Environmental impact of autonomous vehicles

Author: María Irene Fluxá Iñiguez [1]
Supervisor: Juan de Norverto Moriñigo [2]

[1] Universidad Pontificia de Comillas (ICAI); 201707157@alu.comillas.edu
[2] Universidad Pontificia de Comillas (ICAI); jnorvert@comillas.edu

Abstract: The implementation of autonomous vehicles could become a key factor in transforming the transport sector into a more sustainable one. In this project, a life cycle assessment study was carried out using SimaPro software to evaluate the environmental impact of autonomous vehicles, compare them with gasoline-powered internal combustion vehicles, and propose solutions that could improve road transport. The results for the global warming impact category indicate that the impact of autonomous electric vehicles is 1.73 times greater than that of conventional electric vehicles, i.e. their impact increases by 73.26%. The results obtained show that the manufacture of additional electronic equipment to equip the vehicle with SAE Level 3 autonomy has a significant impact on all categories of environmental impact considered. Automated electric vehicles can be an attractive solution due to their energy efficiency and contribute to reducing traffic on the roads. However, this result highlights the need for further research into alternatives for the production of electronic components that have a lower environmental impact.

Keywords: Autonomous Vehicles, Life Cycle Analysis, SimaPro, Mobility

---

1. Introduction

The transport sector is one of the main contributors to global environmental pollution. In Spain, 30.7% of total greenhouse gas emissions are attributable to this sector, with 28.4% coming from road transport. This is motivating the search for more sustainable means of transport. [1]

Alongside the current drive to be more environmentally friendly, technological advances are being made that could significantly change society in the future. In the automotive sector, artificial intelligence is becoming the key tool that will enable the automation of vehicles.

An autonomous vehicle is defined as one that has technological tools capable of imitating human driving skills, thus allowing the vehicle to be driven autonomously without the need for human intervention at any given time. Achieving the ideal level of fully autonomous driving is a major challenge, but in recent years, electronic equipment has been introduced that is contributing to the increasing automation of vehicles. [2]

This revolution in the automotive sector is expected to bring benefits in terms of road safety, efficiency, comfort and the environment. The implementation of autonomous vehicles in the European Union could contribute to achieving the 2050 target of zero road deaths, given that human error is responsible for more than 90% of traffic accidents and automated driving would reduce this risk. [3]

One of the objectives of implementing autonomous vehicles is to generate environmental benefits. By eliminating the human factor from driving, it is expected that the ADS system will drive almost perfectly, respecting the speed limits established in each zone and avoiding speeding that would require the driver to brake suddenly. By eliminating the human factor from driving, the ADS system is expected to drive almost perfectly, respecting the speed limits established in each area and avoiding speeding that forces it to brake or, in other cases, accelerate. This efficient driving would reduce battery energy consumption on each car journey. On the other hand, the implementation of autonomous vehicles in society can contribute to reducing urban congestion in large cities by promoting constant traffic flows, reducing the number of vehicles needed in households and encouraging the optimisation of their use by implementing the car-sharing mobility model. [4]

Although the environmental impact of electric vehicles may appear to be reduced because they do not burn fossil fuels (petrol and diesel) to operate and do not generate direct emissions while driving, it is true that the production of both internal combustion engine and electric vehicles has negative environmental consequences on groundwater, soil, aquatic and terrestrial ecosystems, as it generates a high percentage of waste and pollutants during their manufacturing processes. [5]

In addition, the use and development of artificial intelligence tools for autonomous vehicles will require high levels of energy consumption. This will mean that more data processing centres will have to be built and created. Data centres currently consume 2% of the world's electricity, and this figure is expected to increase in the coming years. [6]

In this project, the Life Cycle Assessment tool has been used to provide an estimate of how autonomous electric vehicles could impact different impact categories and what solutions could offset their impact.

2. State of the Art

The Society of Automotive Engineers (SAE) establishes six different levels of autonomy. The lowest level is 0, which includes vehicles that do not have any complex driver assistance systems. Next is level 1, where the vehicle has an assistance system capable of controlling acceleration and deceleration or steering. To be classified at this level, the vehicle only needs to be able to perform one of the two tasks. If the vehicle can control both assistance systems, it would fall into the category of partial automation, i.e. level 2. Next is level 3, characterized as conditional automation, as it requires the driver to respond to any request for intervention even though the automation system is capable of autonomous driving. The next step is level 4, which, like level 3, means that the vehicle is capable of performing all driving tasks and even the ADAS system is capable of responding correctly if the driver does not respond to a request for intervention. Finally, there is level 5, which represents full automation, where the autonomous vehicle has all the necessary tools to perform all driving tasks, to the point that the driver can be omitted. [3]

Today's vehicles incorporate Advanced Driver Assistance Systems, also known as ADAS. These are a set of intelligent systems capable of enhancing the safety of the vehicle, its occupants and the environment while driving the vehicle. Depending on the systems integrated into the vehicle, a higher or lower level of automation will be achieved. Vehicle manufacturers have been implementing some of these intelligent systems in the manufacture of their vehicles over the last few years. Currently, there is a regulation in Europe that requires car manufacturers to incorporate a series of ADAS in order to ensure road safety. [7]

ADAS systems work by integrating various electronic and control devices. First, sensors act as the vehicle's eyes. These devices include cameras, radars, LiDAR, speed sensors, and motion detection sensors, among others. The information captured by the sensors is sent to the electronic control units (ECUs), which process the information received in real time using artificial intelligence algorithms. Once the situation is understood, they send commands to the vehicle's actuators to execute the established actions. The vehicle's actuators correspond, among other things, to the control of the vehicle's acceleration, power steering control and the activation of warning elements for the driver, such as lights and acoustic signals. [7]

