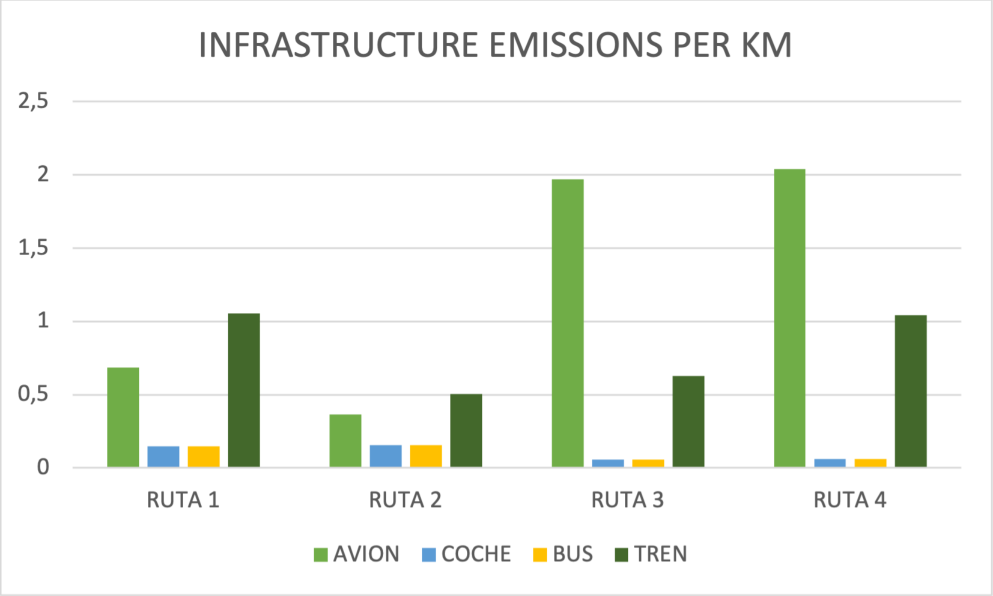


Figure 8.8: Emissions produced for infrastructure per km in each of the routes.

8.2.3 Operation

Economic cost

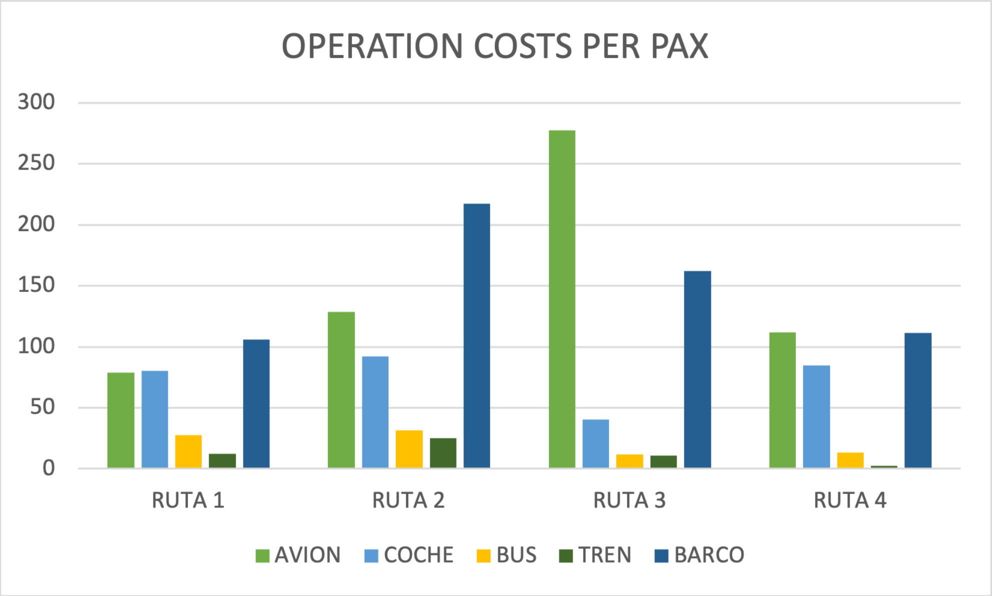


Figure 8.9: Operation cost per PAX in each of the routes.

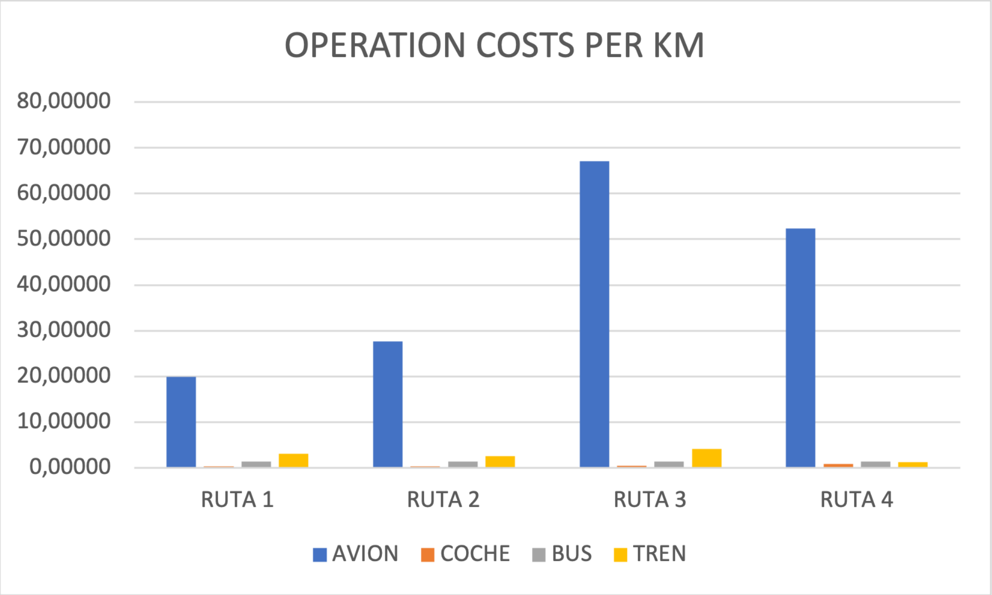


Figure 8.10: Operation cost per km in each of the routes.

Emissions produced

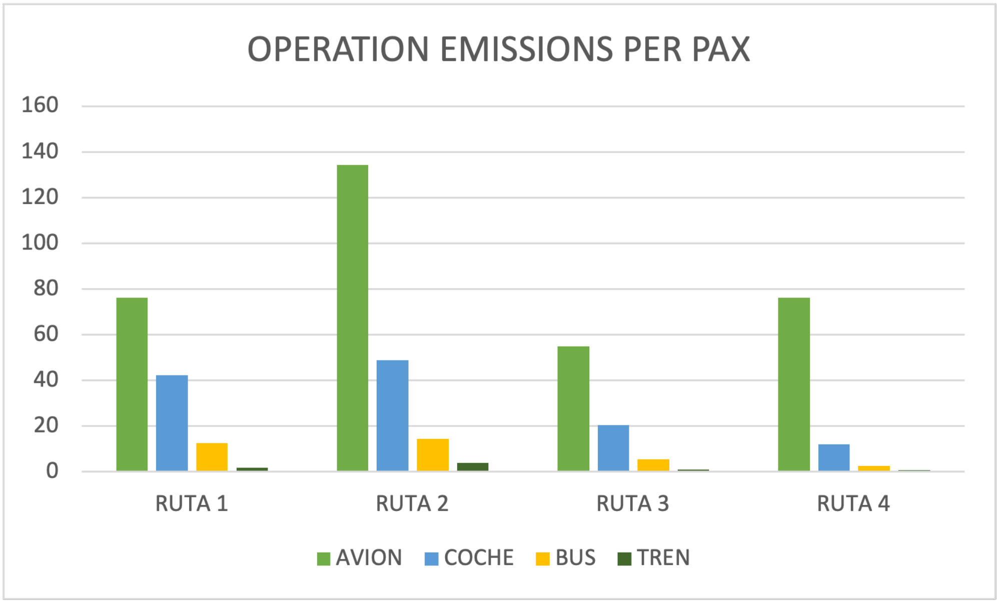


Figure 8.11: Emissions produced for operation per PAX in each of the routes.

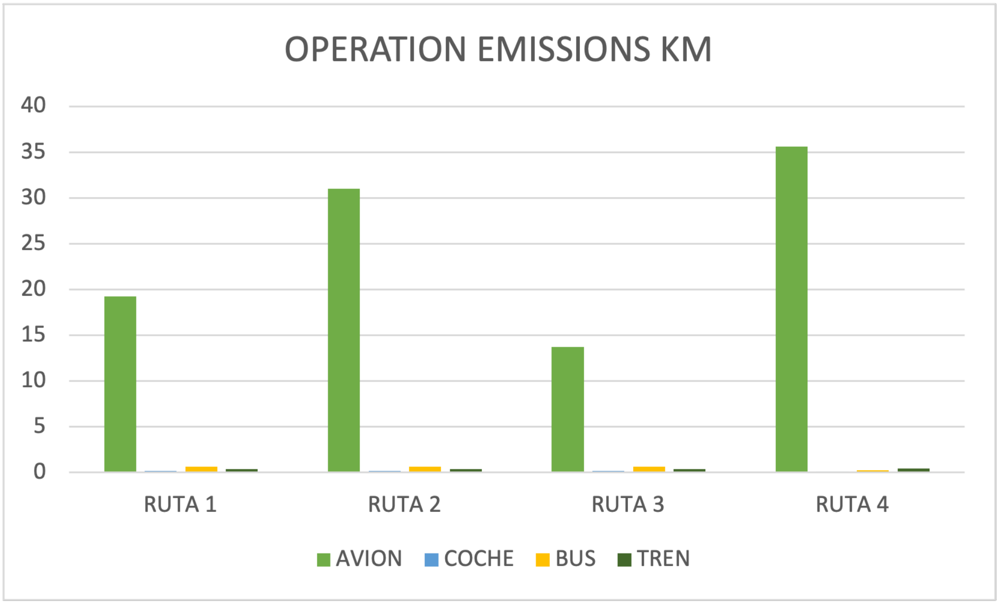


Figure 8.12: Emissions produced for operation per km in each of the routes.

