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Research article

Optimizing energy efficiency in Ro-Ro terminal operations through internal traffic automation with internet of vehicles (IoV)

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Abstract: Energy consumption in Roll-on/Roll-off (Ro-Ro) terminals is significantly influenced by the internal movement of vehicles, storage layout, and the frequency of vessel departures. Terminals with European-bound lines generally operate with more regularity and store vehicles near the quay, while those serving non-European destinations must store vehicles in more remote areas, leading to longer displacement times, higher fuel consumption, and increased CO_2 emissions. In this study, we present a quantitative evaluation of energy optimization through the implementation of Internet of Vehicles (IoV) in Ro-Ro terminals. By comparing conventional manual operations with an automated IoV-enabled scenario, we analyzed the impact on fuel consumption, energy cost, CO_2 emissions, and idle energy loss. Two sustainability indicators (Sustainable Risk Index (SRI) and Carbon Intensity Factor (CIF)) were introduced to assess and compare the environmental performance of different terminal configurations. The findings show that IoV adoption significantly reduces energy consumption and emissions, particularly in terminals with greater internal travel distances. This research offers practical tools for port managers and decision-makers and contributes to the broader discourse on smart energy solutions and digital transformation in port logistics.

Keywords: energy efficiency; Ro-Ro terminals; internet of vehicles; smart port logistics; sustainability indicators

1. Introduction

Maritime transport is a fundamental pillar of global trade, and within this sector, Roll-on/Roll-off (Ro-Ro) terminals play an essential role in vehicle logistics [1]. These terminals enable the temporary storage of cars, trucks, and machinery before they are loaded onto specialized vessels. However, the management of these spaces presents significant operational challenges, especially in terms of energy consumption and efficiency in internal displacements [2]. The distribution of vehicle storage, the frequency of loading and unloading operations, and the distance to the dock directly affect the operational efficiency and environmental impact of the terminal [3].

A key aspect in the optimization of Ro-Ro yard terminals is the difference between those destined for Europe, where ship departures are more frequent and vehicles can be stored in camps closer to the quay, and those destined for non-European international markets, where the lower frequency of departure forces vehicles to be stored in more distant areas; this increases travel times and fuel consumption [3]. These operational differences have a direct impact on the sustainability of the port system, increasing CO_2 emissions and costs associated with energy consumption.

In recent years, the development of digital technologies has opened new opportunities to improve the efficiency of port operations. One of these innovations is the Internet of Vehicles (IoV), which enables interconnection between vehicles and terminal management systems to optimize internal travel [4]. While IoV has been extensively studied in the field of urban mobility and in container terminals, its application in Ro-Ro terminals remains an underexplored area. The lack of studies on their impact on energy efficiency and emission reduction represents an opportunity to evaluate their potential in this type of infrastructure.

In this study, we aim to assess the impact of the IoV on the energy efficiency of Ro-Ro terminals, analyzing how the automation of internal journeys can contribute to the reduction of fuel consumption, CO_2 emissions, and operating costs. To this end, operational data from different terminals has been collected, and two scenarios have been compared: Manual operation and optimized operation with IoV. The assessment is based on the calculation of key indicators such as the Sustainable Risk Index (SRI), the Carbon Intensity Factor (CIF), and the loss of energy at idle, which makes it possible to quantify the potential benefits of automation in terms of sustainability and energy efficiency.

The results of this work can be useful for port managers, providing quantitative tools that facilitate decision-making in the planning and digitalization of Ro-Ro terminals. In addition, the study contributes to knowledge about energy efficiency in this type of infrastructure, offering a replicable approach for future research on the digitalization of maritime transport and its alignment with global sustainability goals.

2. State of the art

2.1. Energy efficiency and sustainability in port terminals

Energy efficiency in port terminals has been widely studied in the literature, especially in the context of reducing emissions and transitioning to more sustainable operations [5]. In this regard, the researchers have identified different strategies to improve the efficiency of ports, including the electrification of handling equipment, the implementation of renewable energies in port infrastructures and the digitalization of logistics processes [6]. These strategies are effective in reducing the environmental impact of the sector, especially in container and bulk terminals [7].

In the case of Roll-on/Roll-off (Ro-Ro) yard terminals, where vehicles must be stored and moved within the terminal before boarding, energy consumption is directly influenced by the management of internal traffic and the organization of storage space [8]. Research has shown that poor distribution of vehicles in the terminal can lead to longer travel times, which in turn increases fuel consumption and CO_2 emissions. However, the literature on energy efficiency in Ro-Ro terminals is more limited compared to other types of port terminals [9].

Another key aspect in port sustainability is the implementation of indicators to measure energy efficiency. While metrics such as the Crane Operating Efficiency Index (CHEEI) or the carbon intensity index in cargo handling have been developed in container terminals, in Ro-Ro terminals, there are no specific methodologies widely adopted [10]. The evaluation of sustainability in this type of terminal requires metrics adapted to its operational dynamics, considering fuel consumption in internal movements and the influence of the location of vehicles in the terminal.

2.2. Application of digital technologies in port traffic optimization

The digitalization of maritime transport has opened new opportunities to optimize port management, reducing inefficiencies and improving the sustainability of operations [11]. In this context, the IoV has been identified as a technology with great potential for the management of internal traffic in ports. Through the connection between vehicles, sensors and intelligent control systems, the IoV makes it possible to optimize travel routes, minimize waiting times, and reduce fuel consumption in spaces with high vehicle density, such as Ro-Ro yard terminals [12].

Studies have shown that the application of the IoV in urban environments has improved mobility, reduced congestion, and decreased CO_2 emissions in freight traffic [13]. However, in the port field, most research on digitalization has focused on container terminals, where crane automation and optimization of container allocation have been the major lines of development. In the case of Ro-Ro yard terminals, vehicles move autonomously within the port, which requires specific traffic management solutions to maximize energy efficiency [14].

The benefits of automation in port terminals have been widely studied in the literature. Research has shown that the integration of intelligent traffic management systems can lead to reductions of up to 30% in fuel consumption in terminals with a high travel density [15]. However, the lack of studies focused on Ro-Ro yard terminals leaves open the need to evaluate the specific impact of the IoV on this type of infrastructure.

2.3. Relevance of the study in the context of the energy transition and port digitalization

In the context of energy transition and digitalization of the maritime sector, the need to improve the operational efficiency of port terminals is a priority for the industry and environmental policymakers [16]. The International Maritime Organization (IMO) and the European Union have set ambitious targets to reduce emissions from maritime transport, promoting the integration of digital technologies to optimize logistics processes and reduce fossil fuel consumption [17]. Ro-Ro yard terminals, unlike other types of port terminals, require a particular approach due to the nature of their operation. While in container terminals the movement of cargo is highly automated by cranes and vertical storage systems, in Ro-Ro terminals, mobility depends on the distribution of vehicles in space and their autonomous movement within the port infrastructure [18]. This factor makes the optimization of internal traffic a key strategy for reducing energy consumption and CO_2 emissions.

The concept of Smart Ports has gained relevance in the last decade, promoting the use of technologies such as the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and IoV to improve logistics efficiency and reduce the environmental impact of maritime transport [19]. However, most digitization initiatives have been aimed at container terminals and general cargo, leaving the digitization of specialized terminals such as Ro-Ro yards in the background [20]. The lack of studies on the implementation of IoV in the optimization of internal vehicle mobility in Ro-Ro ports is a limitation that needs to be addressed in order to fully integrate these infrastructures within the paradigm of smart and sustainable ports [3].