The implementation of autonomous vehicles in society is conditioned, in addition to the technological complexity involved, by legal limitations. Regulation on the integration of autonomous driving into society must primarily address the following aspects: that autonomous driving is safe, that in the event of an incident, responsibilities can be assigned, and that it includes issues of data protection and cybersecurity, given that modern vehicles are increasingly connected and such attacks can pose a serious danger to society. In order for regulations to cover these different issues, it is essential that the various stakeholders involved come together. The main stakeholders are government agencies, vehicle manufacturers, technology companies involved in the manufacture, development and operation of autonomous vehicles, and traffic management agencies such as the General Directorate of Traffic (DGT) in Spain. [8]

Although European and Spanish regulations currently impose limitations on the introduction of autonomous vehicles into society, pilot projects are being carried out in Spain under the Framework Programme for the Evaluation of Safety and Technology of Automated Vehicles known as the ES-AV programme. This programme is part of Royal Legislative Decree 6/2015 and is responsible for authorising and supervising the tests and trials carried out by autonomous vehicles on public roads. The automated vehicles that can be authorised by this programme are SAE level 2 to SAE level 5. [9]

Following the Framework Programme for the Evaluation of Safety and Technology in Automated Vehicles, various tests are being carried out on public roads with autonomous vehicles. Below are some of these cases and their results to date. [9]

- E-BUSKAR: this project consisted of an autonomous city bus in Leganés (Community of Madrid). Its level of automation corresponded to SAE 4 and it was operational from 9 January 2025 to 28 February 2025. It travelled a total of 279.2 km and there were no serious incidents. [9]
- ALSA: this project began on 11 February 2025 and will continue to operate until 10 February 2027. This project consists of an electric minibus (shuttle) with SAE 4 automation level, which runs a route on the Cantoblanco Campus of the Autonomous University of Madrid. So far, there have been no serious incidents. [9]

As for the study of this type of automation technology and its life cycle analysis, there are already studies that consider the environmental impact of autonomous vehicles. However, the introduction of autonomous vehicles is still in the experimental phase, which means that the information available in life cycle analysis software databases is limited. Among the studies reviewed for the development of this project, it is worth highlighting the study on Environmental Impact Assessment of Autonomous Transportation Systems developed by researchers from the Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, Department of Mechanical Engineering, South Dakota School of Mines and Technology, Department of Chemistry, Biology, and Health Sciences, South Dakota School of Mines and Technology, published in June 2023, which assesses the environmental impacts of autonomous vehicles. [10]

3. Objectives

The main objectives to be developed in the preparation of this master's thesis are shown below.

- Classify and analyze autonomous vehicles according to their degree of autonomy, establishing their characteristics and differences with respect to conventional vehicles.

- Evaluate the environmental and energy impacts of autonomous vehicles during their life cycle, taking into account emissions into the atmosphere, energy consumption, impact on infrastructure and the management of critical materials. And compare their performance with conventional vehicles.

- Learn useful software tools for conducting Life Cycle Assessments (LCA) such as SimaPro, which enable a quantitative assessment of the environmental impact of autonomous vehicles.

4. Life Cycle Analysis methodology

The methodology used in this study corresponds to that of Life Cycle Analysis. It is used to assess the environmental impacts of a product, process or activity throughout its life cycle. This methodology makes it possible to identify opportunities that contribute to reducing potentially negative impacts at different stages of the life cycle of the product, process or activity. It is also useful for comparing products or processes from an environmental perspective, providing information on product design to make it more sustainable, obtaining environmental product declarations, applying the results for marketing purposes, creating optimal industrial or logistical processes, verifying compliance with environmental regulations and promoting sustainability. [11] [12]

The LCA methodology is based on:

1. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework

2. International Standard ISO 14044:2006 Environmental management - Life cycle assessment Requirements and guidelines

The LCA methodology defined by ISO 14040 and 14044 consists of four phases.

1. Definition of the objective and scope of the analysis. Depending on the objective of the study, the level of precision may differ significantly. In this phase, the boundaries, the desired level of precision, and the functional unit of the system are defined. [11]

   The scope of the study determines its level of breadth and detail. Depending on the objectives of the study, a narrower or broader scope will be selected. [13]

   The types of scope are presented below:

   - Gate to gate: this is a more limited type of scope as it only considers the production phase of the product.

   - Cradle to gate: this includes the phases of obtaining raw materials, transport to the factory and manufacturing processes. [14]

   - Cradle to grave: includes the phases of obtaining raw materials, transport to the factory, production processes, distribution to customers, the use phase and the end-of-life phase, where waste management is carried out at the end of the product's useful life. [14]

   - Cradle to cradle: encompasses the same phases as the cradle to grave scope, but also incorporates the management of waste at the end of its useful life and reuses it as raw material to be reintroduced into the first phase of the life cycle. [14]

2. Life cycle inventory analysis (LCIA): this phase is responsible for identifying and quantifying the inputs and outputs of the product system. Inputs correspond to the consumption of raw materials and resources used, and outputs correspond to the generation of waste and pollution from emissions to air, soil and water. [14]

3. Life cycle impact assessment (LCIA): after obtaining the results from the life cycle analysis, the potential environmental impacts of the system are assessed. [14]

4. Interpretation: the results obtained in the LCI or LCIA phases, or both, are summarized. This summary is then used to draw conclusions about the environmental impact of the system. [11]

It should be noted that the phases of the life cycle analysis should not be understood as a sequential process. The LCA should be developed iteratively, as in order to achieve accurate and robust results, it may be necessary to make improvements on an ongoing basis throughout the study process. [15]

Life cycle analysis software allows the different stages of the life cycle of a product, process or service to be modelled with the aim of quantifying their environmental impacts. These tools have access to internationally recognized environmental databases and are capable of applying various environmental assessment methodologies. This study uses SimaPro life cycle analysis software. This software includes databases such as Ecoinvent and Agri-footprint and the application of various methodologies such as ReCiPe, CML-IA, IPCC and ILDC. SimaPro offers advanced tools that enable accurate and reliable simulation. Due to the features, it offers, it is often one of the tools selected for LCA development in research work and complex studies. Among the most notable tools is the graphical representation of the model, which allows the visualization of material flows and facilitates the identification of possible inconsistencies in the flows, if any exists.