8.2.4 Totsl

Economic cost

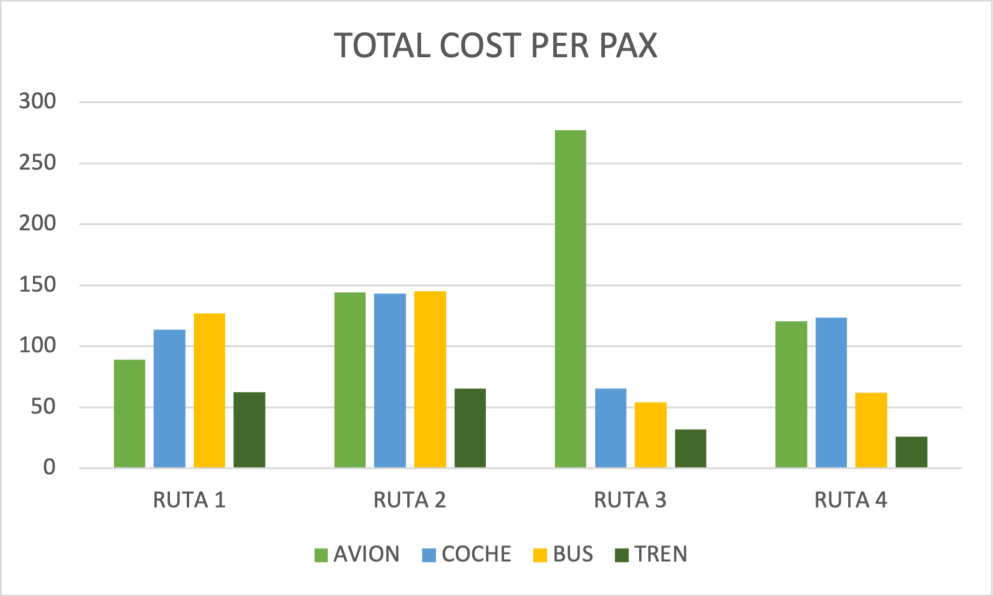


Figure 8.13: Total cost per PAX in each of the routes.

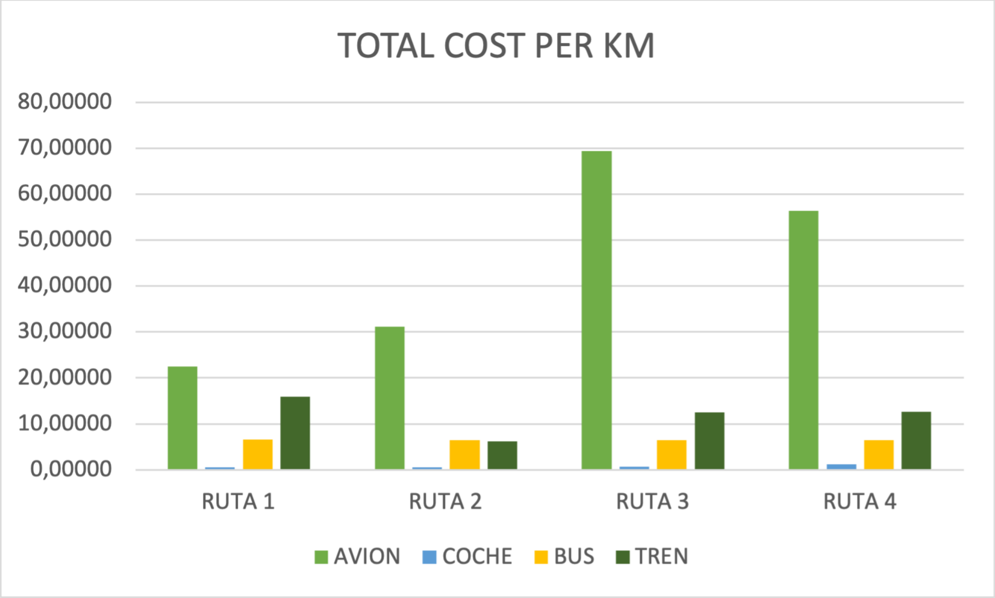


Figure 8.14: Total cost per km in each of the routes.

Emissions produced

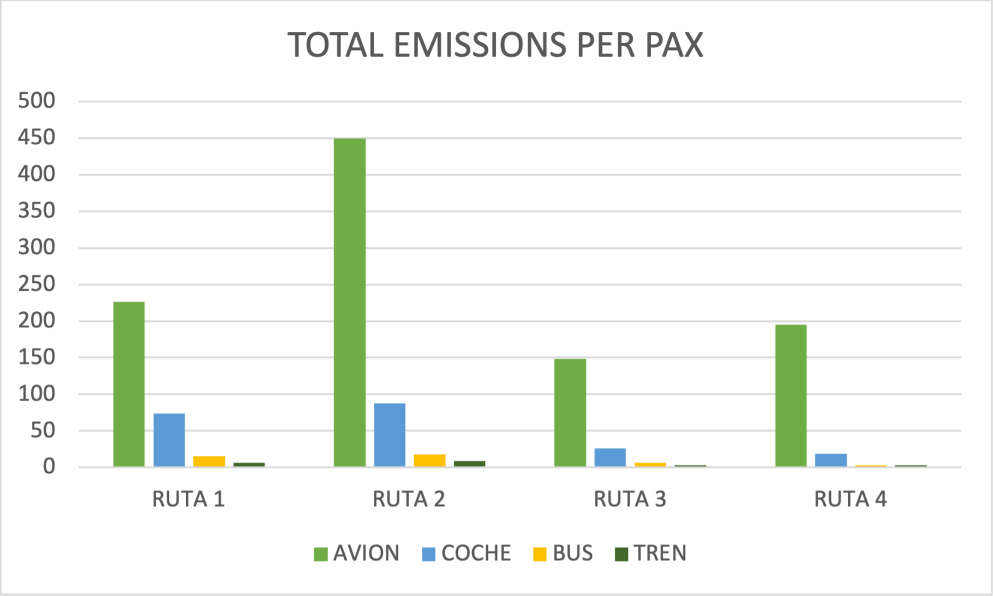


Figure 8.15: Emissions produced in total per PAX in each of the routes.

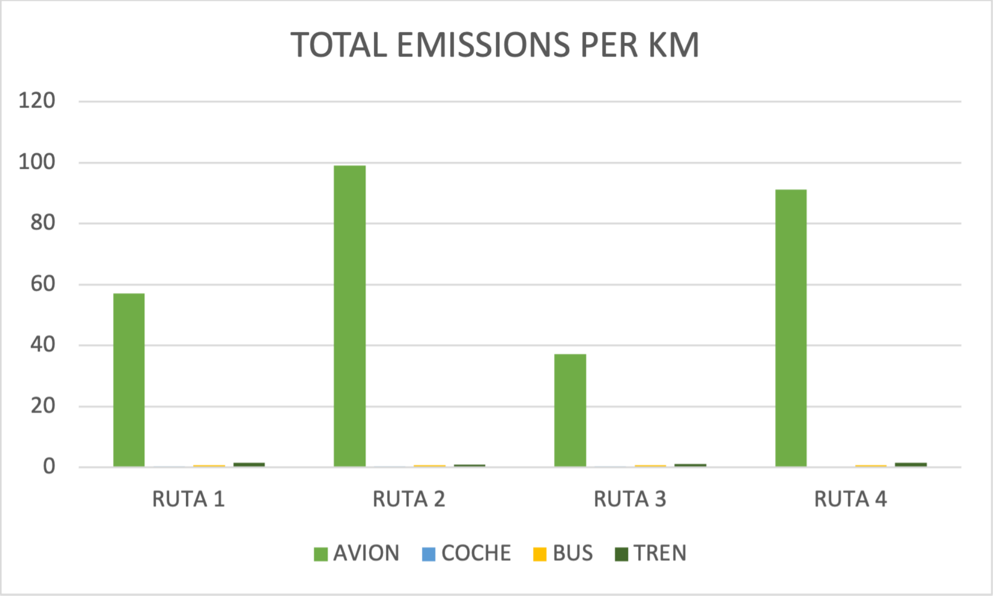


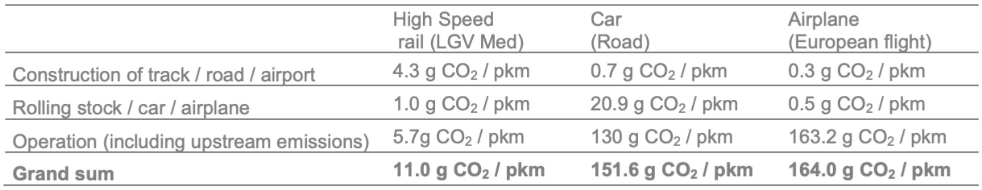
Figure 8.16: Emissions produced in total per km in each of the routes.

8.2.5 Conclusions

In general lines, we can take the following conclusions:

- Regarding the most important information, the one related to the PAX, we can clearly see that the train is dominant when we talk about less emissions, as expected.
- On the other hand, it can be seen that aviation is the industry that pollutes the most and in most of the cases has a higher cost to produce, create the infrastructure and operate it
- Nautical industry has been erased from most of the graphics as it has an overrated value all over the others.
- For short distances, the difference between bus and train, both considered public transport is very closed, specially the one related with the cost. The emissions produced are by far lower in train.
- The total cost in a short route is very similar between planes and carbus, not the same in emissions.

Comparing with some real values, we can see a slightly difference. It is because the numbers there don't take into account the production and the use of the infrastructure. Besides, for example in a plane, car o bus, the time of utilization is much higher really that doing only a round trip, so it's obvious to think that the numbers are going to be different. From a document where it's calculated the CF of a high-speed railway construction, without the production and giving some approximate values for another MOTs that are compared with, we can see the difference between our values and the others. From image 2.27 we can also take a visual information to compare [78]:



	High Speed rail (LGV Med)	Car (Road)	Airplane (European flight)
Construction of track / road / airport	4.3 g CO_2 / pkm	0.7 g CO_2 / pkm	0.3 g CO_2 / pkm
Rolling stock / car / airplane	1.0 g CO_2 / pkm	20.9 g CO_2 / pkm	0.5 g CO_2 / pkm
Operation (including upstream emissions)	5.7g CO_2 / pkm	130 g CO_2 / pkm	163.2 g CO_2 / pkm
Grand sum	**11.0 g CO_2 / pkm**	**151.6 g CO_2 / pkm**	**164.0 g CO_2 / pkm**

Figure 8.17: CF footprint in different MOTs.