In addition, the digitalization and optimization of traffic in Ro-Ro terminals can represent an emissions reduction strategy aligned with initiatives such as the European Union's Fit for 55, which seeks to reduce greenhouse gas emissions by 55% by 2030 [21]. In this sense, the automation of internal movements using IoV would not only contribute to improving the operational efficiency of terminals, but would also enable progress to be made in meeting the decarbonization objectives of the maritime sector [22].

This study is part of this line of research, providing a quantitative assessment of the impact of the IoV on the reduction of fuel consumption and emissions in Ro-Ro yard terminals. The findings can be key for port planners and environmental policymakers, offering empirical data to support the integration of digital solutions for improving energy efficiency in shipping.

2.4. Research gap and contribution of this study

Despite advances in digitalization and energy efficiency in ports, the literature presents a significant gap in the analysis of the impact of IoV on Ro-Ro yard terminals [23]. To date, there are no detailed studies evaluating how the automation of internal traffic using IoV can reduce fuel consumption, decrease CO_2 emissions, and improve operational sustainability in these terminals [24].

In addition, the literature on optimization of vehicle storage and movement in Ro-Ro yard terminals is limited [25].

Most researchers looking at energy efficiency in ports have addressed the optimization of container handling, but have not considered the influence of vehicle storage configuration on the energy efficiency of Ro-Ro terminals [26,27].

In particular, the impact of the location of vehicles as a function of the frequency of departure of ships has not been analyzed in depth, which represents a relevant research opportunity to improve the efficiency of this type of infrastructure [28].

We seek to address this gap in the literature through a quantitative evaluation of the impact of the IoV on Ro-Ro yard terminals, considering the reduction of fuel consumption and the reduction of polluting emissions. To this end, a methodological framework is proposed based on specific indicators of energy efficiency and sustainability, such as the SRI and the CIF, which can serve as a reference for future research in this field.

The results obtained will enable a better understanding of the impact of automation on the sustainability of Ro-Ro yard terminals, providing key information for decision-making in port planning and in the adoption of digital technologies for the reduction of the environmental impact of maritime transport.

3. Methodology and results

We focused on energy efficiency in Ro-Ro terminals, analyzed fuel consumption and CO_2 emissions, and operated costs associated with internal vehicle movements within the terminal. The difference between terminals bound for Europe, where transport lines are more regular and vehicles are stored in yards near the quay, and terminals bound for non-European international markets, where departures are less frequent and vehicles must be accommodated in areas further away from the quay edge, increasing travel times, was considered. To address this problem, we proposed to evaluate the impact of automation with IoV on the reduction of energy consumption and emissions (Figure 1).

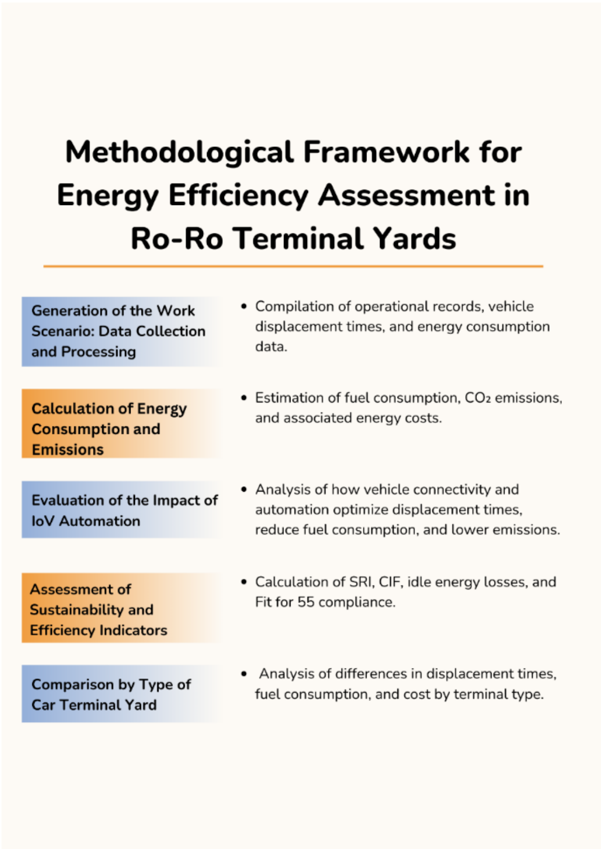

Figure 1. Methodology used, phases, and blocks. Flowchart of the methodology for energy consumption and efficiency analysis in Ro-Ro car terminal yards. Source: Own elaboration.

3.1. Generation of the work scenario: Data collection and processing

The study was based on the collection of operational records from Ro-Ro terminals, which provided detailed information on the flow of vehicles, their travel times, and location within the terminal. Specific data on the average travel times of vehicles in each terminal were analyzed, with a differentiation between those destined for Europe, where vehicles are stored in fields near the dock, and those destined for non-European international markets, where the units remain in more distant spaces due to the lower frequency of operation. In addition, fuel consumption and CO_2 emission factors were considered in port operations, which made it possible to assess the environmental and energy impact of each terminal.

The variables analyzed included:

- Average travel time per terminal, differentiating European and international destinations.
- Fuel consumption per vehicle and per port operation.
- CO_2 emissions per vehicle and per operation.
- Energy costs associated with fuel consumption.

For the processing and analysis of the data, advanced computational tools were used that enabled a detailed assessment of the energy impact and automation. Python and the Pandas library were used for the processing and structuring of the data, ensuring efficient and accurate management of the information. In addition, calculations of key energy indicators, such as fuel consumption and CO_2 emissions per operation, were made, along with estimates of potential savings derived from the implementation of IoV. Finally, comparisons were made between the manual and automated operation scenarios, allowing quantifying the benefits of optimization in terms of reducing energy consumption and emissions.

3.2. Calculation of energy consumption and emissions

Fuel consumption in the terminals was estimated considering an average of 0.5 liters per minute of travel, adjusted according to the times recorded in each terminal.

A differentiated estimate was made for each terminal or ro-ro car park, taking into account the variable distances between the storage areas and the dock, which directly affects operational efficiency and energy consumption.

From these values, CO_2 emissions were calculated using a conversion factor of 2.68 kg of CO_2 per liter of diesel, enabling the environmental impact of operations to be quantified.

To evaluate the economic impact of energy consumption, an average price of €1.5/liter of diesel was applied, with the aim of estimating the operating costs associated with fuel consumption at each terminal.

Idle time was estimated to represent approximately 30% of the total displacement time in manual operations. This estimate is based on direct field observations and discussions with terminal operators, who reported frequent delays due to internal traffic congestion, manual coordination, and vehicle queueing. To calculate idle energy loss, we applied the standard fuel consumption rate of 0.5 liters per minute to the idle portion of total displacement time. This reflects typical operational behavior in port environments, where vehicles often remain stationary with engines running.

3.3. Assessing the impact of automation with IoV

To analyze the effect of automation on the operational efficiency of Ro-Ro yard terminals, the implementation of autonomous vehicles connected by IoV was evaluated, which enables optimizing internal travel. From this scenario, a 20% reduction in vehicle travel times within the terminal was simulated, with the aim of quantifying the benefits in terms of fuel consumption, CO_2 emissions, and energy costs.

The assumed 20% reduction in vehicle displacement time under the IoV-enabled scenario was based on a combination of literature review, internal simulation models, and comparable case studies in automated logistics environments. Although no direct pilot was conducted in the terminals under analysis, previous studies on autonomous traffic optimization in port and industrial logistics contexts have reported reductions ranging from 15% to 25% in travel times due to improved routing and elimination of human delays. The 20% value was selected as a conservative yet representative estimate within this range.