The methodologies correspond to industry standards that convert inventory information such as waste generation, emissions generated, and resource use into environmental impact indicators. The methodology used in this study corresponds to CML-IA: The Centre for Environmental Sciences at Leiden University proposed the CML-IA methodology in 2001. This LCA methodology, based on a midpoint perspective (intermediate impacts), introduces a set of impact categories and a characterization methodology to be applied to Life Cycle Impact Assessment (LCIA). This methodology is included in the SimaPro LCA software, which offers two types of versions. The first version, known as baseline, uses the ten most relevant impact categories, and the second version is more extensive and also includes other categories. The impact categories used in the baseline version (the one used in the study) are: Abiotic depletion, Abiotic depletion (fossil fuels), Global warming, Depletion of the stratospheric ozone layer, Human toxicity, Freshwater aquatic ecotoxicity, Marine ecotoxicity, Terrestrial ecotoxicity, Formation of photo-oxidants, Acidification and Eutrophication. [16]

The database used in the project is Ecoinvent. It was created in Switzerland and has the advantage of offering over 18,000 processes from different areas, including agriculture, transport, materials and energy, among others. In addition, it is a database compatible with various software programmes such as SimaPro.

5. Life Cycle Analysis study

5.1 Definition of the objective and scope of the analysis

The purpose of this study is to identify the environmental impacts of the life cycle of a vehicle with autonomous driving features, following the ISO 14040 and ISO 14044 standards, which establish the methodology to be followed for the development of a Life Cycle Analysis. This study aims to identify which processes, materials, and equipment that form part of the life cycle of an autonomous vehicle have the greatest environmental impact and in what ways this new technology differs from conventional internal combustion vehicles from an environmental point of view.

The scope chosen in the preparation of this life cycle analysis follows a partial cradle-to-grave approach. It includes all stages of material extraction, vehicle manufacturing (considering that it includes delivery to the customer), the use phase, the maintenance phase, and the end-of-life phase, which includes the dismantling of the bodywork. However, the end-of-life phase does not include an analysis of battery and other electronic equipment management due to a lack of available data, although it is recognized that their inclusion could have a significant environmental impact.

Figure 1 shows the boundaries chosen for the life cycle analysis of the project. Within the boundaries of the system are the phases that represent the cradle-to-grave approach, and the connection of the system to the outside world is provided by the inputs and outputs to the system. The inputs to the system would be the raw materials needed to manufacture the vehicle, and the energy required for the various processes within the system. The output from the system would be emissions pollutants to the atmosphere, soil and aquatic environments, solid waste and equipment to be subsequently recycled.

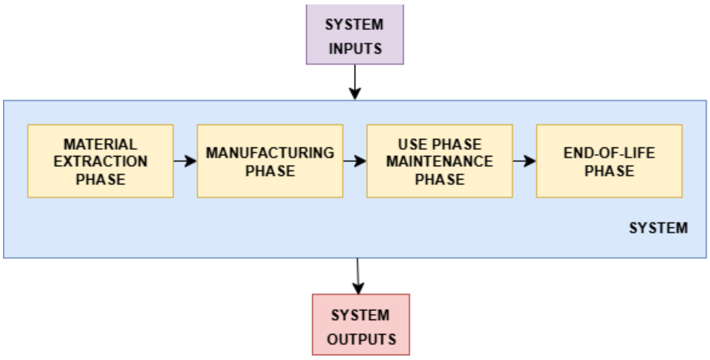


Figure 1 Study system limits [Own elaboration]

For this life cycle assessment study on autonomous vehicles, 1 km travelled has been chosen as the functional unit. The functional unit serves as the basis for calculating material and energy balances and facilitates comparisons of environmental impacts with other technologies. [17]

The following aspects have also been assumed for the development of this life cycle analysis:

- The useful life selected for the autonomous vehicle under study is 150,000 km travelled.
- The autonomous vehicle under study is assumed to be an electric vehicle with characteristics that make it a level 3 autonomous vehicle.

5.2 Inventory analysis (LCI)

The following shows the processes introduced in each of the phases considered in the study for modelling the autonomous vehicle in SimaPro.

5.2.1 Manufacturing phase of the autonomous vehicle

For the manufacturing phase of the autonomous vehicle, existing processes in the Ecoinvent database have been used, including their inputs and outputs. The processes used correspond to:

- *Passenger car, electric, without battery {GLO}*: This process includes the production of the vehicle without the battery. The production of the vehicle in the process consists of the production of the body (Glider) and the production of the electric motor and transmission (Drivetrain). The process also includes emissions, energy, materials and infrastructure required for manufacturing and manual dismantling at the end of the vehicle's useful life, as well as the waste generated during dismantling. It should be noted that this process does not cover the vehicle's use phase.