Chapter 9

Environmental study

After a whole document talking about CF and how the different analyzed MOT affect and harm the environment, it's time to find alternatives, projects and ways to reduce it. As this study ventures into the aeronautical industry and compares the emissions produced by it, it has been found that the emissions it produces are much higher than those produced by most other means of transportation. Several projects being undertaken by the aeronautical industry to reduce emissions will be explained. Some of the ways and proposals for reducing emissions in other means of transportation will also be mentioned, but in a less detailed and superficial manner than in the first case.

9.1 How to reduce the impact of CF in aviation industry

In this section we are going to talk about different projects and proposals under development from the main aviation organisms that would contribute to reduce the emissions of CO_2 This section will discuss, explain, and comment on some of the projects that are being carried out to reduce emissions of CO_2 and therefore the CF impact in the aeronautical industry. The projects are as follows:

- Project 1. IATA Fly Net Zero 2050.

  The IATA Fly Net Zero 2050 project is an initiative of the International Air Transport Association (IATA) that aims to achieve net-zero carbon dioxide emissions for the aviation industry by 2050 [79]. To achieve this goal, the initiative focuses on a range of measures such as improving fuel efficiency, introducing cleaner technologies, developing biofuels, and offsetting emissions. The initiative also seeks to engage governments and other key stakeholders to ensure that necessary steps are taken towards achieving a sustainable aviation industry. The different ways to reduce emissions in order to achieve the goal over the total it's forecasted to be as follows:

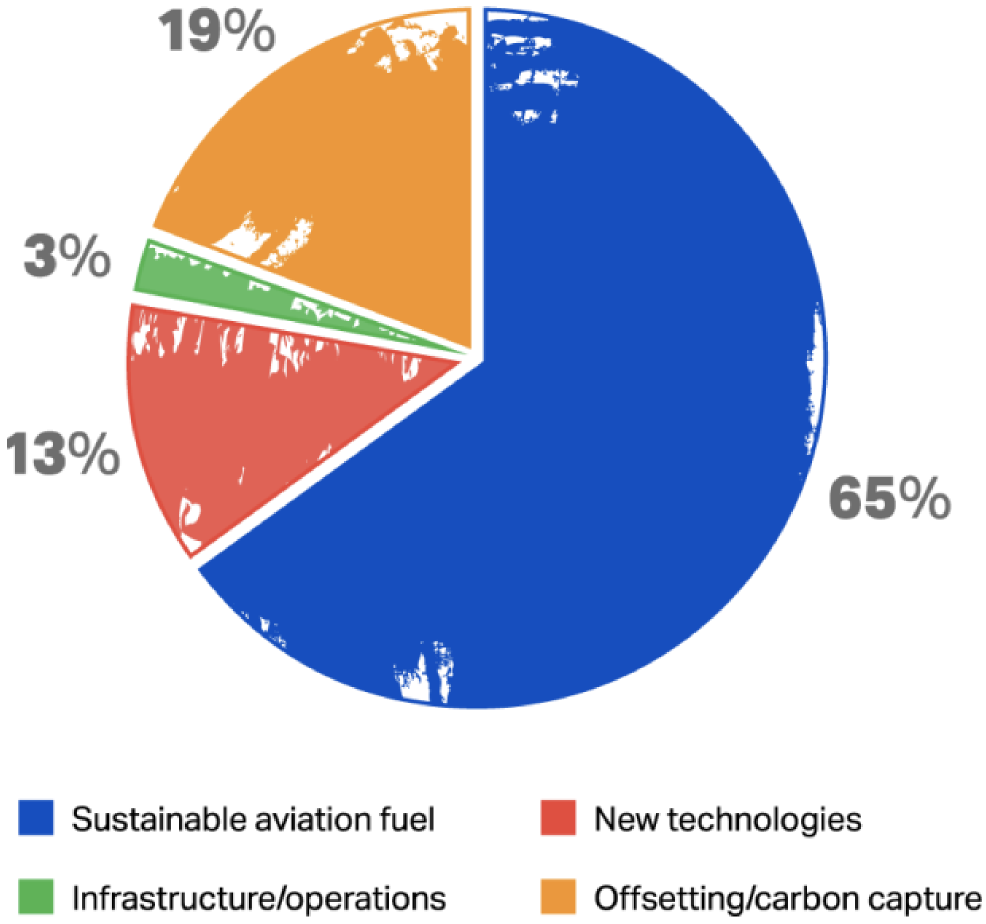


Figure 9.1: IATA Fly Net Zero.

Another interesting data for the project is that their current projections estimate that demand for individual air passenger journeys in 2050 could exceed 10 billion:

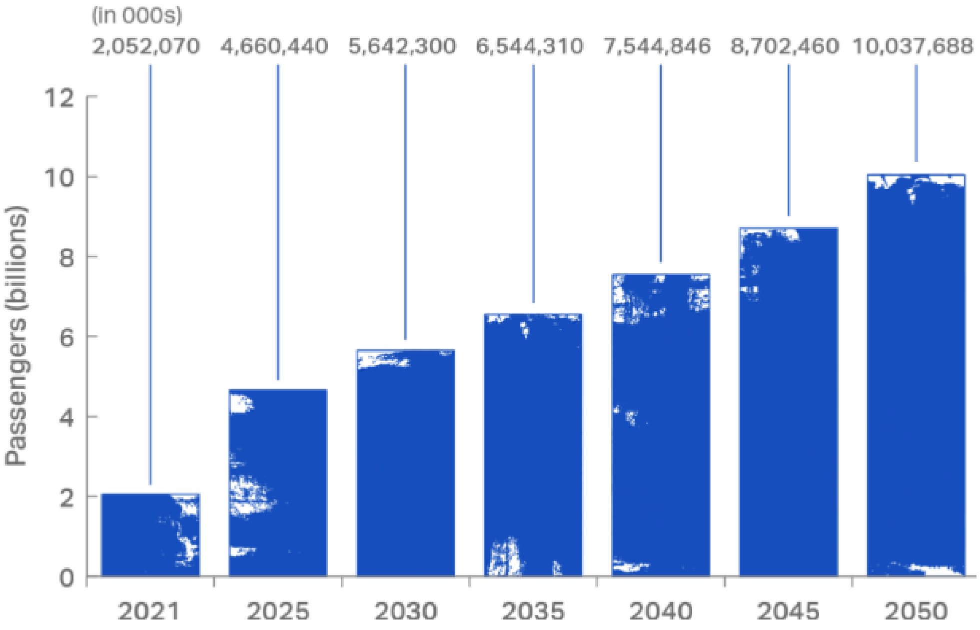


Figure 9.2: IATA forecast traffic evolution.

Finally, the expected carbon emissions on a 'business as usual' trajectory over the 2021-2050 period is approximately 21.2 gigatons of CO2. Mitigating that amount of carbon will be an enormous technological challenge.

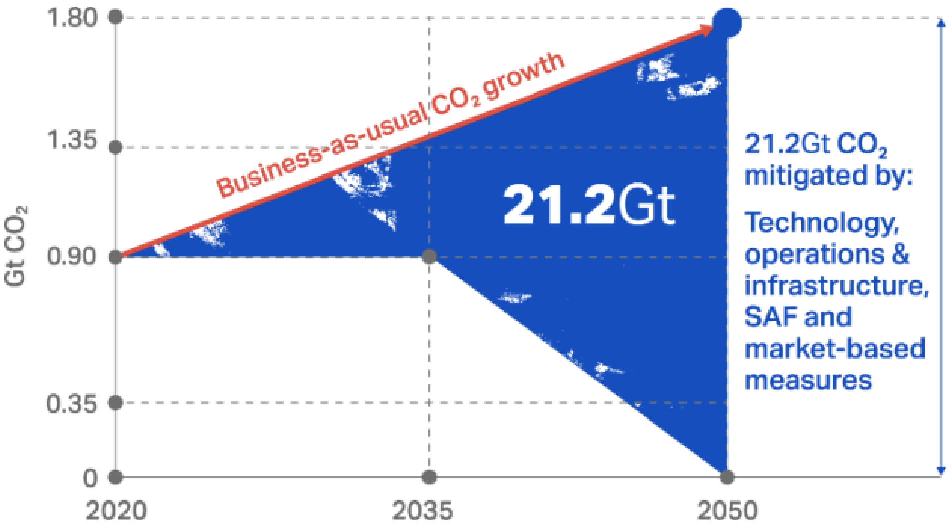


Figure 9.3: Emissions abated 2050.

Each of the different ways to reduce emissions from 9.2 [80], are deeply explained in the Annex. Here some important figures will be shown:

- SAF

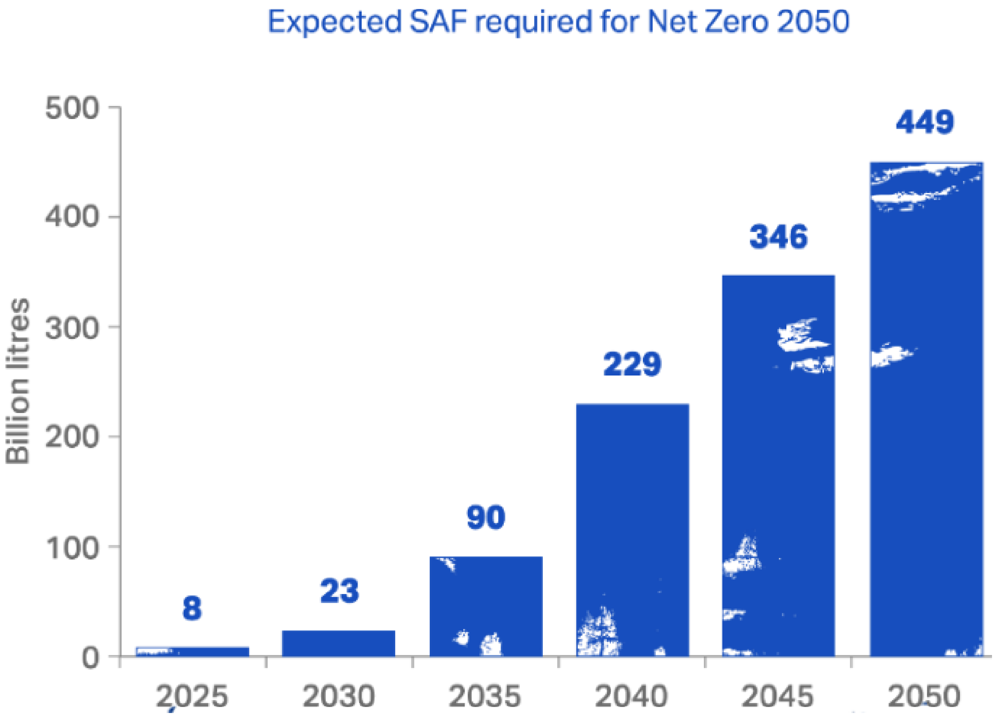


Figure 9.4: Expected SAF Net Zero.

