Review

Vehicle Platooning: A Detailed Literature Review on Environmental Impacts and Future Research Directions

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Abstract: This paper provides a detailed literature review of the environmental implications of vehicle platooning, a topic gaining significant attention in transportation. While previous reviews have focused on the safety, planning, fuel economy, and microsimulation aspects of platooning, this paper delves into environmental aspects. It identifies a lack of research adopting a holistic approach to transport and environmental benefits and emphasizes the need for further research to enhance vehicle efficiency and improve air quality and health conditions. This study traces the historical evolution of platooning, highlighting the shift in research focus over the decades. It advocates for more research on platooning’s environmental aspects, particularly pollutant emissions and air quality. The primary contributions of this work are threefold and include the following: firstly, it delineates simulation methodologies for platooning and the associated pollutant emissions; secondly, it offers a critical assessment of the existing literature on vehicle emissions, fuel consumption, and energy savings; and thirdly, it illuminates the prospective research challenges within the specialized domain of vehicle platooning.

Keywords: platooning; fuel; energy; emissions; traffic model; drag coefficient

1. Introduction

With its origins dating back to the World’s Fair in New York in 1939, platooning as an idea has been around for a long time [1]. It started firstly as a vision from General Motors of driverless vehicles that maintained distance to each other by way of automatic radio control, but today, it is not yet a reality after several successful tests. The concept of platooning has evolved throughout the decades and can currently be described as a group of vehicles traveling closely together with synchronized driving dynamics. In the context of heavy-duty vehicles, operating a platoon with a single driver leading the formation offers advantages in certain operational settings. This is achieved with connected and autonomous or semi-autonomous systems that control the vehicle to keep it close to the other vehicles [2]. The reasons to use such a system are increased road capacity, increased safety, and reductions in energy use and pollutant emissions [3].

The research topics on platooning are expected to have evolved throughout the years for such an old concept in the field of transportation. In the 1970s, the research in platooning was focused on algorithms for vehicle gaps and ramp entrances [4]. This work was based on using computational platforms to carry out all the necessary calculations to ensure a safe ramp entrance. Through the 1980s, the focus was on optimizing traffic flow, and safety appeared as a key aspect related to platooning [5–8]. During the 1990s, mathematical models were resurging to study traffic and platooning. Those innovations were supported by the introduction of sensors, computer vision, and actuators for vehicle control and automation [9–12]. The 2000s saw the introduction of intelligent vehicle highway systems...
as a focus topic, expanding from vehicle to multi-agent systems. Advances in computer simulation made it possible to study platooning algorithms [13], traffic control [14], and path creation [15]. Ad hoc networks appeared as a new way of communication [16], and the longitudinal control of vehicles [17] expanded to nonlinear control [18]. The 2010s saw a rise in cooperative adaptive cruise control (CACC) [19]. Autonomous vehicles [20] and communication between vehicles and the highways (infrastructure) [21] were again considered hot topics, in addition to the introduction of 5G mobile communication systems [22]. Conventional transport engineering topics such as road capacity [23] became important as the number of road users and transport requirements increased.

Fuel economy and aerodynamic drag became crucial factors for platooning because of the need for more efficient transport systems [3]. The start of the 2020s already showed the important topics for this including CACC systems, vehicle communications, and fuel economy [24]. Fuel economy is a topic that has been gaining traction for the last decades as an advantage of platooning. With lower fuel consumption also comes a reduction in air pollutant emissions. In particular, the mitigation of nitrogen oxides (NOx) and particulate matter (PM) emissions is critical to minimize the health crises caused by air pollution. At the same time, this increased efficiency could contribute to climate change mitigation (related to carbon dioxide (CO2) emissions). According to the European Environment Agency, pre-pandemic (2017) road transport exhaust emissions accounted for 28% of NOx emissions, 18% of carbon monoxide (CO), 3% of PM10, and 5% of PM2.5. The transport sector represents more than half of total NOx emissions, 21% of CO, 13% of PM10 and 20% of PM2.5, in addition to 12% of sulfur oxides (SOx) emissions and 10% of non-methane volatile organic compounds (NMVOC) [25].