- *Battery, Li-ion, rechargeable, prismatic {RoW}*: This process models the manufacture of 1 kg of LFP-type Li-ion battery. The system represents a 203 kg pack with 23.5 kWh, composed of 137 prismatic cells (3.6V-46 Ah). This process includes the inputs of materials and components necessary for the manufacture of the battery, the production of the batteries and the infrastructure necessary during the process.

- *Electronic component, active, unspecified {GLO}*: This process represents the manufacture of sensor, radar, camera and electronic circuit components used in autonomous vehicles. This process was used in the study because it was the most representative process in the database for the manufacture of electronic components such as sensors, radars, cameras and electronic circuits.

- *High voltage system, for Li-ion battery {GLO}*: This process represents the manufacture of a lithium-ion battery management system. It is necessary to include this equipment in the manufacture of autonomous vehicles because it manages energy between modules, provides protection for high-voltage circuits, protects against short circuits and overloads, and can even power other equipment installed in the vehicle, such as sensors and processing units.

- *Printed wiring board, for power supply unit, desktop computer, Pb free {GLO}*: This process represents the manufacture of a printed circuit board assembly that is usually included in the electronic systems of autonomous vehicles. To date, there is no specific process for this equipment for vehicles in the database, so this one has been chosen as it is the most representative one available at the present time.

- *Integrated circuit, logic type {GLO}*: This process represents the manufacture of artificial intelligence systems, logic processors, control chips and other electronic equipment required to achieve the level of autonomy selected for the autonomous vehicle.

In the Product Stages tab in the SimaPro software, specifically in the assembly section, a specific assembly has been created that represents the overall process of manufacturing an autonomous vehicle. This assembly includes the processes mentioned for the different components needed to obtain an autonomous vehicle by entering their corresponding value in kg (representation). Table 1 shows the values assigned to each component or set of elements:

Table 1. Introduction to the processes involved in manufacturing an autonomous vehicle

PROCESS NAME	QUANTITY (KG)
PASSENGER CAR, ELECTRIC, WITHOUT BATTERY	1234
BATTERY, LI-ION, RECHARGEABLE, PRISMATIC	478
ELECTRONIC COMPONENT, ACTIVE, UNSPECIFIED	10
HIGH VOLTAGE SYSTEM, FOR LI-ION BATTERY	30
PRINTED WIRING BOARD, FOR POWER SUPPLY UNIT, DESKTOP COMPUTER, PB FREE	3
INTEGRATED CIRCUIT, LOGIC TYPE	1

5.2.2 Use phase of the autonomous vehicle

For the use phase of an autonomous vehicle, the Ecoinvent database process "*Electricity low voltage {ES}| market for electricity*" is used. Electricity consumption in kWh (value entered considering the functional unit) represents the electricity consumption of an electric vehicle and the additional consumption of a level 3 autonomous vehicle. After reviewing various scientific publications on studies of autonomous vehicles, electricity consumption (kWh) per km has been entered as 0.17716 kWh/km. [10]

5.2.3 Maintenance phase of the autonomous vehicle

To model the maintenance phase of the autonomous vehicle during its useful life, two processes have been used:

- *Maintenance, Passenger car, electric, without battery {GLO}*: This process covers the maintenance and replacement needs of equipment due to wear and tear throughout the useful life of the electric vehicle.

- Maintenance of additional electronic equipment: Given that the above maintenance process only covers the maintenance of an electric vehicle, a process has been created that includes replacement equipment that enables autonomous driving (such as sensors and radars) and a replacement battery. It has been assumed that, over the lifetime of the autonomous vehicle, it will be necessary to replace the battery.

5.2.4 End-of-life phase of the autonomous vehicle

For the end-of-life phase, no specific process is introduced for the dismantling of the vehicle, given that the manufacturing process for the vehicle used 'Passenger car, electric, without battery {GLO}' includes its dismantling. What is not included in the SimaPro modelling due to lack of data is the management of the battery and other additional electronic equipment.

In order to model the life cycle of the autonomous vehicle in SimaPro, the stages of manufacturing, use and maintenance have been considered. It is important to clarify that the manufacturing stage includes processes that consider the dismantling of some parts of the vehicle and that the maintenance stage consists of a specific maintenance process for electric vehicles and an additional maintenance process considering spare parts for the battery and additional electronic equipment. To integrate the three stages (manufacturing, use and maintenance) into a single system, each stage has been standardised to the functional unit corresponding to 1 km travelled, based on a useful life of 150,000 km for the vehicle under study.

5.3 Results and discussion (Impact Assessment and Interpretation)

Network diagrams are used to illustrate the environmental impact of each process in the system. This diagram is useful for showing how the different processes in the system are connected to each other, and it also makes it easier to identify the critical processes for each impact category. Each process is represented by a node, and the arrows connecting the nodes vary in thickness depending on the impact of each process. Although SimaPro software allows network diagrams to be obtained for each impact category, this study only includes diagrams corresponding to the impact categories of global warming and human toxicity.

Figure 2, shows the contribution of the life cycle processes of an autonomous vehicle in the global warming impact category.