- Offsetting/carbon capture

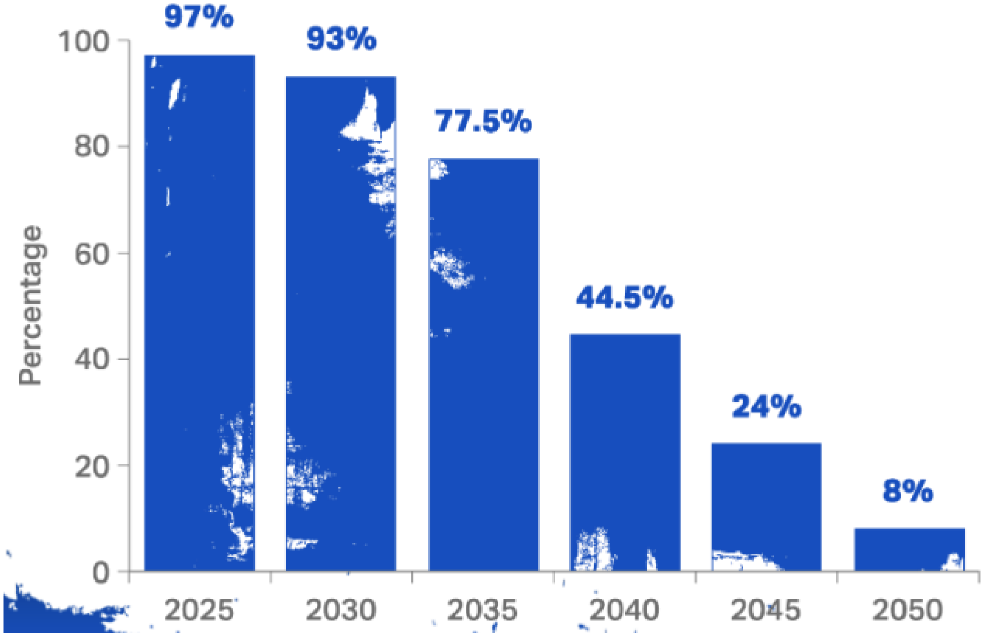
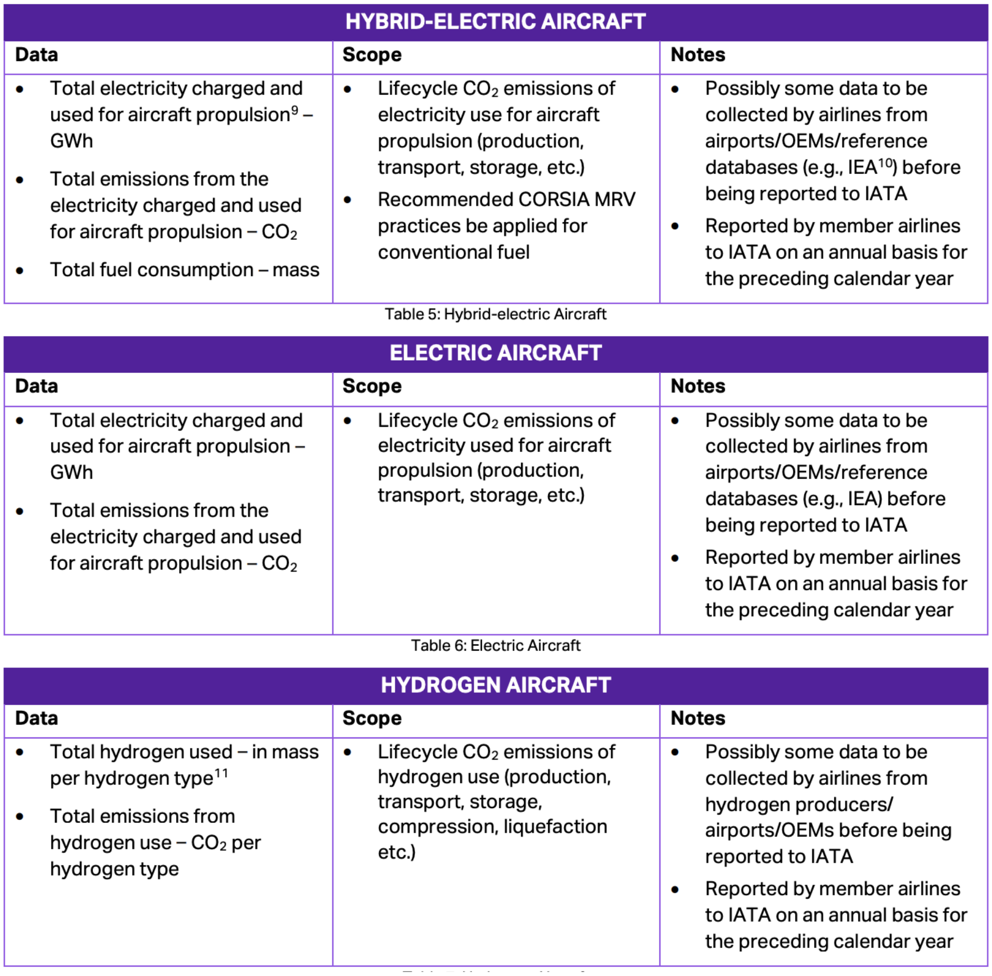


Figure 9.5: IATA Offsets CO2 Net Zero 2050.

- New technologies



HYBRID-ELECTRIC AIRCRAFT

Data	Scope	Notes
• Total electricity charged and used for aircraft propulsion[9] – GWh • Total emissions from the electricity charged and used for aircraft propulsion – CO_2 • Total fuel consumption – mass	• Lifecycle CO_2 emissions of electricity use for aircraft propulsion (production, transport, storage, etc.) • Recommended CORSIA MRV practices be applied for conventional fuel	• Possibly some data to be collected by airlines from airports/OEMs/reference databases (e.g., IEA[10]) before being reported to IATA • Reported by member airlines to IATA on an annual basis for the preceding calendar year

Table 5: Hybrid-electric Aircraft

ELECTRIC AIRCRAFT

Data	Scope	Notes
• Total electricity charged and used for aircraft propulsion – GWh • Total emissions from the electricity charged and used for aircraft propulsion – CO_2	• Lifecycle CO_2 emissions of electricity used for aircraft propulsion (production, transport, storage, etc.)	• Possibly some data to be collected by airlines from airports/OEMs/reference databases (e.g., IEA) before being reported to IATA • Reported by member airlines to IATA on an annual basis for the preceding calendar year

Table 6: Electric Aircraft

HYDROGEN AIRCRAFT

Data	Scope	Notes
• Total hydrogen used – in mass per hydrogen type[11] • Total emissions from hydrogen use – CO_2 per hydrogen type	• Lifecycle CO_2 emissions of hydrogen use (production, transport, storage, compression, liquefaction etc.)	• Possibly some data to be collected by airlines from hydrogen producers/ airports/OEMs before being reported to IATA • Reported by member airlines to IATA on an annual basis for the preceding calendar year

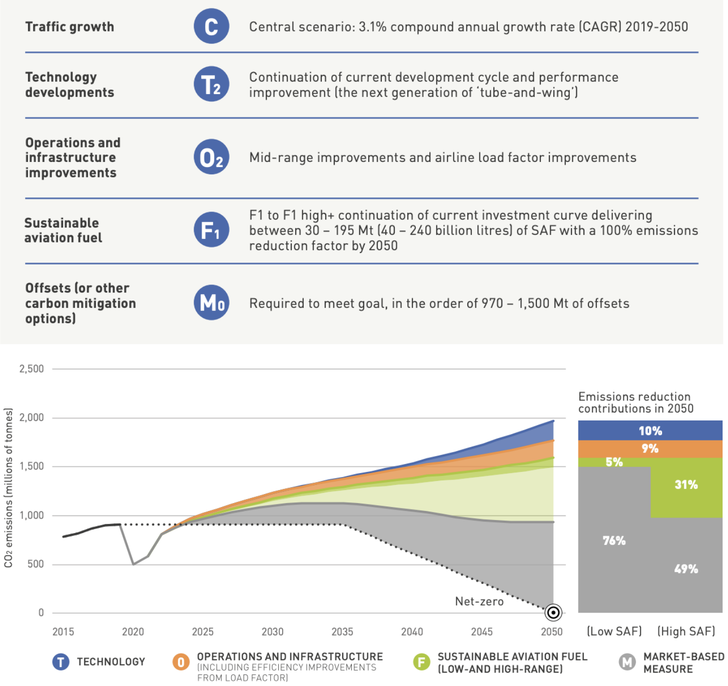
Figure 9.6: IATA Fly Net Zero new technologies.

- Project 2. Program Waypoint 2050

The Waypoint 2050 project is an initiative led by the European Aviation Safety Agency (EASA) that aims to define and develop a new regulatory framework for the aviation industry to achieve carbon-neutral growth by 2050. The project focuses on identifying and implementing new technologies and operational procedures that will reduce aviation's environmental impact, such as developing sustainable aviation fuels, improving aircraft design and propulsion systems, and implementing more efficient air traffic management systems. [81].