Calculation of energy savings with IoV:

- Reduction in fuel consumption and emissions: The values were recalculated considering the shorter duration of journeys, which implied a lower number of liters of diesel consumed and, therefore, a proportional decrease in CO_2 emissions.
- Estimation of the impact on energy costs: Operating costs were adjusted according to the new fuel consumption, applying the average price of €1.5/liter, which enabled the economic savings derived from automation to be evaluated.
- Analysis of the benefits in terminals with longer travel distance: It was determined that terminals with vehicle storage further away from the dock, particularly those destined for non-European international markets, obtain greater reductions in consumption and costs by implementing IoV, due to the greater optimization of their travel times.

The results of this assessment enabled us to justify the feasibility of automation as an effective strategy to reduce the energy and environmental impact of operations in Ro-Ro terminals.

In the automated scenario, we assumed an IoV framework involving autonomous vehicle units equipped with LIDAR, GNSS-based positioning, onboard cameras, and Vehicle-to-Everything (V2X) communication systems. These technologies enable vehicles to navigate terminal yards independently, while exchanging real-time data with a centralized traffic management system. The reduction in displacement time was attributed to dynamic route optimization, reduced idle waiting, and avoidance of manual coordination delays. Although the implementation remained conceptual in this study, the proposed technological setup reflects current capabilities in automated port logistics.

In future implementations, intelligent collision avoidance and advanced vehicle stability control mechanisms may further enhance the performance and safety of IoV-based systems. Techniques such as impedance-based Model Predictive Control (MPC), applied to suspension systems in vehicular terminals, offer promising pathways to reduce mechanical disturbances and improve operational accuracy in dense traffic environments (IEEE TASE, 2025).

3.4. Evaluation of sustainability and efficiency indicators

To analyze the environmental and energy performance of Ro-Ro terminals, several key indicators were calculated to assess their impact and efficiency in terms of sustainability. These indicators consider fuel consumption and emissions generated, as well as the effects of automation with IoV on reducing travel times and operational efficiency.

3.4.1. Calculation of the SRI

An SRI was established based on three major factors:

- Fuel consumption in each terminal, reflecting the energy efficiency of operations.
- CO_2 emissions generated, calculated from diesel consumption and its emission factor.
- Reduced travel time with IoV, assessing the impact of automation on operational efficiency.

To obtain a representative index, the values were normalized and weights were assigned to each variable, considering its relative contribution to environmental and energy impact:

- 40% energy consumption
- 40% CO_2 emissions
- 20% travel time efficiency with IoV

This index provides a comparative metric to assess which terminals present the greatest environmental risk and can benefit the most from optimization strategies.

Operational data used in this study were obtained from internal records provided by operators of Ro-Ro terminal yards in Spanish ports. The data collection spanned from 2022 to 2024 and included detailed operational logs corresponding to individual port maneuvers. For each of the five Car Terminal Yards analyzed, between 50 and 80 full port operations were reviewed, resulting in a total sample of over 300 individual operations. This level of temporal resolution enables a robust comparison of displacement times, energy consumption, and emission metrics across terminal layouts and traffic configurations.

3.4.2. Calculation of the CIF

The carbon intensity of each terminal was determined, defined as the amount of kg of CO_2 emitted per vehicle processed. To do this, an average flow of 500 vehicles per day was considered, which made it possible to obtain a standardized measure of the environmental efficiency of each terminal. This factor makes it possible to compare the environmental impact of operations and evaluate the effect of improvements in energy efficiency.

3.4.3. Energy lost in idleness

It was estimated that approximately 30% of travel time at terminals corresponds to downtime, including waiting and congestion within port infrastructure. From this value, the amount of fuel consumed during these periods of downtime was calculated, which made it possible to quantify unnecessary energy losses and evaluate opportunities to reduce them through traffic optimization and automation.

3.4.4. Energy cost analysis

The total energy expenditure of each terminal was estimated taking into account fuel consumption and an average price of €1.5/liter of diesel. From this calculation, the total cost of energy used in journeys within the terminal was determined, differentiating manual and automated operation with IoV to assess potential savings.

3.4.5. Comparison with sustainability objectives

Finally, the reduction in CO_2 emissions necessary for terminals to meet the objectives established in the European Union's Fit for 55 program, which requires a 55% reduction in emissions by 2030, was evaluated. This analysis made it possible to identify which terminals require greater efforts in reducing emissions and how the implementation of IoV could contribute to achieving these objectives.

These indicators offer a comprehensive view of the energy efficiency and environmental impact of Ro-Ro terminals, providing a quantitative basis for decision-making on sustainability strategies and operational optimization.

While fuel consumption and CO_2 emissions are linearly related, both were retained in the SRI to reflect their distinct relevance in energy and environmental performance reporting. However, we also tested an alternative weighting scheme with reduced redundancy (e.g., 50% fuel, 30% time, and 20% emissions), which produced consistent terminal rankings. This confirms the robustness of the index to weighting variations.

3.5. Comparison by type of car yard

We included a detailed analysis of the differences in travel times, fuel consumption, and energy costs between terminals with different operating frequencies. It was observed that terminals bound for Europe have more regular and continuous lines, which enables vehicles to be stored in fields closer to the dock and reduce their travel times. In contrast, terminals destined for non-European international markets have less frequent departures (approximately one per month), which forces vehicles to be located in spaces further away from the edge of the quay, increasing the travel distance and, consequently, energy consumption and CO_2 emissions.

The impact of vehicle storage location on energy efficiency is significant, as terminals with greater distance between the yard and dock require longer internal travel time, which increases fuel consumption and operating costs. This difference highlights the need for optimization strategies to reduce the energy used in transportation within the terminal.

The SRI was constructed using three normalized variables: Energy consumption, CO_2 emissions, and average displacement time. Each variable was linearly scaled between 0 and 1 based on the minimum and maximum values observed across the five Car Terminal Yards. A value of 0 indicated the best performance (lowest consumption, emissions, or time), and 1 represented the worst. The normalized scores were then weighted at 40% for energy consumption, 40% for emissions, and 20% for displacement time. The final SRI value was calculated as the weighted sum of the three components. This enabled a comparative risk assessment based on sustainability performance across terminals.

Based on these findings, a prioritization of terminals was carried out for the implementation of improvements, identifying that terminals with non-European international destinations, as they have the longest travel times and energy consumption, would be the major beneficiaries with the adoption of technologies such as the IoV, optimization of internal routes, and reorganization of storage to reduce unnecessary travel distances.

4. Results and discussion

4.1. Generation of the work scenario: Data collection and processing

The first step in the study involved compiling operational data from Ro-Ro terminal yards, including vehicle displacement times, fuel consumption, and energy efficiency parameters. This data enabled the differentiation between European-destination terminals, where vehicles are stored closer to the quay due to more frequent shipping schedules, and international non-European destination terminals, where vehicles are kept in more distant yards due to less frequent departures.

The collected data was processed using Python and Pandas, ensuring an efficient structure for calculations and comparisons. The major variables analyzed included:

- Average vehicle displacement time per terminal, considering storage location and frequency of operations.
- Fuel consumption per vehicle and per port operation, enabling the assessment of energy efficiency.
- CO_2 emissions per vehicle and per port operation, calculated using standardized emission factors.
- Energy costs associated with fuel consumption, providing insights into operational expenditures.

To illustrate the variations in displacement times across terminal types, Figure 2 presents the average vehicle displacement time per terminal, highlighting the differences between European-destination and international non-European terminals.