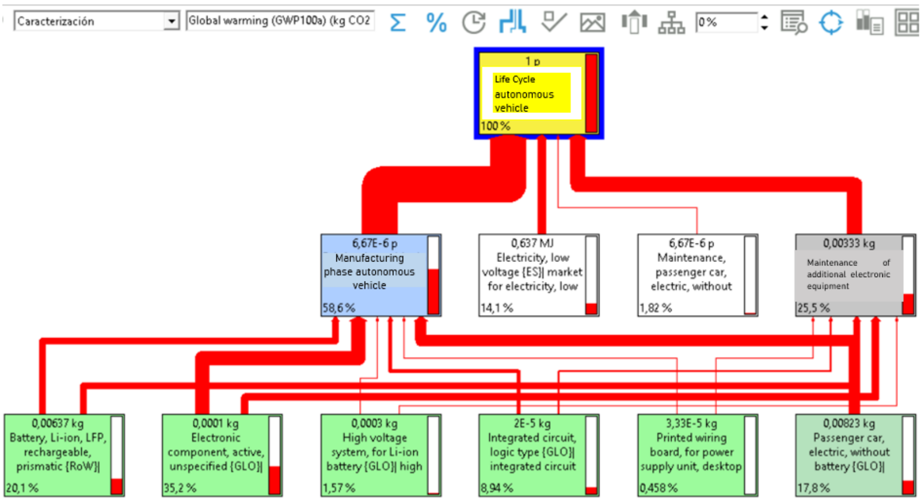


Figure 2 Contribution of processes within the life cycle of an autonomous vehicle in the global warming impact category (Own elaboration)

As can be seen in Figure 2, the stage with the greatest impact on global warming is the manufacture of the autonomous vehicle, accounting for 58.6% of the total, followed by the maintenance of additional electronic equipment to achieve SAE 3 autonomy for the vehicle. Among all the processes included in the network diagram, the manufacturing process for active electronic components stands out as the main contributor to the impact associated with global warming. This makes sense considering that the production of active electronic components is characterised by high energy consumption in metal extraction and subsequent processing.

Figure 3 reflects the case of how the processes included in the autonomous vehicle life cycle system affect the human toxicity impact category.

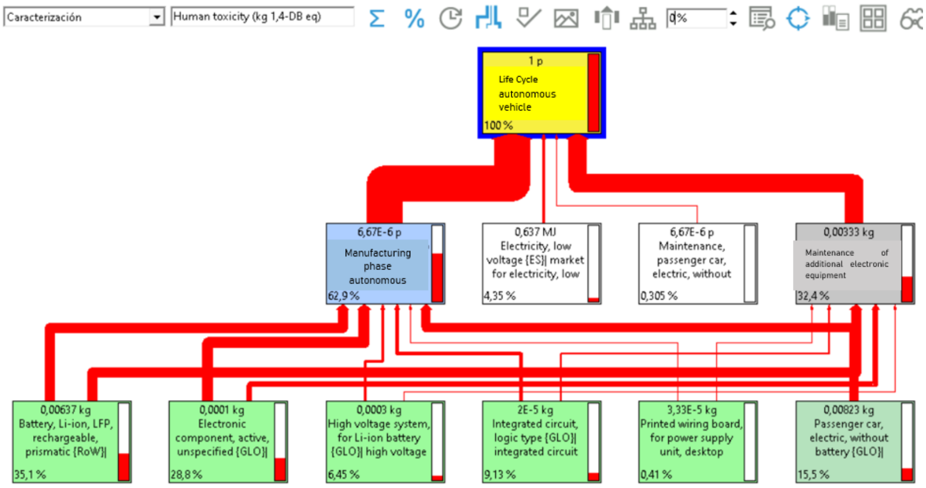


Figure 3 Contribution of processes within the life cycle of an autonomous vehicle in the human toxicity impact category (Own elaboration)

In the case of Figure 3, it can also be seen that the vehicle manufacturing stage remains the stage with the greatest impact compared to vehicle use (electricity consumption) and maintenance, but the manufacturing process for active electronic components is not the only factor primarily responsible for the human toxicity impact. In this case, the human toxicity impact is mainly caused by the production of lithium-ion batteries, active electronic components and the manufacturing process of electric vehicles without batteries. On the other hand, it can be seen that the use stage (electricity consumption) does not reach 5% of the impact on the human toxicity category. However, for the global warming category, its impact is more significant. This is in line with expectations, given that the electricity consumption process during the use stage of the electric vehicle represents the energy mix available in Spain according to the Ecoinvent database, in which part of the electricity generated comes from fossil fuel sources. These sources generate CO_2 emissions, which contribute negatively to global warming. While the electricity generation process does not affect the human toxicity impact category as significantly as it does the climate change impact.

The SimaPro software also allows to visualise how the system processes impact each of the impact categories together in a bar chart. In Figure A1 (see Appendix A**)**, dark green represents the manufacturing phase of the autonomous vehicle, light green represents the electricity consumption phase, orange represents the maintenance phase of the electric vehicle without the battery, and yellow represents the maintenance phase of the additional electronic equipment and replacement batteries.

Figure A1 summarises some of the observations discussed. As can be seen, the manufacturing phase of the autonomous vehicle corresponds to the phase with the greatest impact in all impact categories, and the next phase corresponds to the maintenance of electronic equipment, which makes sense given that it also involves the manufacturing processes of various electronic devices and batteries, which have a significant environmental impact during their manufacture. With regard to the use phase (electricity production), it can be seen that it has a greater impact in the categories of abiotic depletion (fossil fuels) and global warming (climate change). This is consistent, given that the Spanish energy mix used includes electricity from polluting sources (fossil fuels), which means that this process has a more significant impact in these categories.

The following section assesses the environmental impact of an autonomous electric vehicle compared to a conventional electric vehicle, i.e. one driven by a person (SAE autonomy level 0). To make the comparison, in addition to removing the electronic equipment to simulate a level 0 automated electric vehicle, an increase in electricity consumption is applied during the use phase of the non-automated electric vehicle compared to that introduced for the autonomous electric vehicle, given that the autonomous electric vehicle is considered to run more efficiently than an electric vehicle driven by a person. The consumption entered is 0.206 kWh/km. [10]

Table 2 shows the results of the environmental impact of the life cycle of a conventional electric vehicle and an autonomous electric vehicle in the categories of global warming and human toxicity.