In order to reduce the complexity of forecasting across a wide range of variables, Waypoint 2050 has identified consolidated scenarios. These are built on a range of sub-scenarios covering traffic growth forecasts, technology developments, operations and infrastructure improvements, sustainable aviation fuel, and the role of offsets to fill any remaining gaps. The central traffic growth projection used shows that, by 2050, around 10 billion passengers will fly each year a distance of 22 trillion revenue passenger kilometres. Without any intervention (keeping the current fleet and current level of operational efficiency), this activity would generate some 2,800 million tonnes of CO2 and require over 620 Mt of fuel. The different scenarios and their explanations are:

  - Scenario 0. Traffic growth is around 3.1% per annum with conservative technology improvements, resulting in a continuation of the current rate of improvement. Sustainable aviation fuel is introduced based on current rates, resulting in 30 to 195 million tonnes in 2050. Investments in operations and infrastructure lead to net improvements and CO2 reductions, but offsets are needed to address residual emissions in 2050.



Traffic growth	C	Central scenario: 3.1% compound annual growth rate (CAGR) 2019-2050
Technology developments	T_2	Continuation of current development cycle and performance improvement (the next generation of 'tube-and-wing')
Operations and infrastructure improvements	O_2	Mid-range improvements and airline load factor improvements
Sustainable aviation fuel	F_1	F1 to F1 high+ continuation of current investment curve delivering between 30 – 195 Mt (40 – 240 billion litres) of SAF with a 100% emissions reduction factor by 2050
Offsets (or other carbon mitigation options)	M_0	Required to meet goal, in the order of 970 – 1,500 Mt of offsets

Figure 9.7: Scenario 0 Program Waypoint 2050.

– Scenario 1. Technology improvements are prioritized with a transition towards hybrid/-electric aircraft starting in 2035/40. Investments in operations and infrastructure result in significant improvements and CO2 reductions. Sustainable aviation fuel is used to fulfill the gap between CO2 emissions and the 2050 carbon goal. Offsets are required to clear residual emissions in 2050, but may be needed during the transition period.

Traffic growth	C	Central scenario: 3.1% compound annual growth rate (CAGR) 2019-2050
Technology developments	T_4	Prioritised development of electric and hybrid electric aircraft in the short-range and <100 seat category with entry into service from 2035/2040 and further enhancements for larger aircraft.
Operations and infrastructure improvements	O_3	High-range improvements and airline load factor improvements
Sustainable aviation fuel	F_2	Backcast of what is required (around 1,200 Mt CO_2 reduction) to replace 90% of conventional jet fuel: 380 Mt (480 billion litres) of SAF with a 100% emissions reduction factor by 2050
Offsets (or other carbon mitigation options)	M_1	Around 135 million tonnes worth of offsets may be required to close the emissions gap to net-zero

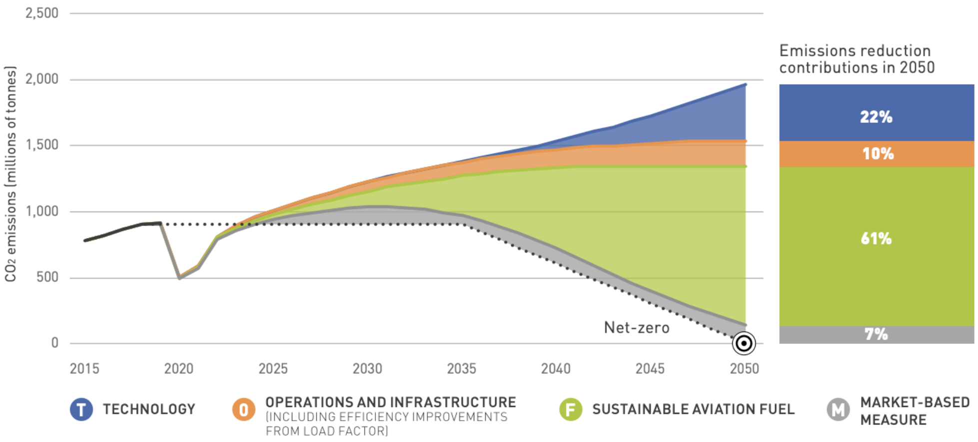
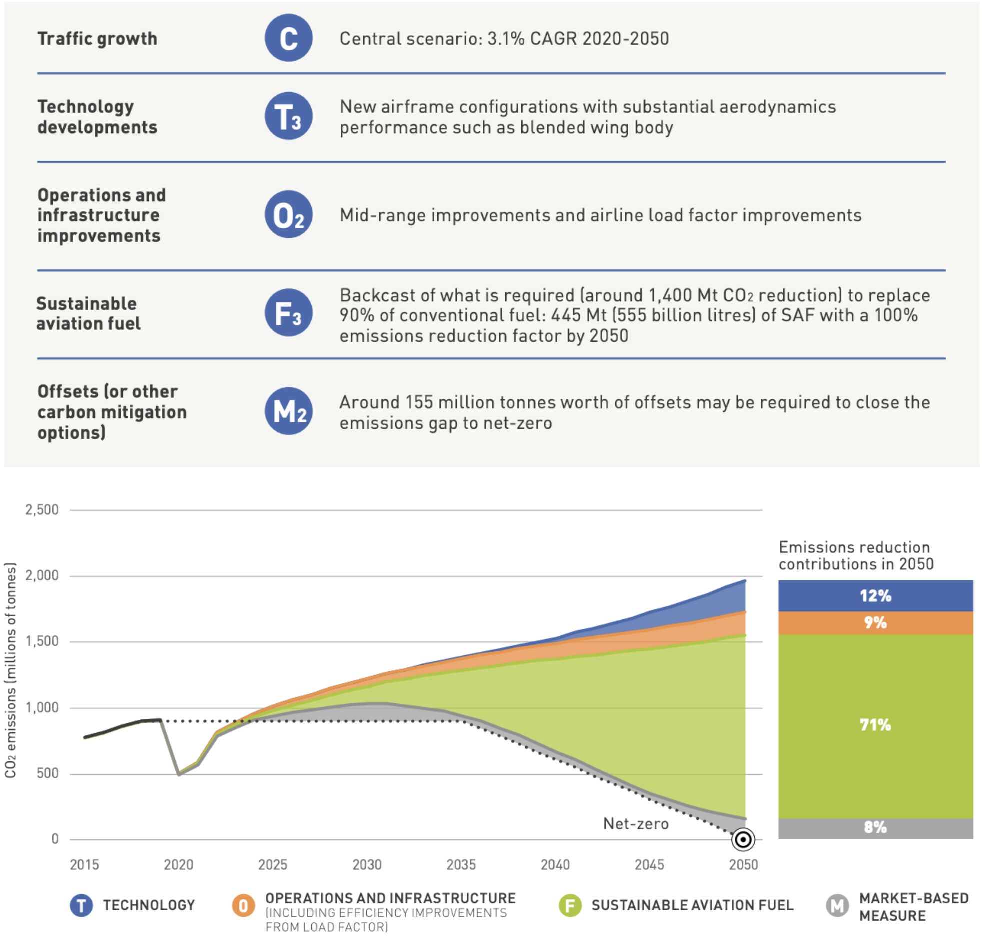


Figure 9.8: Scenario 1 Program Waypoint 2050.

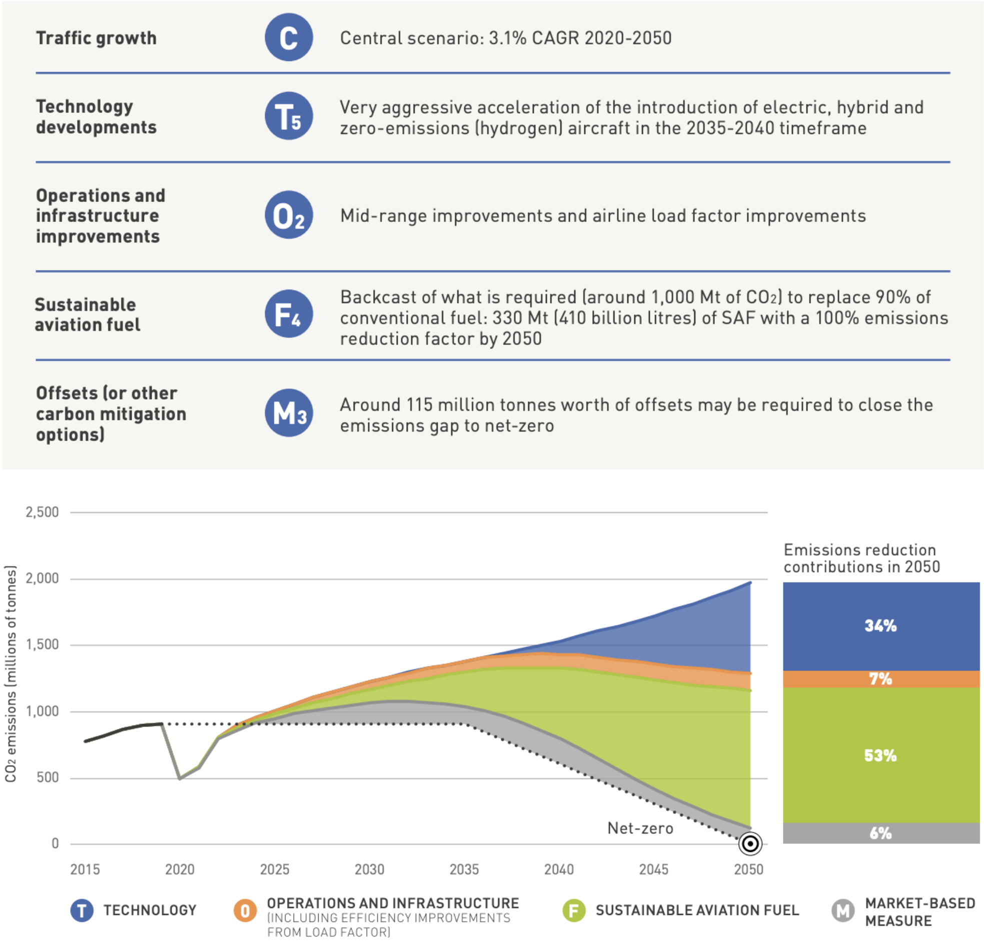
– Scenario 2. Technology improvements are ambitious with new aircraft configurations such as blended wing body options. Investments in operations and infrastructure result in some net improvements and CO2 reductions. The gap between CO2 emissions and the 2050 carbon goal is fulfilled with sustainable aviation fuels, requiring significant amounts of SAF with high emissions reduction factors. Offsets are needed to clear residual emissions in 2050, but may be required during the transition period.