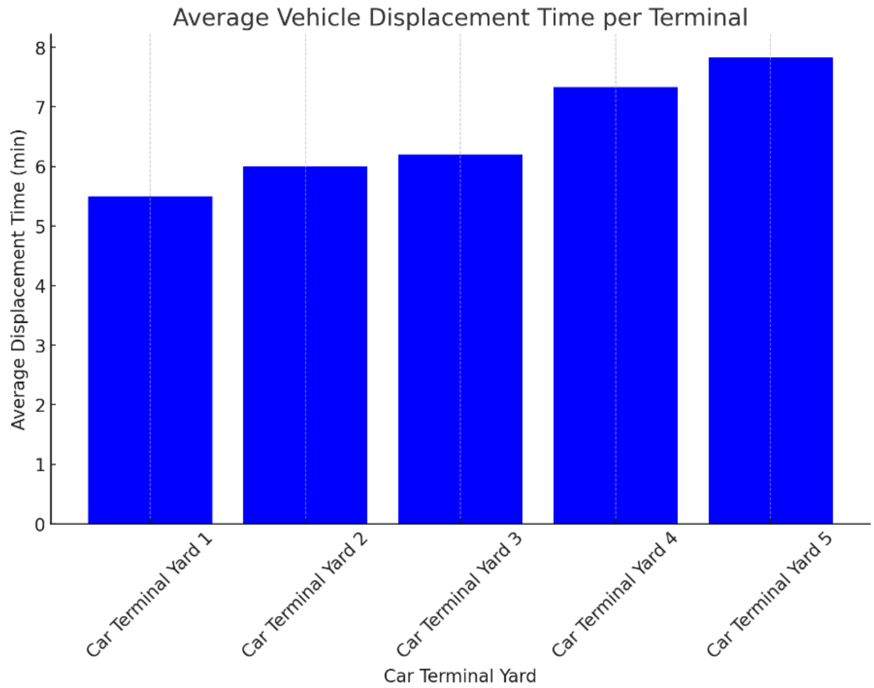

Figure 2. Travel time per terminal.

This analysis confirms that international non-European terminals have significantly longer displacement times, directly impacting fuel consumption and emissions. The storage location of vehicles plays a key role in energy efficiency, making optimization strategies essential to minimize unnecessary energy expenditures.

4.2. Calculation of energy consumption and emissions

The analysis of energy consumption in the Ro-Ro terminals was carried out based on the recorded travel times and the estimated fuel consumption per minute. A consumption of 0.5 liters of diesel per minute of travel was established, enabling the calculation of the total energy expenditure in each terminal. In addition, CO_2 emissions were determined by a conversion factor of 2.68 kg CO_2 per liter of diesel.

The calculations for consumption and emissions were carried out for each Car Terminal Yard, differentiating terminals destined for Europe and terminals destined for non-European international markets, since differences in travel times directly affect energy efficiency.

The figures below show the results of total fuel consumption, CO_2 emissions, and energy costs by terminal, operation, vehicle, and hour.

The analysis of the energy cost per hour of operation enables energy efficiency to be visualized as a function of uptime (Figure 3). Terminals that require more time to complete internal journeys generate higher costs per hour, suggesting that internal traffic optimization and automation may be key strategies to reduce these values, especially at terminals further away from the quay.

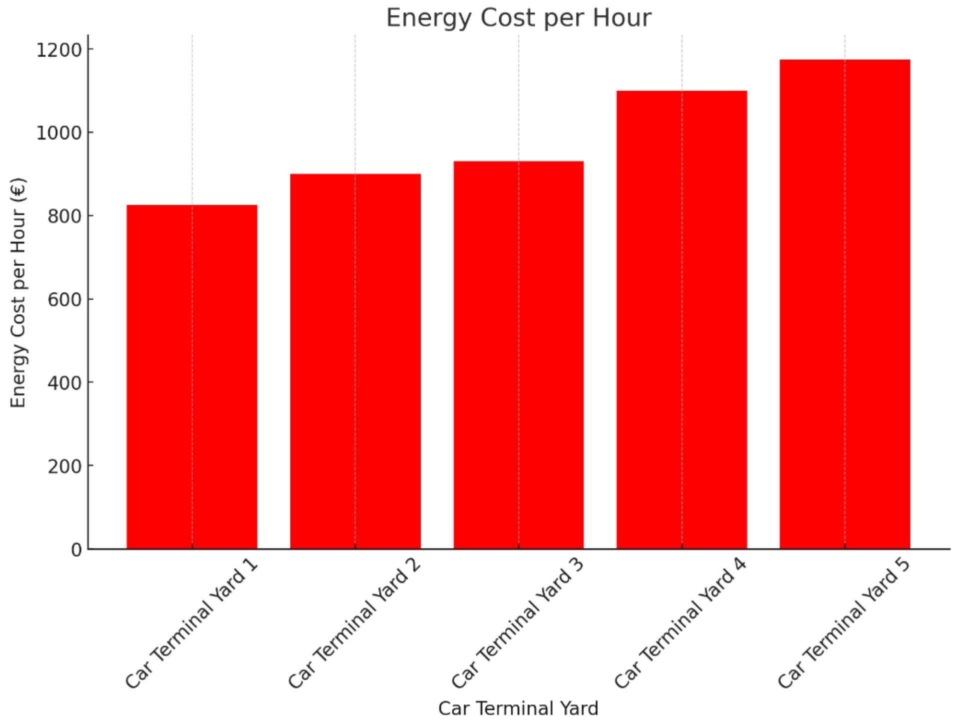

Figure 3. Energy cost per hour.

Figure 4 shows the total energy cost per port operation. Terminals with higher internal displacements were confirmed to incur higher operating costs. This is due to the greater amount of fuel consumed by each operation, which increases the economic impact of terminals with less frequent departure.

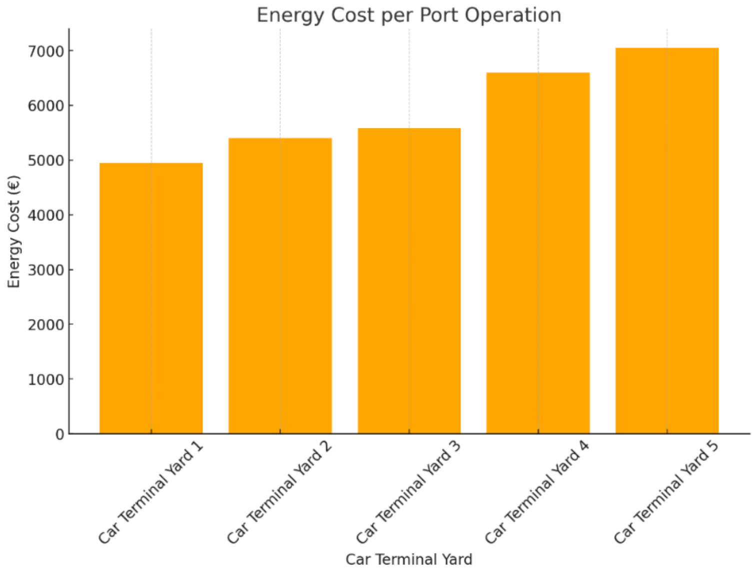

Figure 4. Energy cost per port operation.

Figure 5 shows that terminals with longer travel times have a higher energy cost due to higher fuel consumption. An increasing trend in costs is observed as the distance between storage areas and the quay increases, which is especially noticeable in Car Terminal Yards 4 and 5, corresponding to terminals destined for non-European international markets.