Several review papers have been conducted regarding platooning. Previous articles have focused on different areas such as safety aspects [26], transport planning [27], fuel economy [28], and microsimulation of longitudinal dynamics [29]. However, to our best knowledge, none of the previous review papers focused on the environmental aspects of platoons. In contrast, this review paper adopts a unique focus by comprehensively examining the environmental impacts of platooning—specifically related to air pollutant emissions and air quality—an area underrepresented in the existing research. Therefore, the primary contributions of this work are as follows:

- To evaluate simulation methods for platooning and pollutant emission;
- To assess the available literature on vehicle pollutant emission and fuel and energy savings systematically and critically, including the methods by which these are calculated;
- To discuss the limitations of these previous works and identify the research challenges in this specific platooning thematic area.

To this end, a literature review and meta-analysis were performed. This paper is structured as follows. The Introduction Section (Section 1) identifies the most researched topics on platooning throughout the decades from 1970 to the current day and identifies relevant documents from each subject and decade. The Materials and Methods Section (Section 2) explains the literature review process, starting with an initial search of all the relevant platooning documents found within the Scopus database and a second search with those that explore the environmental aspects of platooning. The Results and Discussion section (Section 3) provides a broad characterization of the literature review, focused on the environmental factors of platooning. The limitations of the applied methodology and the research gaps that were identified by the analysis are discussed in Section 4. Finally, the Conclusion Section (Section 5) establishes the current state of platooning, alongside future research considerations.

2. Materials and Methods

A detailed literature review is a research methodology that can characterize the state of knowledge of a specific topic, enhance its collective understanding, and identify underexplored research areas [30]. Literature reviews cover previously published literature within chosen databases and use carefully selected keyword strings that answer a specific
research question [31]. A detailed literature review was applied in this work in two different steps. In the first phase, a literature search was carried out in the Scopus database using the keyword “platooning”. This keyword was intentionally vague to allow for wide coverage, so it was searched across all publication fields. While there are other academic search systems available for literature reviews, Scopus is often preferred because of its large collection of peer-reviewed literature, including scientific journals, books, and conference proceedings [32]. A recent study found that Scopus was one of the most suitable databases for conducting reviews. No language or year restrictions were imposed during this search. Therefore, all studies published since 1973 were considered. Our focus was on prioritizing research findings that were subjected to a rigorous screening process to ensure that this review was built upon a solid foundation of studies demonstrating established methodological soundness. While conference papers can offer valuable preliminary insights, our emphasis was on research findings published in traditional, peer-reviewed, academic journals that underwent a thorough and stringent review process. This first phase aimed to identify under-researched areas of platooning as well as to discuss the overall state of research on the topic of platooning. A total of 1900 documents were found with potential interest from the initial search. These documents were organized into four distinct categories—Energy Efficiency, Global Safety, Traffic Flow and Road Capacity, and Global Objectives—following the categorization proposed by Sturm et al. [33]. The Energy Efficiency category included works focused on energy and fuel efficiency or environmental benefits of a vehicle driving in a platoon or the overall benefits of all the vehicles that compose a platoon. The Global Safety category included the prevention of accidents within a platoon and between a platoon and other non-platooning vehicles. The aspects of secure communications and overall cybersecurity were also included in the Global Safety category. As the name suggests, the Traffic Flow and Road Capacity category included works related to algorithms, models, and other controlling devices that manage road capacity and traffic flow. Finally, the Global Objectives category incorporated works that could belong to more than one category, including documents with a holistic approach to platooning. The documents found in the literature search were then categorized by the matching listed in Table 1 for each area of work to the indexed and the authors’ keywords.

Table 1. Keywords and their link to the respective areas of work.