Traffic growth	C	Central scenario: 3.1% CAGR 2020-2050
Technology developments	T_3	New airframe configurations with substantial aerodynamics performance such as blended wing body
Operations and infrastructure improvements	O_2	Mid-range improvements and airline load factor improvements
Sustainable aviation fuel	F_3	Backcast of what is required (around 1,400 Mt CO_2 reduction) to replace 90% of conventional fuel: 445 Mt (555 billion litres) of SAF with a 100% emissions reduction factor by 2050
Offsets (or other carbon mitigation options)	M_2	Around 155 million tonnes worth of offsets may be required to close the emissions gap to net-zero

Figure 9.9: Scenario 2 Program Waypoint 2050.

– Scenario 3. Technology improvements are very ambitious with zero-emissions aircraft powered by green hydrogen for the 100-200 seat segment and hybrid-electric powered unconventional aircraft configurations for larger aircraft. Investments in operations and infrastructure result in some net improvements and CO2 reductions. Sustainable aviation fuel is used to fulfill the gap between CO2 emissions and the 2050 carbon goal, requiring significant amounts of SAF with high emissions reduction factors. Offsets are needed to clear residual emissions in 2050, but may be required during the transition period.



Traffic growth	C	Central scenario: 3.1% CAGR 2020-2050
Technology developments	T5	Very aggressive acceleration of the introduction of electric, hybrid and zero-emissions (hydrogen) aircraft in the 2035-2040 timeframe
Operations and infrastructure improvements	O2	Mid-range improvements and airline load factor improvements
Sustainable aviation fuel	F4	Backcast of what is required (around 1,000 Mt of CO_2) to replace 90% of conventional fuel: 330 Mt (410 billion litres) of SAF with a 100% emissions reduction factor by 2050
Offsets (or other carbon mitigation options)	M3	Around 115 million tonnes worth of offsets may be required to close the emissions gap to net-zero

Figure 9.10: Scenario 3 Program Waypoint 2050.

From the previous images we can see that this program focus the ways to reduce emissions in 5 core points, similar to the ones of IATA's Fly Net Zero 2050: traffic growth, technology developments, operations and infrastructure improvements, SAF and offsets and carbon mitigation options. All his proposals appear in the Annex.

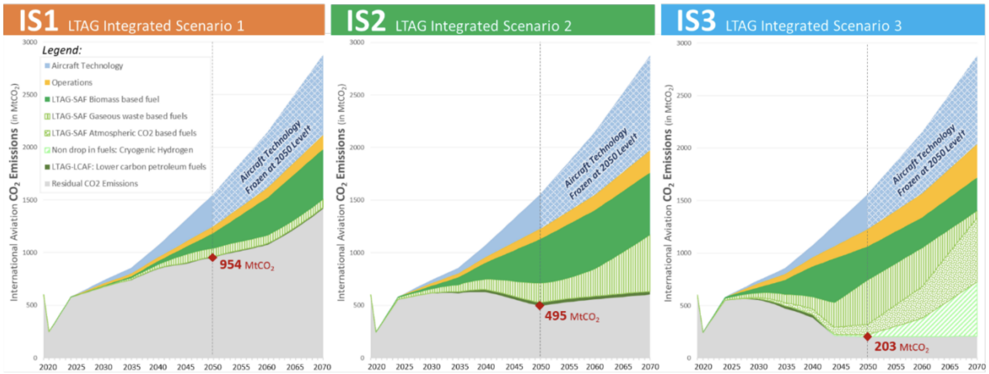
- Project 3. ICAO long-term global aspirational goal (LTAG)

  The International Civil Aviation Organization (ICAO) has established a Long-Term Global Aspirational Goal (LTAG) for the aviation industry, which aims to achieve carbon-neutral growth by 2020 and to reduce CO2 emissions by 50% by 2050 compared to 2005 levels. This goal was established to address the environmental impact of aviation and to ensure sustainable growth for the industry. The ICAO has also developed a set of measures to achieve this goal, which include technology development, operational improvements, and sustainable aviation fuel (SAF) use. The LTAG has been adopted by many countries and industry stakeholders, and progress is being monitored and reported regularly by the ICAO. The Non-drop-in fuels analysed are [82]:

  [83]

  1. Electricty. Electrification of aircraft including both hybrid and fully electric airframes. As they do not require significant changes at the airport level with regard to energy supply systems and only supplement conventional fueling processes, their impact from a fuels perspective is limited
  2. Liquefied gas aviation fuels (ASKT) require changes to existing engines and airframe architecture. ASKT is included as a case study for applicability in remote areas with stranded hydrocarbon resources, such as arctic regions, due to its unique applicability and specific chemical features
  3. Cryogenic hydrogen (LH2) can be used in a dedicated aircraft fleet. Evaluated for systems that use direct combustion of liquid hydrogen in gas turbine engines. Defined by the availability of systems and technologies to be developed

  In order to decrease the emissions and the ammount of GHG gases, there are some ways to do so. Carbon capture technologies are available for both waste CO_2 streams and atmospheric CO_2 through Direct Air Capture (DAC). Absorption is the most widely used technology for capturing waste CO_2, while low-temperature DAC technologies using ammine-functionalized sorbents are suitable for integration with a heat source. Upstream GHG emissions reductions technologies include minimizing gas flaring and venting, where technologies such as Leak Detection and Repair (LDAR) programs can be applied to identify and repair/replace leaking equipment. Refining GHG emissions reductions technologies include Carbon Capture and Storage (CCS), renewable steam and electricity, and low carbon hydrogen production. Carbon capture involves the capture of CO_2 from fuel combustion or industrial processes and its permanent storage in geological formations. The generation of main refinery utilities via renewable sources and low carbon hydrogen production can result in a reduction in carbon intensity [84].



† Caution required with the interpretation of absolute CO_2 emissions levels after 2050 due to modelling assumptions e.g., frozen aircraft technology after 2050. Under these assumptions, CO_2 emissions are higher than in an alternative scenario (and modelling approach) where aircraft technology would continue to improve after 2050.

Figure 9.11: Scenarios project ICAO LTAG

From the previous image, we can differentiate the 3 scenarios represented in each the graphics. From each of them, the conclusions that we can have are:

1. IS1 scenario, CO2 emissions after reductions from aircraft technology, operations and fuels could reach approximately 950 MtCO2 in 2050 (1.6x from the 2019 CO2 emissions level) and 1420 MtCO2 in 2070 (2.3x). Under this low/nominal scenario, emissions in 2050 would be reduced by 39% from the baseline scenario (IS0) broken down into 20% from aircraft technologies, 4% from operations and 15% from fuels. By 2070, aircraft technology, operations and fuels could contribute to reductions in emissions of 26%, 5%, and 20% respectively. Under this scenario, residual CO2 emissions would not stabilize and would continue to grow above a 2019 CO2 emission levels (as proxy for pre-COVID-19 pandemic 2020 level). Through 2050, global fuel efficiency measured in fuel/RTK would improve by 1.20 to1.31% per annum (vs. the 2% ICAO global fuel efficiency aspirational goal).
2. IS2 scenario, CO2 emissions could reach = 500 MtCO2 in 2050 (0.8x from 2019 CO2 emissions level) and stabilize at roughly 2019 CO2 emission level. Emissions in 2050 would be reduced by 68% from an IS0 baseline, broken down into 21% from aircraft technologies, 6% from operations, and 41% from fuels. Through 2050, global fuel efficiency measured in fuel/RTK would improve by 1.35 to 1.47% per annum (vs. the 2% ICAO global fuel efficiency aspirational goal).
3. IS3 scenario, residual CO2 emissions could reach = 200 MtCO2 in 2050 (a third of the 2019 CO2 emissions level) and 210 MtCO2 in 2070. Emissions in 2050 would be reduced by 87% from the baseline scenario (IS0) broken down into 21% from aircraft technologies, 11% from operations and 55% from fuels. Through 2035, global fuel efficiency measured in fuel/RTK would improve by 1.42 to 1.60% per annum. Under this scenario which involves the use of non-drop in fuels such as hydrogen, the 2% ICAO global fuel efficiency aspirational goal becomes obsolete (based on jet fuel/RTK metric) and would need to be adjusted. Through 2050, global fuel energy efficiency measured in MJ/RTK would improve by 1.55 to 1.67% per annum.

- Project 4. Airbus

  Airbus' ZEROe project is a series of concept designs for zero-emission commercial aircraft. The project focuses on three main technologies: hydrogen fuel cells, hybrid-electric propulsion, and all-electric propulsion [85].

  The first concept design, the ZEROe turbofan, is a hybrid-electric aircraft that features two rear-mounted turbofans and a distributed electric propulsion (DEP) system. The DEP system consists of six electric motors mounted on the wing that provide additional thrust during takeoff and climb. The aircraft's power source is a modified gas turbine engine that runs on hydrogen, which is stored in tanks in the rear fuselage. The aircraft can carry up to 200 passengers and has a range of 2,000 nautical miles.

  The second concept design, the ZEROe turboprop, is a regional aircraft that uses hydrogen fuel cells to power its two turboprop engines. The aircraft has a range of up to 1,000 nautical miles and can carry up to 100 passengers.

  The third concept design, the ZEROe blended-wing body, is an all-electric aircraft with a unique, blended-wing body design. The aircraft's wing and fuselage blend together to form a single, continuous shape that provides additional lift and reduces drag. The aircraft has six electric motors mounted on the wing and can carry up to 200 passengers with a range of up to 2,000 nautical miles.

  All of these concept designs are still in the early stages of development and testing, and it will likely be several years before they become commercially viable. However, the ZEROe project demonstrates Airbus' commitment to developing sustainable aviation solutions that can reduce the industry's carbon footprint and contribute to a more sustainable future.