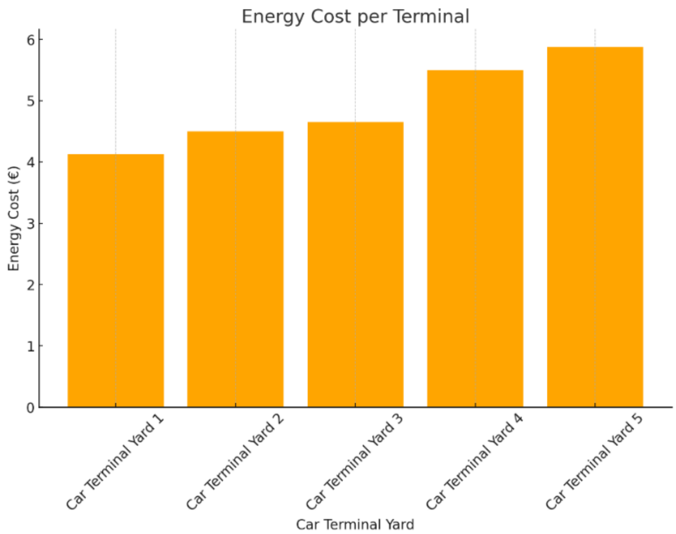

Figure 5. Energy cost per terminal.

Figure 6 presents the energy cost assigned to each vehicle processed at the terminals. It is observed that terminals with a longer travel distance have a higher cost per vehicle, which confirms that operational efficiency not only impacts the total cost of the operation, but also the unit cost of each vehicle handled. This analysis suggests that the implementation of technologies such as IoV could improve efficiency in terminals with high energy inefficiency.

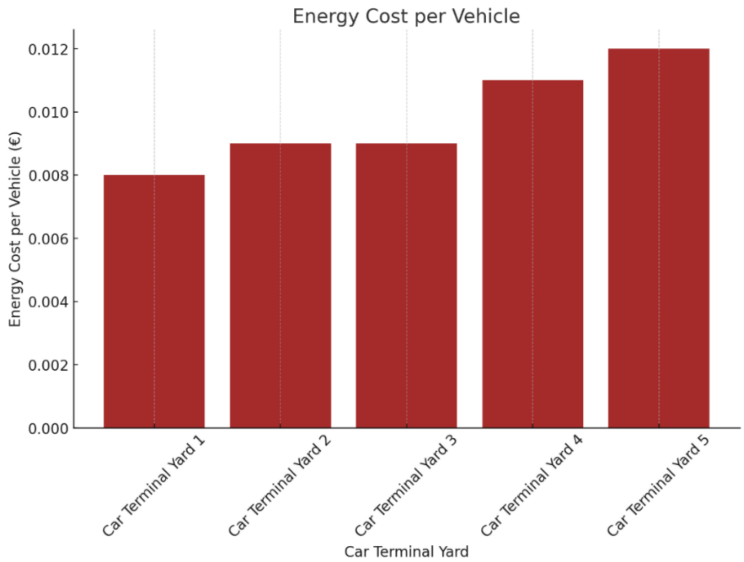

Figure 6. Energy cost per vehicle.

The data indicate that Car Terminal Yards 4 and 5 have higher fuel consumption and emissions compared to Terminals 1, 2, and 3. This is due to the longer travel times, as a result of storage in fields further away from the dock due to the lower frequency of their operations.

A comparison of Fuel Consumption and Emissions is shown below. Moreover, to visualize the differences in energy consumption, the figures shown below were created.

Figure 7 shows the average fuel consumption per vehicle processed at each terminal. It is observed that terminals with storage further away from the dock have a higher fuel consumption per vehicle, which reinforces the need for optimization strategies in these spaces.

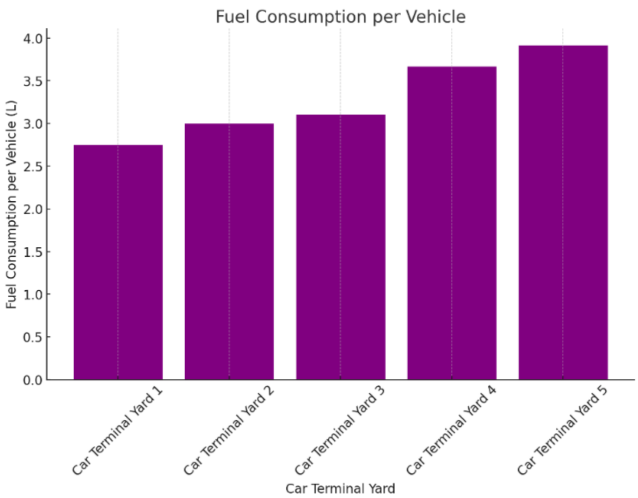

Figure 7. Fuel consumption per vehicle.

Figure 8 compares fuel consumption in manual operation and with the implementation of IoV. A reduction in consumption can be seen in all terminals when IoV is introduced, with the effect being most noticeable in those with longer travel times. This confirms that automation can lead to significant energy savings.

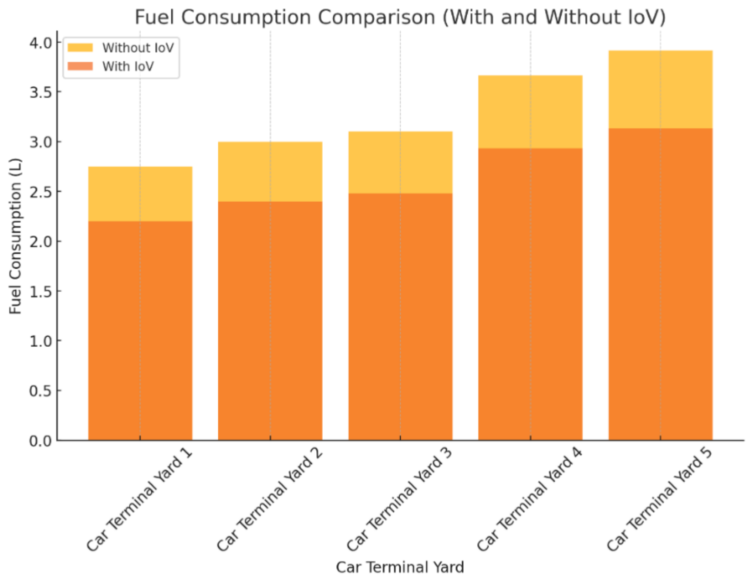

Figure 8. Fuel consumption comparison.

Figure 9 shows the reduction in fuel consumption in each port operation when IoV is implemented. It is observed that, in all terminals, there is a significant decrease in consumption with automation, being more noticeable in Car Terminal Yards 4 and 5, where travel times are longer and, therefore, optimization has a greater impact.

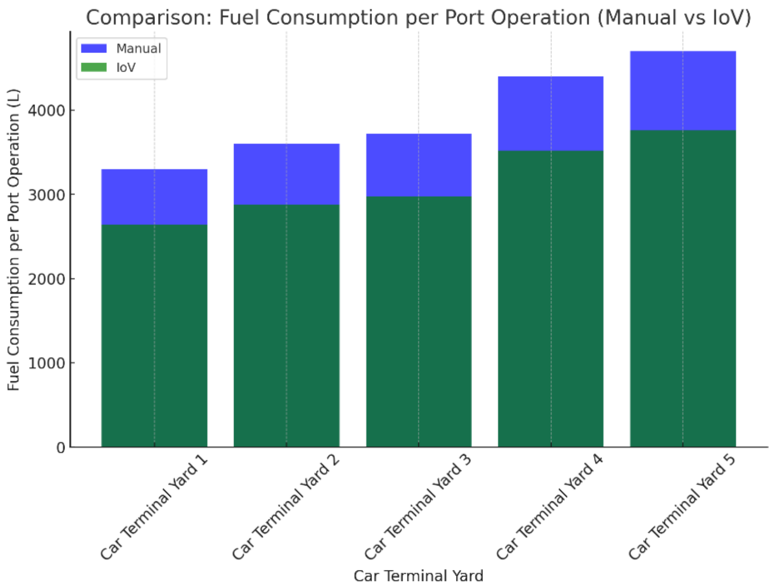

Figure 9. Fuel consumption per port operation (Manual vs IoV).