Table 2. Environmental impact results of the life cycle of a conventional electric vehicle and an autonomous electric vehicle in the categories of global warming and human toxicity (Own elaboration)

Impact Category	Conventional electric vehicle	Autonomous electric vehicle
Global Warming (GWP100a) [kg CO_2 eq/km]	0,2011278	0,34847791
Human toxicity [kg 1,4 DB eq/km]	1,1398076	1,8254623

Based on these results, autonomous electric vehicles have an impact on global warming 1.73 times greater than that of a conventional electric vehicle, i.e. an increase of 73.26%. Emissions of kg CO_2 eq/km correspond to 0.34847791 kg CO_2 eq/km for autonomous electric vehicles and 0.2011278 kg CO_2 eq/km for conventional electric vehicles. Much of the global warming environmental impact of the life cycle of a conventional electric vehicle continues to come from the vehicle production phase and battery production.

From the perspective of the human toxicity impact category, the factor is 1.6 times the impact of a conventional electric vehicle, i.e. an increase of 60.16%. Going from 1.1398076 kg 1.4-DB eq/km to 1.8254623 kg 1.4-DB eq/km. Much of the environmental impact of human toxicity in the life cycle of a conventional electric vehicle continues to come from the vehicle production phase and battery production.

Figure A2 (see Appendix A) shows a graph comparing the life cycle of the simulated electric vehicle with the life cycle of a petrol internal combustion vehicle. Figure A2 shows the result of this comparison, in which the life cycle impacts of an autonomous electric vehicle are represented in dark green and the life cycle impacts of a petrol internal combustion vehicle are represented in light green. The results obtained show that internal combustion vehicles have a greater impact in the categories of abiotic depletion (fossil fuels), global warming and photochemical oxidation. This is as expected, given that the emissions generated during the use phase of an internal combustion vehicle have a significant impact on these categories. The rest of the categories are more affected by the life cycle of the autonomous vehicle.

To end the study's evaluation, a sensitivity analysis is performed. The aim of this analysis is to study how the contribution of the autonomous vehicle's use phase to global warming changes if a 100% renewable electricity generation process were used. In the base case, the energy mix for Spain (2014-2022) available in the database used was employed, composed mainly of electricity from non-renewable, nuclear, fossil and renewable sources. Given that the mix used in the base case is not made up solely of 100% renewable sources, it is to be expected that the results will show that the use phase reduces its impact in terms of global warming. This can be seen in Figure 4, where the impact has been reduced by 12.87%. Going from 14.1% impact (see Figure 2) to 1.23% in this case.

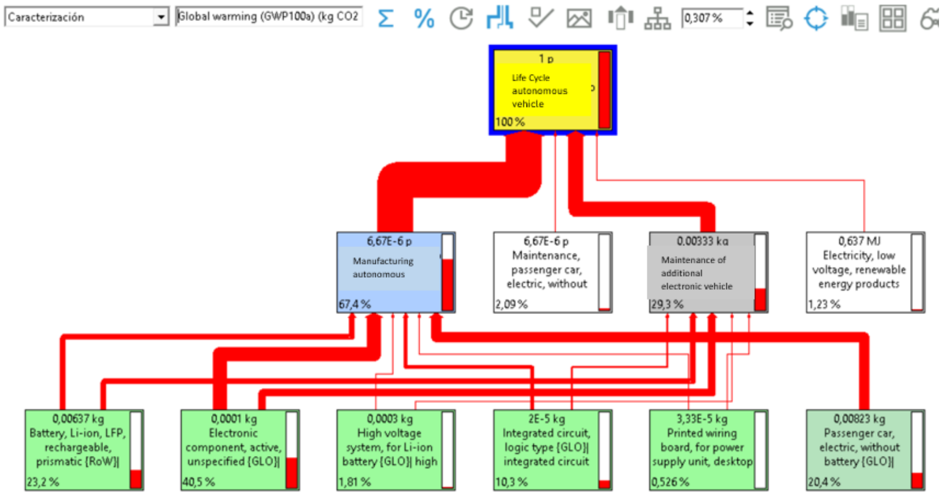


Figure 4 Contribution of processes within the life cycle of an autonomous vehicle in the global warming impact category using electricity generation from 100% renewable sources (Own elaboration)

6. Conclusions

This project used the Life Cycle Assessment tool to provide an estimate of how the project could impact different impact categories and what solutions could offset its impact. The main conclusions drawn from the study are included below:

- Autonomous vehicle technology is still in its development phase. Although there are already pilot and implementation cases in various countries, the information in life cycle analysis software databases is limited or outdated, which has made it difficult to carry out this project with an optimal level of accuracy.

- Autonomous electric vehicles have an impact in the global warming impact category 1.73 times greater than that of a conventional electric vehicle. This means that the integration of automation into an electric vehicle increases its impact by 73.26%. From the perspective of the human toxicity impact category, the factor is 1.6 times that of a conventional electric vehicle, meaning the impact increases by 60.16%. These results show that the manufacture of additional electronic equipment to equip the vehicle with SAE Level 3 autonomy generates a significant impact in the environmental impact categories considered. Although self-driving electric vehicles may be an attractive solution due to their energy efficiency and their contribution to reducing road traffic, this result highlights the need for further research into alternatives for producing electronic components that have a lower environmental impact. This could be achieved by optimizing manufacturing processes, using renewable energy in energy-intensive processes, and implementing appropriate lifecycle management that encourages reuse and recycling, reintroducing as many components and materials as possible into the lifecycle. These initiatives would contribute to applying the principles of the circular economy to extend the lifespan of materials, thereby reducing the extraction processes for critical materials and, consequently, reducing the emissions associated with the manufacturing processes of new equipment.