Figure 9.12: Zeroe Airbus project.

2022 marks a new and exciting phase for ZEROe – Airbus' ambition to develop the world's first hydrogen-powered commercial aircraft by 2035. The multi-year demonstrator programme has officially been launched with the objective to test a variety of hydrogen technologies both on the ground and in the air [86].

Figure 9.13: Airbus Zeroe hydrogen project.

- Project 5. Boeing Eco-Demonstrator program

  The Boeing ecoDemonstrator program is a partnership between Boeing and various industry and government partners to develop and test new technologies that improve the environmental performance of aviation. The 2022 ecoDemonstrator will focus on improving sustainability, safety, and efficiency by testing a range of technologies including advanced cockpit systems, sustainable aviation fuel, and aerodynamic improvements. The goal is to accelerate the development and adoption of these technologies, ultimately reducing the environmental impact of aviation and enhancing the safety and efficiency of the air transportation system [87].

  Boeing's 2022 ecoDemonstrator program will test 30 new sustainable technologies on a 777-200ER aircraft, with a focus on reducing aviation emissions and improving sustainability. The technologies to be tested include new advanced cockpit systems, materials and technologies to reduce noise and improve fuel efficiency, and alternative sources of energy such as hydrogen fuel cells. The ecoDemonstrator program is a collaborative effort with industry partners and government agencies, aimed at accelerating the development of sustainable aviation technologies and reducing the environmental impact of aviation. The data and lessons learned from the program will be shared with regulators and industry stakeholders to drive broader adoption of these sustainable technologies [88].

9.2 How to reduce the impact of CF in automotive industry

In order to reduce the GHG emissions in automobile industry and from different organisms, different alternatives for the gas or diesel are being studied, as well as some proposals for the industry. All the following options to make cleaner fuels can be applied either the automobile industry and the public transportation one.

Regarding the combustibles under development, EPA has approved fuel pathways under the RFS program under all four categories of renewable fuel. Some of them have already been approved and tested [89] [90]:

- Ethanol made from sugarcane

  To produce ethanol from sugarcane, the first step is to extract juice from the cane stalks, which is high in sugar content. This juice is then fermented with yeast to create ethanol. The plant commonly burns the remaining fibrous material, or bagasse, to produce heat and electricity. Once the fermentation process is complete, the liquid, called beer, is distilled to obtain the ethanol. The purity of the ethanol can reach up to 92-95%, requiring further separation from water. This process generates two residues, namely bagasse and vinasse. Bagasse can be utilized for generating heat and electricity, while vinasse must undergo treatment before being disposed of and remains a challenge for the sugarcane ethanol production process. [91].

- Cellulosic ethanol made from corn stover

  Stover is the corn plant residues typically left in the field after corn grain harvest—the cobs, husks, leaves, and stalks. It has the advantage of not being a food source like corn itself, and as a by-product of corn production, that means in has less production costs. Research have shown that a little portion of stover can be sustainably harvested for biofuel production on flat and highly productive fields, if erosion is under control and harvest amounts are carefully limited. [92]

- Compressed natural gas from municipal wastewater treatment facility digesters

  Biogas can be obtained from landfills, municipal wastewater treatment facility digesters, agricultural digesters, and separated MSW digesters; and biogas from the cellulosic components of biomass processed in other waste digesters. It's easy to collect and would result in a good biofuel to be used in the future [93]

Some of the studies under development, from different kind of fuels, must meet the following requirements:

- Biomass-based diesel must meet a 50% lifecycle GHG reduction
- Cellulosic biofuel must be produced from cellulose, hemicellulose, or lignin and must meet a 60% lifecycle GHG reduction
- Advanced biofuel can be produced from qualifying renewable biomass (except corn starch) and must meet a 50% GHG reduction
- Renewable (or conventional) fuel typically refers to ethanol derived from corn starch and must meet a 20% lifecycle GHG reduction threshold

Regarding the industry, improving internal combustion engines and focusing on energy from hydrogen, biofuels and other alternative sources offers an opportunity to reduce CO2 emissions. However, a lot depends on vehicle suppliers – their investments in electrification and improving the ecology of production [94].

For this to be possible, a balanced development based on modern and innovative technologies is required. For example, the use of foamed plastics can contribute greatly to the health of EVs in this age of electromobility. Expanded polypropylene (EPP) is entirely recyclable and represents an excellent ecological alternative to conventional raw materials. The process of obtaining parts from EPP does not require large energy input or access to raw materials. Processing does not involve high CO2 emissions, especially when combined with the Industry 4.0 solutions.

To achieve the goal of Net Zero Emissions by 2050, Original Equipment Manufacturers (OEMs) are setting aggressive decarbonization targets. Around 65-80% of automobile emissions come from the tailpipe, which will be reduced through the electrification of powertrains. However, this is not enough for complete decarbonization as material emissions must also be addressed. The increased demand for electric vehicles will lead to an increase in baseline material emissions, and powering EV batteries is expected to account for 60% of the life-cycle emissions, compared to the current 18%.

To reduce material emissions and achieve complete decarbonization, the industry must adopt new technologies and manage changing flows of materials. An analysis has shown that by 2030, 29% of material emissions from internal combustion engine vehicles can be abated in a cost-positive way through electrification of existing processes, use of low-carbon energy sources, adoption of new technologies to reduce process emissions, increased use of recycled materials, and greater material recycling.

For achieving this cost-positive decarbonization, depending on the material, the proposals to be done are:

1. Aluminum
    - More use of recycled aluminum
    - Use of new smelting technologies
    - Use of green electricity in the aluminum's production
2. Plastics
    - Recycle polypropylene or polyethylene for the non-visible parts of the car
    - Use of nylon recycling technologies
3. Electric arc furnaces
4. Direct reduced iron for steel producton
5. Hydrogen-based steelmaking

Some figures about what we have seen previously:

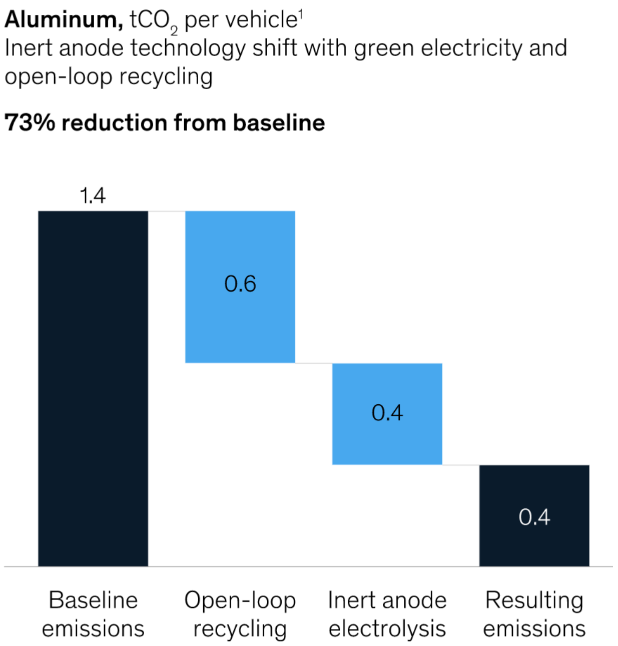


Figure 9.14: Aluminium reduction in cars

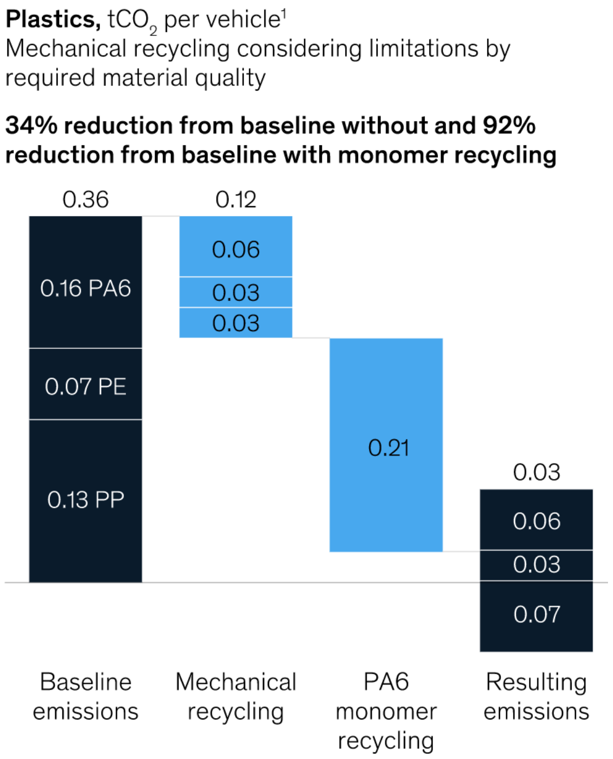


Figure 9.15: Plastic reduction in cars

9.3 How to reduce the impact of CF in railway industry

The railway industry has recognized the need to reduce its environmental impact and is implementing a range of initiatives to address this issue. The following are some ongoing projects aimed at reducing emissions in the railway industry [95]:

- Electrification of rail lines: One of the most effective ways to reduce emissions in the railway industry is to replace diesel locomotives with electric trains. Several countries, including the United Kingdom, Germany, and France, have launched ambitious programs to electrify their rail networks. In addition to reducing emissions, electric trains are quieter, more efficient, and require less maintenance than diesel trains.
- Use of renewable energy: Another way to reduce emissions in the railway industry is to power trains with renewable energy sources, such as wind or solar power. Several railway companies, including the Swiss Federal Railways and the Dutch Railways, have already adopted this approach. In addition to reducing emissions, this approach can also reduce energy costs and increase energy security.
- Improved energy efficiency: Railway companies are also working to improve the energy efficiency of their operations. This includes initiatives such as optimizing train schedules, reducing train weight, and improving the efficiency of lighting and heating systems in stations and trains. Such measures can significantly reduce emissions and lower operating costs.
- Use of low-emission locomotives: While electrification is the most effective way to reduce emissions in the railway industry, some routes may not be suitable for electrification. In such cases, railway companies can use low-emission locomotives powered by cleaner fuels such as natural gas or hydrogen. These locomotives emit less pollutants than diesel locomotives and can significantly reduce emissions on non-electrified routes.
- Modal shift: encouraging more people to travel by train instead of cars or planes can help reduce emissions from transportation.