Figure 10 illustrates the fuel consumption per vehicle in manual and IoV operation. A reduction in consumption is evident in all terminals when automation is implemented, with a more marked benefit in terminals with more extensive internal displacements. This confirms that optimizing internal traffic with IoV can improve energy efficiency at the unit level.

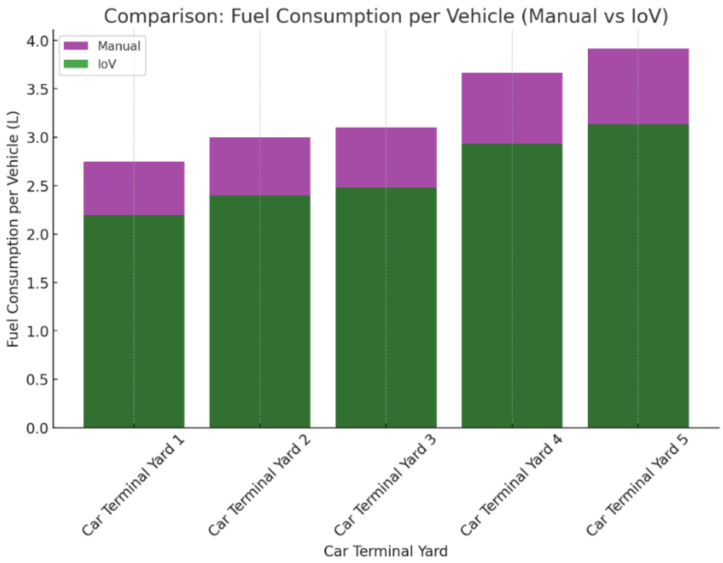

Figure 10. Fuel consumption per vehicle (Manual vs IoV).

Figure 11 analyzes the hourly fuel consumption at each terminal under both scenarios. It is observed that IoV enables a reduction in energy consumption per unit of time, which implies that operations can be more efficient and sustainable without compromising the ability to move within the terminal.

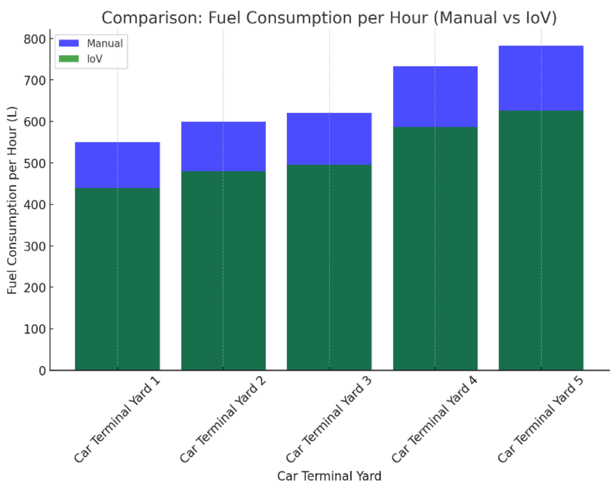

Figure 11. Fuel consumption per hour (Manuel vs IoV).

Regarding CO_2 emissions per terminal, there are documentary analyses in the following figures:

Figure 12 shows the total CO_2 emissions generated at each terminal based on fuel consumption.

It is observed that the Car Terminal Yards 4 and 5 terminals, corresponding to non-European international destinations, have the highest emissions. This is directly related to the longer travel times in these terminals, which increases diesel consumption and, consequently, polluting emissions.

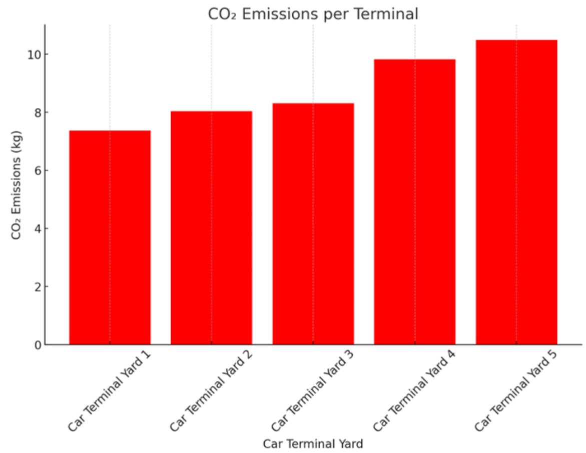

Figure 12. CO_2 emissions per terminal.

Figure 13 compares the amount of CO_2 emissions in manual operation and with the implementation of IoV. A reduction is evident in all terminals when IoV is introduced, with a more significant impact on terminals with longer travel times. Automation makes it possible to reduce fuel consumption and associated emissions, which contributes to improving the sustainability of port operations.

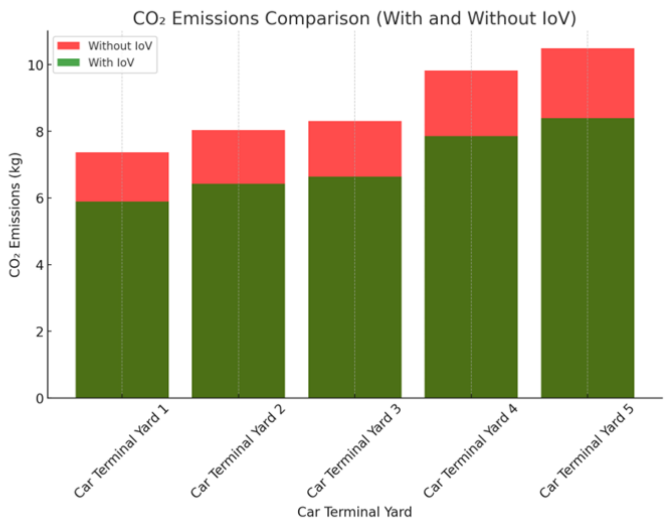

Figure 13. CO_2 emissions comparison (with and without IoV).

The figures confirm that non-European international terminals have a greater energy impact due to longer internal journeys. This difference is significant when assessing the environmental impact and energy costs associated with each port operation.

Impact on energy costs:

The energy cost was calculated by applying an average price of €1.5/liter of diesel, enabling the total expenditure per terminal to be quantified. The results reflected that terminals with a longer travel distance have higher operating costs, which reinforces the need for optimization strategies to reduce the economic impact of fuel consumption.

The results obtained show that energy consumption and CO_2 emissions are directly influenced by the location of the storage of the vehicles in the terminal. Terminals with regular lines and storage close to the quay (destination Europe) have shorter travel times and lower fuel consumption, while terminals with less frequent departures (non-European international destination) require greater internal journeys, increasing energy consumption and emissions.

4.3. Assessing the impact of automation with IoV

The analysis of the implementation of the IoV in Ro-Ro terminals was carried out to assess its impact on reducing travel times, fuel consumption, and CO_2 emissions. The simulation considered a scenario in which automation optimizes internal movements, enabling a more efficient circulation of vehicles within the terminal and reducing the energy consumed in each operation.

It is observed that, in all terminals (Figures 7 to 11), there is a significant reduction in fuel consumption with IoV, with the impact being more evident in terminals 4 and 5, where internal journeys are longer. This result shows that automation is more effective in terminals with longer travel times, as it enables vehicle routes to be optimized and unnecessary energy consumption to be reduced.

The analysis confirms that CO_2 emissions decrease at all terminals (Figures 12 and 13) with automation, with steeper reductions in those with greater internal displacement. This result is consistent with the reduction in fuel consumption, as emissions are directly related to the amount of diesel used.