- The research topic of the environmental impacts of autonomous vehicles offers a wide range of research possibilities. This project proposes a general analysis, but for future work, it would be interesting to delve deeper into the management of the useful life of electronic equipment necessary to achieve high levels of automation, as well as vehicle battery management.

- On the other hand, the life cycle analysis study focuses on a personal vehicle. As discussed in the initial chapters of this document, many of the pilot projects underway or already completed aim to promote the use of autonomous vehicles in shared mobility services and public transportation. This strategy offsets the high levels of pollution associated with the production of autonomous vehicles, given that making them accessible to a greater number of people optimizes the use of resources used to manufacture the vehicle. Furthermore, creating an autonomous transportation system that is efficient and accessible to a large number of people will reduce the need to purchase a personal vehicle and therefore reduce the number of vehicles in circulation. This will also reduce urban congestion and, consequently, reduce emissions associated with road transportation.

In conclusion, after conducting this study, it is considered that the introduction of autonomous vehicles into society is steadily advancing, although it depends on strict legal requirements for its operation. This technology can provide advantages such as road safety, transportation efficiency, a reduction in the number of traffic accidents and fatalities and reduced urban congestion. This does not mean that the manufacturing processes for the vehicle's electronic equipment and battery can cause severe environmental impacts, and therefore require research, a search for sustainable alternatives, and the promotion of their use by applying recycling and reuse techniques.

Appendix A

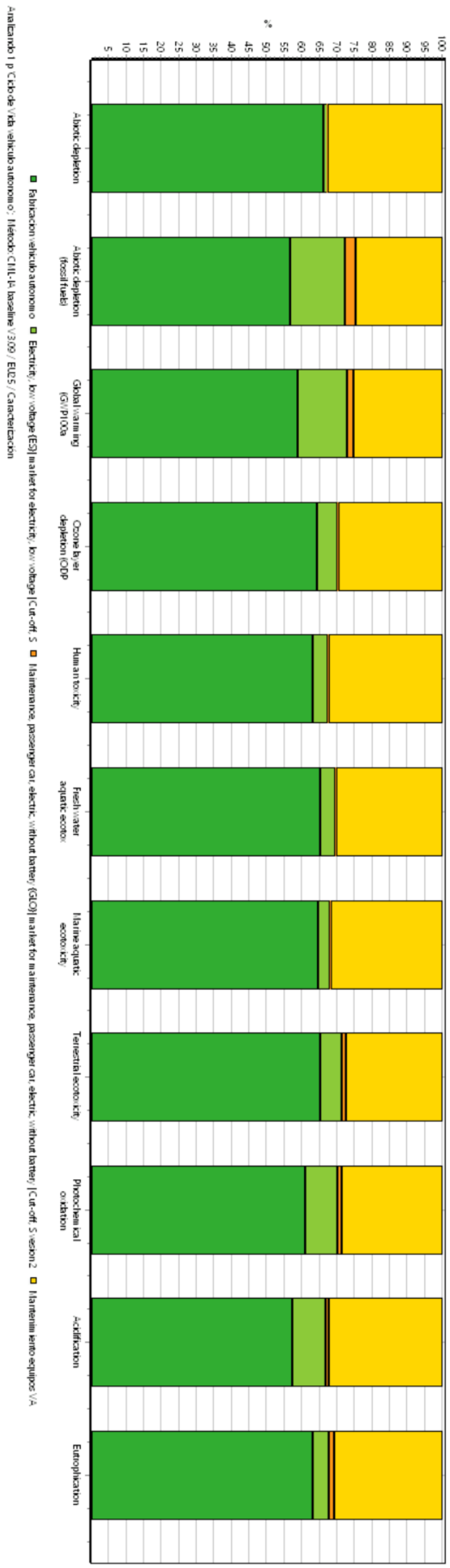
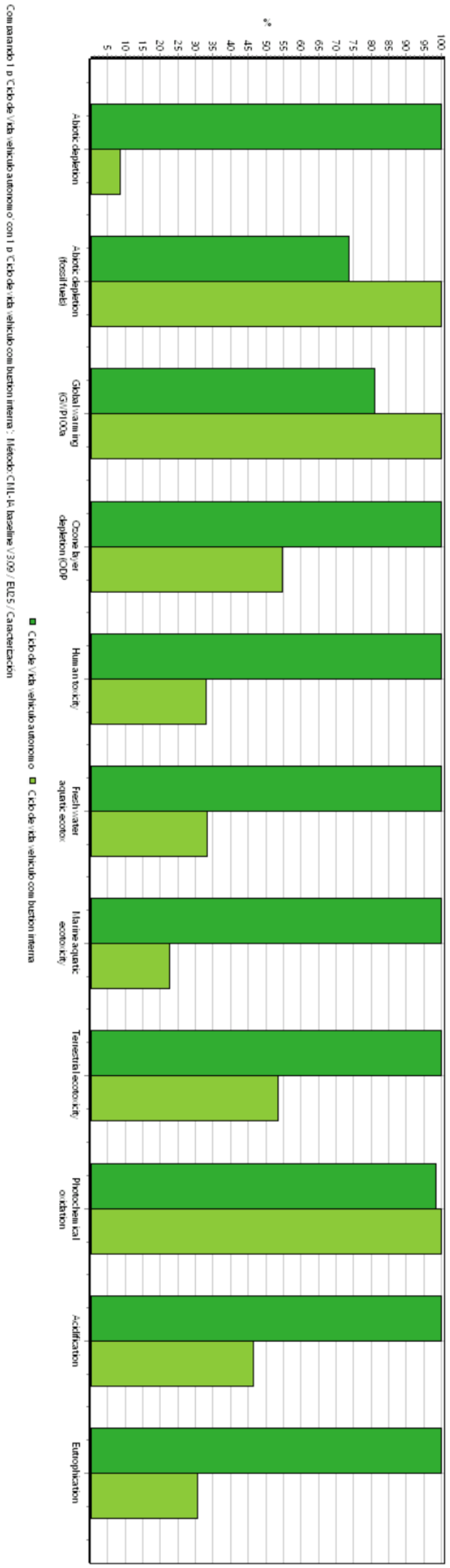