9.4 How to reduce the impact of CF in nautical industry

The nautical industry, which includes shipping and other maritime activities, has a significant impact on the environment and is responsible for a significant portion of global greenhouse gas emissions. In response, the industry is undertaking a range of initiatives aimed at reducing emissions and promoting sustainable practices. The following are some ongoing projects in the nautical industry aimed at reducing emissions:

- Use of alternative fuels: One of the most promising ways to reduce emissions in the nautical industry is to replace traditional fossil fuels with cleaner alternatives. Several projects are underway to explore the use of alternative fuels such as biofuels, hydrogen, and ammonia. For example, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping is developing a zero-emissions container vessel powered by green ammonia, while the Finnish company Wärtsilä is developing a hydrogen-powered ferry.
- Improved energy efficiency: Another approach to reducing emissions in the nautical industry is to improve the energy efficiency of ships. This includes measures such as optimizing ship design, reducing ship weight, and improving engine efficiency. The European Union-funded project EfficienSea2 is developing new technologies to improve navigation and communication systems, which can help ships to navigate more efficiently and reduce fuel consumption.
- Use of renewable energy: Nautical industry companies are also exploring the use of renewable energy sources such as wind and solar power to reduce emissions. For example, the Norwegian company Equinor is developing a floating wind farm to power offshore oil and gas platforms, while the German company Enercon is developing a wind-powered cargo ship.
- Emissions monitoring and reporting: In order to reduce emissions, it is important to accurately monitor and report on emissions levels. The Global Maritime Forum has launched the Poseidon Principles, a set of guidelines for responsible ship finance, which include a requirement for participating banks to monitor and report on emissions levels.

These ongoing projects and initiatives are just a few examples of the nautical industry's efforts to reduce emissions and promote sustainable practices. By embracing innovative technologies and practices, the industry is taking a significant step towards a more sustainable future. For more information on these and other initiatives, visit the websites of the relevant organizations and companies, such as the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Wärtsilä, EfficienSea2, Equinor, and Enercon [96] Furthermore:

- Shipowners around the world are facing the choice of how to adapt to the International Maritime Organization's (IMO) requirements for reduced harmful emissions. One option is to equip vessels with special Exhaust gas purifiers or scrubbers, which enable the use of high-sulfur fuel while complying with emissions standards. It is predicted that by the end of 2020, around 3,000 vessels will be equipped with scrubbers, and another 1,000 scrubbers will be installed by early 2021. The second option, which is preferred by the majority of shipowners, is to use a new special fuel called very low sulfur fuel oil (VLSFO), with sulfur content seven times lower than high sulfur fuel oil (HSFO), making it IMO compliant.
- The shipping industry is also exploring alternative sources of energy, such as solar and wind, to make ships more environmentally friendly. Additionally, there is a trend towards ballast-free systems to minimize the negative impact of ship ballast on water organisms. It also

is adopting innovative technologies to reduce environmental impact, including higher engine efficiency, better water cooling, kite-sail and rig-sail systems, solar panels, newly developed propellers, speed injectors, and improved body paint technologies. These technologies can achieve savings of up to 25% in electricity, 1.5% in fuel, and reduce harmful emissions.

- IoT solutions, like Fuel Optimization Systems, use data from sensors on ships, satellites, and embedded trackers to recommend the most economical route. For example, Marine Digital FOS collects data on 5 main categories out of 40 parameters, each factor affecting fuel consumption from 3 to 7%, and the combined effect can save up to 12% of fuel and reduce emissions.
- One of the latest innovative developments is the FastRigs system, which consists of smart vertical aerofoils mounted on vessels. With a sophisticated analysis system, it calculates the available wind to any ship, reducing fuel consumption by at least a fifth initially. The wing sails are "intelligent" and retract autonomously when approaching a bridge or dangerous wind speeds.

Finally, about future fuel for shipping [97]:

- Ammonia is a potential fuel for boats that can be produced using renewable energy sources. It is considered to be a carbon-free fuel, meaning that it does not emit carbon dioxide when burned. However, the production of ammonia itself does generate carbon emissions, so the overall carbon footprint of using ammonia as a fuel depends on how it is produced. One advantage of ammonia is that it has a high energy density, which means that it can provide a lot of energy per unit of volume. However, ammonia is toxic and requires careful handling and storage.
- Biofuels are fuels made from renewable biomass sources, such as plants or waste products. They can be used as a replacement for fossil fuels in boats and other vehicles. Biofuels can have a lower carbon footprint than fossil fuels, but their overall environmental impact depends on how they are produced. Some biofuels, such as biodiesel, can be used in existing boat engines with little or no modification.
- Hydrogen is a clean-burning fuel that can be used in boats and other vehicles. When burned, it produces only water vapor and does not emit any carbon dioxide or other harmful pollutants. Hydrogen can be produced using renewable energy sources, such as wind or solar power, making it a carbon-free fuel option. However, hydrogen is currently more expensive to produce and store than other fuels, and it requires specialized infrastructure to transport and use.
- Methanol is a liquid fuel that can be produced from a variety of sources, including natural gas, coal, and biomass. It can be used as a replacement for gasoline or diesel fuel in boat engines. Methanol burns cleanly, producing fewer emissions than fossil fuels, and it can be produced using renewable energy sources. However, methanol is toxic and flammable, and it requires specialized storage and handling procedures. Additionally, some boat engines may need to be modified to use methanol as a fuel.

9.5 How to reduce the impact of CF in our daily life

To finish, some actions that could be taken by everyone daily could help to reduce our impact in the CF. These are:

1. Use public transport every time we can. The use of public transport means that a car/motorbike or similar is being unused, not emitting any kind of GHG
2. Responsible consumption. This will be based on the consumption of proximity products, which avoids all the transportation from the place they are elaborated until the facilitation where we buy it. Also on an products elaborated in a sustainable way, meaning that polluting the air as less as possible and being as nearer as carbon zero as possible, not damaging so much the environment.
3. Use of zero carbon emissions MOT. And with that we don't mean electric vehicles of similar, it's easieas than this. Walking or cycling it's the cleanest way, as it doesn't consume nothing and doesn't emit any kind of GHG to the atmosphere
4. Use less contaminant vehicles. Nowadays all the specifications are given once we look at the datasheet, included the consumption. Every gram that the vehicles less emits, the better we are doing to emit as minimum GHG as possible
5. Use of 100% renewable energy for the consumption. This is one of the main points to be achieved for the countries if they want to be neutral zero for the future. These includes solar energy, eolical, geothermal, hydropower, bioenergy, marine, passive daytime radiative cooling, artificial photosyntesis and earth infrared thermal radiation.
6. Low consumption electrical household appliance. As well as for the cars, the datasheet of every household appliance we use at home includes how much energy it wastes. If all the humans would buy the less contaminants of them, the indirect emissions from the use of less energy will be considered.
7. Heating and air conditioning regulation. The regulation of both of them to standard temperatures, that means neither too cold or too hot, also reduces indirectly the emissions, as less quantity of energy is required to use them.
8. Self awareness about the importance of reduce CF. Maybe the first point that the people should start learning. Understanding what is CF could help people to understand the importance of the GHG emissions and how it damages our planet.
9. Decrease the quantity of residues generated. For example, reusing or recycling containers, reusing things that could be used twice instead of using them only once.

Chapter 10

Improvements

Here some improvements to the methodology used in this report to improve it:

- Unifying criteria between all modes of transportation is a critical aspect of creating a more equitable comparison between different modes of transport. Inconsistencies in the measurement criteria make it difficult to accurately compare the impact of different transportation methods. For example, different modes of transportation may use different units to measure fuel consumption, which can create confusion and make it difficult to compare data. By unifying the criteria used to measure transportation impact, it will be easier to make an accurate comparison and choose the most environmentally friendly option. It has been seen that not following the same procedure could have been the fault for obtaining results too many different in some cases.
- It is essential to adopt a holistic approach that involves unifying criteria between all means of transportation to allow for a more just comparison, utilizing the same data for all modes of transport, determining the exact ratio and amount of each GHG emitted by each mode of transportation, and choosing locations based on their typology.
- Utilizing the same data for all modes of transport is another essential step in improving the environmental impact of transportation. In some cases, data may not be readily available for certain modes of transport. By collecting and sharing data across all modes of transport, it will be easier to determine the exact environmental impact of each mode of transportation.
- Determining the exact ratio and amount of each greenhouse gas emitted by each mode of transportation is also crucial. Currently, it is challenging to determine the exact amount of greenhouse gases emitted by different modes of transportation.
- Choosing locations based on their typology is also a critical aspect of reducing the environmental impact of transportation. Different locations have different characteristics, which can impact the environmental impact of transportation. For example, a port that is primarily used for industrial purposes may have a greater environmental impact than a port that is primarily used for recreational purposes (case that Hamburg).

In conclusion, adopting a holistic approach that involves unifying criteria between all MOT, utilizing the same data for all modes of transport, determining the exact ratio and amount of each greenhouse gas emitted by each MOT, and choosing locations based on their typology is essential to reducing the environmental impact of transportation. By working together and implementing these improvements, we can create a more sustainable future for generations to come.

Chapter 11

Conclusions

The purpose of this study was to analyze the emissions associated with the main means of transportation and the costs involved in terms of the production of the vehicle to be used, the infrastructure required for its operation, and the operation itself.

Based on various studies, reports, and real data, the initial assumption was that, in general, and for the main objective of the study (the emissions produced by the different means of transportation), the cleanest one should be the train, followed by a public transportation such as the bus. Initially, it was thought that the most polluting means of transportation would be the airplane, but as the study progressed, it was discovered that cruises are even more polluting.

Although some values obtained differ from real data, which is attributed to the lack of certain necessary information to perform calculations correctly and the use of different methods for each means of transportation, the order expected to be obtained regarding the transported PAX has been fulfilled.

Different projects that are underway to make each of the vehicles studied much less polluting in the future have also been studied and learned from.

In general, the study can be considered valid, and satisfactory results have been obtained regarding comparison, but not so much regarding the obtained values, since greater accuracy could have been achieved if the necessary tools were available.

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