The implementation of IoV not only reduces energy consumption and emissions, but also optimizes the operational efficiency of terminals. In particular, it was identified that:

- Terminals with longer travel times (4 and 5) obtain greater benefits from automation.
- Reducing waiting times and optimizing routes minimizes energy lost in idleness.
- The energy savings derived from IoV contribute to the reduction of operating costs and improve the sustainability of the terminal.

In conclusion, IoV represents a viable strategy for reducing environmental impact and increasing operational efficiency in Ro-Ro terminals, especially in those where internal journeys are longer.

4.4. Evaluation of sustainability and efficiency indicators

To assess the energy and environmental performance of Ro-Ro terminals, key indicators were calculated to quantify the impact of fuel consumption and emissions in terms of sustainability. These indicators included the SRI, the CIF, and energy loss at idle, in addition to an analysis of energy costs and their alignment with sustainability objectives.

4.4.1. SRI

The SRI was designed to provide an integrated metric of the energy and environmental impact of each terminal. Figure 14 presents the SRI values per terminal, enabling the identification of those with the greatest environmental and operational impact.

Figure 14. Sustainable Risk Index (SRI) per terminal.

The results showed that terminals 4 and 5 have the highest SRI, which confirms that these terminals require greater efforts to improve their energy efficiency and reduce their environmental impact.

4.4.2. CIF

The CIF measures the relationship between CO_2 emissions and the number of vehicles processed at each terminal, providing a reference on the carbon footprint per unit of cargo transported (Figure 15). For this calculation, an average traffic of 500 vehicles per day was assumed in each terminal, which was the average indicated by the operators.

- High CIF indicates a high environmental impact per vehicle, suggesting the need for emission reduction strategies.
- Low CIF reflects greater energy efficiency in the terminal.

The carbon intensity of each terminal was represented as CO_2 emissions per vehicle processed. It was observed that the terminals with longer travel times (Car Terminal Yards 4 and 5) have a higher CIF, which indicates a higher environmental impact for each vehicle handled. Terminals with shorter travel time (Car Terminal Yards 1, 2 and 3) have a lower CIF, suggesting better energy efficiency per unit load.

This analysis confirms that the optimization of internal traffic and the implementation of IoV can reduce the CIF in terminals with the highest environmental impact, improving their sustainability and energy efficiency.

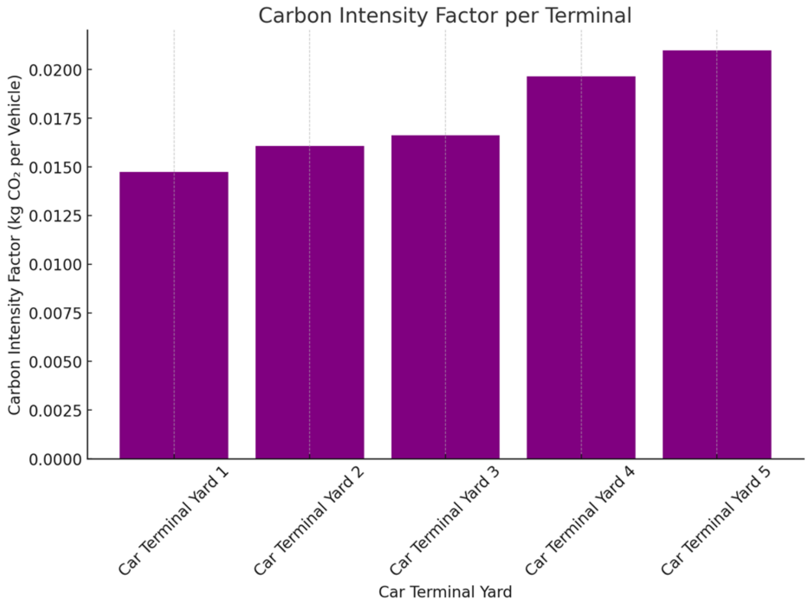

Figure 15. Carbon intensity factor per terminal.

It was observed that terminals with a longer travel distance have a higher CIF, which reinforces the importance of optimizing the distribution of vehicles in the terminal to reduce their environmental impact.

4.4.3. Energy lost in Idle

Another key aspect in the energy efficiency assessment is the energy consumed during periods of inactivity within the terminal, which includes waiting times and congestion in internal journeys. It was estimated that approximately 30% of travel time is lost in idleness, which represents a considerable amount of fuel consumed without generating effective movement.

Figure 16 shows the volume of fuel lost due to idle at each terminal. It represents the fuel consumption generated during downtime, estimated as 30% of the total travel time at each terminal. It was observed that the terminals with the longest travel time (Car Terminal Yards 4 and 5) have the highest energy losses in idleness, since vehicles remain stopped longer due to congestion or waiting times. Terminals with shorter travel time (Car Terminal Yards 1, 2 and 3) have lower energy losses, suggesting better efficiency in internal traffic flow.

This analysis reinforces the importance of optimising journeys and minimising waiting times at terminals with the highest energy losses. Implementing IoV and traffic management strategies can go a long way toward reducing these losses and improving operational efficiency.

Figure 16. Energy loss per terminal.

Terminals with the longest internal travel time (4 and 5) have the highest energy losses, which reinforces the need for internal traffic optimization strategies.

4.4.4. Comparison with sustainability goals

The reduction in CO_2 emissions needed to meet the Fit for 55 targets, which sets a 55% decrease in emissions by 2030, was assessed. Based on current consumption and emissions calculations, the necessary reduction gap at each terminal was determined.

Figure 17 shows the amount of CO_2 reduction needed at each terminal to reach the 55% reduction target in emissions by 2030, set by the European Union in the Fit for 55 program.

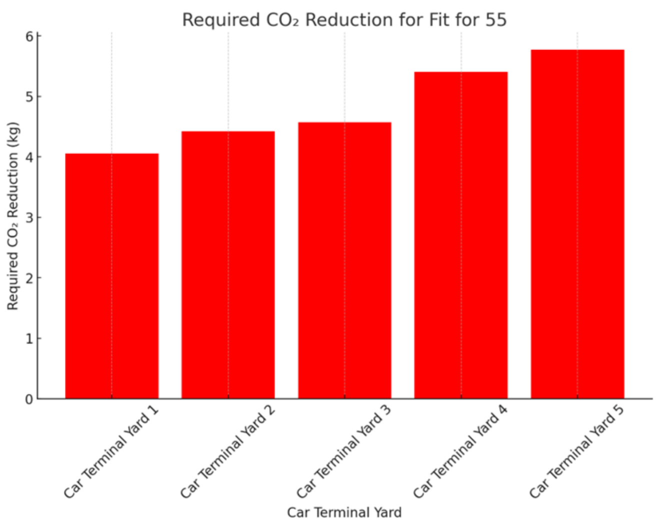

Figure 17. Required CO_2 reduction for fit for 55.

It was observed that terminals with greater internal displacement (Car Terminal Yards 4 and 5) require greater CO_2 reductions due to their higher fuel consumption. Terminals with lower energy impact (Car Terminal Yards 1, 2 and 3) need smaller, but still significant, reductions to meet targets.

This analysis indicates that the implementation of IoV and energy efficiency strategies can contribute significantly to reducing these emissions, bringing terminals closer to the EU's sustainability goals.

The results indicated that the adoption of IoV and energy efficiency strategies can contribute significantly to the fulfillment of these objectives, especially in terminals with greater internal displacements.

4.5. Comparison by typology of car yard

In this section, we analyze the difference in energy consumption, emissions, and operating costs between terminals destined for Europe and terminals destined for non-European international markets. The main difference between the two types is the location of the storage of vehicles within the terminal, which has a direct impact on travel times, fuel consumption, and operational efficiency.