Figure 1 A Impact of each stage of the autonomous vehicle life cycle according to impact categories (Own elaboration)



547

Figure 1 B Results of the comparison between the life cycles of an autonomous vehicle and an internal combustion vehicle (Own elaboration)

References

[1] M. p. l. T. E. y. e. R. Demográfico, «Sector del transporte,» [En línea]. Available: https://www.miteco.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y.

[2] Y. Li, «Vehículos autónomos: Innovación en la logística urbana,» 06 2018. [En línea]. Available: https://core.ac.uk/download/pdf/234019727.pdf. [Último acceso: 06 2025].

[3] D. G. d. T. DGT, «Vehículos de conducción automatizada,» 21 03 2014. [En línea]. Available: https://www.dgt.es/muevete-con-seguridad/tecnologia-e-innovacion-en-carretera/vehiculos-de-conduccion-automatizada/.

[4] M. Navarro, «Neumáticos en verde,» 17 10 2021. [En línea]. Available: https://blog.signus.es/coche-autonomo-menos-contaminacion/#:~:text=Un%20humano%20no%20realiza%20una,una%20menor%20cont aminaci%C3%B3n%20del%20aire.

[5] AIXAM, «¿Cuál es el impacto de los coches en el medio ambiente?,» [En línea]. Available: https://www.aixam-mega.com/es/-cual-es-el-impacto-de-los-coches-en-el-medio-ambiente.

[6] J. C. Saloz, «Google está construyendo tres centrales nucleares con un único propósito: alimentar a sus sistemas de Inteligencia Artificial,» 16 05 2025. [En línea]. Available: https://www.lavanguardia.com/neo/20250516/10690953/google-esta-construyendo-tres-centrales-nucleares-unico-proposito-alimentar-sistemas-inteligencia-artificial.html.

[7] D. g. d. T. DGT, «Sistemas avanzados de ayuda a la conducción,» 24 04 2023. [En línea]. Available: https://www.dgt.es/muevete-con-seguridad/sistemas-avanzados-ayuda-conduccion/Sistemas-avanzados-de-ayuda-a-la-conduccion-ADAS-/.

[8] D. g. d. T. DGT, «Vehículos automatizados: Los vehículos de conducción automatizada representan una revolución para la movilidad del futuro,» 01 07 2025. [En línea]. Available: https://www.dgt.es/muevete-con-seguridad/vehiculos-seguros/conduccion-automatizada/vehiculos-de-conduccion-automatizada/.

[9] D. Dirección General de Tráfico, «Marco de autorización de pruebas de vehículos automatizados: ES-AV,» 30 06 2025. [En línea]. Available: https://www.dgt.es/muevete-con-seguridad/vehiculos-seguros/conduccion-automatizada/marco-pruebas-vehiculos-automatizados/.

[10] E. E. C. A. D. R. V. G. S. S. D. A. R. I. C. Samantha Heiberg, «Environmental Impact Assessment of Autonomous Transportation Systems,» 28 06 2023. [En línea]. Available: Environmental_Impact_Assessment_of_Autonomous_Tran.pdf.

[11] I. International Organization for Standardization, «Gestión ambiental-Análisis del ciclo de vida,» [En línea]. Available: https://www.iso.org/obp/ui#iso:std:iso:14040:ed-2:v1:es.

[12] Geoinnova, «Principales herramientas para el Análisis de Ciclo de Vida: comparativa completa de software,» 11 06 2025. [En línea]. Available: https://geoinnova.org/blog-territorio/principales-herramientas-para-el-analisis-de-ciclo-de-vida/#3_Comparativa_de_softwares_de_Analisis_de_Ciclo_de_Vida_ACV.

[13] G. d. I. S. e. l. c. y. e. l. industria, «Análisis del ciclo de vida (ACV),» 19 05 2022. [En línea]. Available: http://blogs.upm.es/gisci/2022/05/19/analisis-del-ciclo-de-vida-acv-una-guia-completa-de-los-acv/.

[14] D. Nuevo, «TECPA: ¿Qué es el análisis de ciclo de vida ACV?,» 27 03 2023. [En línea]. Available: https://www.tecpa.es/que-es-el-analisis-de-ciclo-de.

[15] I. C. Ruiz, «Comparativa medioambiental de diferentes tipos de transporte de viajeros utilizando una perspectiva de análisis de ciclo de vida,» Madrid, 2019.

[16] v. a. PRé, «SimaPro Database Manual Methods Library,» 06 2020. [En línea]. Available: https://simapro.com/wp-content/uploads/2020/06/DatabaseManualMethods.pdf.

[17] F. d. I. G. Ambiental, «Análisis del Ciclo de Vida,» [En línea]. Available: https://portal.camins.upc.edu/materials_guia/250504/2013/Analisis%20del%20Ciclo%20de%20Vida.pdf.