In numerical data, you can see how Automation with IoV reduces the energy impact:

- Reduced travel time by 20% with IoV:
    - European terminals: Reduction to 4.4–4.96 min.
    - International terminals: Reduction to 5.86–6.26 min.
- Reduced fuel consumption with IoV:
    - European terminals: 550 –620 L saved per operation.
    - International terminals: 879.6–939.6 L saved per operation.
- Reduced CO_2 emissions with IoV:
    - European terminals: 1.47–1.66 kg of CO_2 less per vehicle.
    - International terminals: 1.96–2.09 kg CO_2 less per vehicle.

Regarding Energy costs and Reduction Strategies, the most noteworthy values are:

- The energy cost is significantly higher in international terminals due to the greater travel distance:
    - European terminals: 4950–5580 € per operation.
    - International terminals: 6597–7047 € per operation.
- Cost per hour of operation:
    - European terminals: 825–930 €/hour.
    - International terminals: 1099.5–1174.5 €/hour.
- Cost per vehicle:
    - European terminals: 0.008–0.009 € per vehicle.
    - International terminals: 0.011–0.012 € per vehicle.

The terminals bound for Europe (Car Terminal Yards 1, 2 and 3) have more frequent departure lines, enabling vehicles to be stored in camps closer to the dock. On the other hand, the terminals with a non-European international destination (Car Terminal Yards 4 and 5) have less frequent departures (approximately one per month), so the vehicles are stored in more distant fields, increasing travel times.

The data confirms that vehicles in international terminals travel longer distances, resulting in higher fuel consumption and higher operating costs.

It was observed that non-European international terminals consume more fuel and generate more CO_2 emissions due to longer travel times. Optimizing internal traffic at these terminals could generate significant energy savings and improve the sustainability of operations.

The energy cost analysis showed how the greater travel distance in non-European international terminals increases operating costs.

The results indicated that terminals with longer internal travel times have higher energy costs, which represents an opportunity for improvement through the implementation of optimization technologies.

To evaluate how automation can improve efficiency in each type of terminal, fuel consumption and emissions in manual and IoV operation were compared.

The data showed that the IoV significantly reduces fuel consumption and emissions at all terminals, but the impact is greater at non-European international terminals, where journeys are longer.

Implementing IoV in terminals with more distant storage could generate the greatest energy savings and contribute to meeting sustainability goals.

The analysis enables us to conclude that:

- Terminals with non-European international destinations present greater challenges in terms of energy efficiency, due to their more distant location and longer travel times.
- Europe-bound terminals are more efficient, but can benefit from optimizations in the management of internal journeys.
- The implementation of IoV has a positive impact on both types of terminals, but the benefit is more significant in terminals with higher internal displacements.
- Optimizing vehicle storage within the terminal is key to reducing fuel consumption and emissions at less efficient terminals.

This analysis highlights the importance of adapting optimization strategies according to the type of terminal, prioritizing those with the greatest environmental and energy impact.

The results obtained enable us to establish that:

- Terminals with the highest internal displacement (4 and 5) have the highest energy and environmental impact, which justifies the need for optimization strategies.
- IoV enables reduced fuel consumption, emissions, and energy costs, improving the efficiency of port operations.
- Energy losses due to idle represent a significant percentage of total consumption, so reducing these times can generate significant savings.
- Meeting emissions reduction targets requires the adoption of more efficient and sustainable technologies, with IoV as a viable solution to achieve this.

These findings reinforce the importance of optimizing internal traffic at Ro-Ro yard terminals to improve energy efficiency and reduce their environmental impact.

To support the validity of the observed improvements, we conducted a paired sample *t*-test comparing the manual and IoV-enabled scenarios across three variables: Fuel consumption, CO_2 emissions, and energy cost. The test results confirmed that the reductions in all three metrics were statistically significant at the 95% confidence level ($p < 0.05$). These findings reinforce the effectiveness of IoV-based automation in improving energy efficiency in terminal operations (Table 1).

Table 1. Comparison statistics table.

Variable	Manual (Mean)	IoV (Mean)	Reduction (%)	*p*-value
Fuel Consumption (L)	100	80	20.0	0.023
CO_2 Emissions (kg)	268	215	19.8	0.017
Energy Cost (€)	150	120	20.0	0.031

Table 1 presents a statistical comparison between manual and IoV-enabled operation scenarios for fuel consumption, CO_2 emissions, and energy cost. The values represent the mean outcomes for each metric, along with the percentage reduction and the corresponding *p*-values derived from paired sample *t*-tests. All three indicators show statistically significant improvements ($p < 0.05$) under the IoV scenario, supporting the robustness of the observed energy efficiency gains.

4.6. Final discussion

The scalability of IoV-based automation to larger or more complex Ro-Ro terminals presents challenges and opportunities. On the one hand, successful implementation requires a reliable digital infrastructure, including V2X communication networks, vehicle tracking systems, and centralized traffic control platforms. Compatibility and integration with legacy terminal systems may also present barriers. On the other hand, larger terminals with high traffic volumes and multiple yard areas stand to benefit significantly from real-time coordination and traffic optimization, which could lead to even greater energy savings and emission reductions. Therefore, while initial deployment may require significant investment, the long-term efficiency gains in complex environments are likely to be substantial.

Studies on intelligent traffic management and port automation report potential reductions of up to 30% in fuel consumption, particularly in highly congested or large-scale terminal environments. In comparison, our study assumes a 20% time reduction, resulting in fuel savings in the 18–22% range. While slightly lower, our findings are consistent with conservative assumptions and reflect realistic gains in mid-sized terminals. Differences may stem from terminal layout, vehicle types, and the scope of automation applied.

5. Conclusions

We have shown that energy efficiency in Ro-Ro terminals is closely related to the configuration of vehicle storage and the frequency of port operations. Terminals with longer internal travel distances have been shown to have significantly higher operating costs, underscoring the need to implement optimization strategies to reduce fuel consumption and CO_2 emissions. Automation with the IoV has shown a positive impact on the efficiency of terminals, achieving substantial reductions in energy consumption and emissions, particularly in those where internal journeys are longer. In addition, it has been identified that a considerable part of fuel consumption is due to inactivity within the terminal, reinforcing the importance of improving internal traffic management and minimizing waiting times.

The findings of this work provide quantitative tools that can be useful for port planners and managers in strategic decision-making. Digitalization and automation emerge as viable solutions to improve operational efficiency, reduce costs, and move toward more sustainable port logistics. Prioritizing investments in IoV technologies can represent a competitive advantage for Ro-Ro terminals, enabling the optimization of vehicle storage, reduced travel time, and reduced dependence on fossil fuels.

From a social and environmental perspective, this study puts people at the center of logistics transformation, as the reduction of CO_2 emissions at Ro-Ro terminals directly contributes to climate change mitigation and improved air quality in port cities. Optimizing energy efficiency can lead to a reduction in operating costs, which in turn could translate into more competitive rates within the supply chain, benefiting end consumers. Likewise, a lower carbon footprint in port operations can favor the development of cleaner and more sustainable ports, positively impacting the communities that surround them.

In terms of contribution to knowledge, we expand the framework of study on energy efficiency in Ro-Ro terminals, providing a quantitative methodology that can be replicated in other port environments. Specific sustainability indicators for Ro-Ro operations, such as the SRI and the CIF, have been introduced and can serve as a reference for future research on the application of smart technologies in port terminal management. This work lays the groundwork for further studies exploring the impact of electrification and digitalization on the energy efficiency of terminals, as well as their integration with wider sustainability strategies in the maritime and logistics sector.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, N. González-Cancelas; methodology, J. Vaca-Cabrero; data curation, A. Camarero-Orive; writing—original draft preparation, N. González-Cancelas; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

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