<table>
<thead>
<tr>
<th>Area of Work</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>energy, climate change, fuel, efficiency, efficient, sustainable</td>
</tr>
<tr>
<td>Global Safety</td>
<td>collision, safety, accident, obstacle detection, safe</td>
</tr>
<tr>
<td>Traffic Flow and Road Capacity</td>
<td>algorithm, traffic, motion control, auto, model, congestion, autonomous, guided vehicles, agents, networks, path, tracking, cooperative</td>
</tr>
<tr>
<td>Global Objectives</td>
<td>costs, performance, platooning design, control, ITS, decision-making, systems analysis, optimization, connected vehicles</td>
</tr>
</tbody>
</table>

The keyword method presented in Table 1 resulted in 215 uncategorized documents. This smaller group of papers was subsequently categorized by reviewing each document’s abstract. The result identified 6 documents that were not related to platooning with vehicles (which were excluded from the analysis), 56 conference papers (which were excluded from this study since they are considered “grey” literature), and 153 documents that were attributed to their specific category. Hence, 62 papers were removed from the original 1900 documents, for a total of 1838 documents used in the analysis. These documents fed the meta-analysis presented in Section 3.1. Figure 1 illustrates a flowchart of the methodology with the included and excluded studies.
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Figure 1. Literature review flowchart for the 1st phase.

For the second literature review phase, new searches were conducted within the documents that were selected in the first phase of this literature review. This approach aimed to identify the records that explored the environmental aspects of platooning, which is the focus of the present work. The keyword “emissions” was used to determine the documents containing this environmental aspect of platooning, resulting in a total of 123 papers. Since platooning has a greater impact on vehicles traveling at higher speeds, the keywords “highways” OR “freeways” OR “motorways” were used within the initial search of phase one, totaling 642 documents. The finer and more focused search of the second phase, which combined both components of the aforementioned searches, allowed for the identification of 44 documents (see Figure 2). An in-depth review of these documents was carried out, which included a detailed analysis of the following data: (i) identification of case study characteristics (such as platoon composition and inter-vehicle gap, among others); (ii) modeling setup applied, focused on traffic, energy, and emission models; and (iii) environmental implications, focused on drag coefficient, emissions (overall, CO, CO₂, hydrocarbons (HCs) and NOx), and fuel or energy consumption. These data are discussed in Section 3.2.

Figure 2. In-depth search keywords and the resulting number of documents for the 2nd phase of this literature review.
3. Results

3.1. Meta-Analysis

Three different approaches were adopted to evaluate how platooning research evolved throughout the years. These approaches included the following:

- Analysis of the geographical distribution of the published documents to assess where the platooning approach to the transport sector is most explored (Figure 3);
- Analysis of the number of published research documents on the topic of platooning over time (Figure 4) to assess the interest in the subject;
- Overview of the areas of work explored on platooning research (Figure 5), following the categories defined in Section 2, to identify the research areas with the highest number of documents throughout the years and if these trends are linked to policy milestones.

![Figure 3](image-url)

**Figure 3.** Geographical distribution of published papers. The blue color darkens with an increase in the number of published documents.

![Figure 4](image-url)

**Figure 4.** Overview of the number of published documents related to “platooning” over time.

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The assessed documents were mostly published by authors from the United States (432), followed by China (241) and Germany (228). This is most likely due to each region’s guidelines for autonomous vehicles, in which platooning is the first viable application of such technology [34]. From the analysis of Figure 3, it is clear that Europe as a continent published the highest number of documents related to platooning. More than half of the published research comes from European countries. One explanation for this is the high number of initiatives and European projects on the subject, such as ENSEMBLE, AEROFLEX, HEADSTART, and others [35].

Research on the topic of platooning started in 1973 with the work of Klee [4] on freeway ramp entrances based on vehicle gaps. In that work, the word platooning meant grouping a lead vehicle followed by consecutive vehicles. This meaning of the term platooning resembles the word’s current use, but the number of published documents on the topic varied greatly from that published nowadays. From 1973 to 1993, there was no continuous stream of published papers on platooning. In fact, for almost half the years, no documents were published on the topic (see Figure 4). During the same timeframe, the year with the highest scientific production was 1991, with a total of five publications, and the most studied topic was related to Traffic Flow and Road Capacity. From this point forward, there were no more gaps in the publication of platooning documents. Between 1994 and 2001, an average of 10 documents per year were published, with a maximum of 15 publications in 1997. Again, the topic of Traffic Flow and Road Capacity was the most studied. From 2002 to 2021, the number of papers produced grew an average of 28% on a year-by-year basis, to the highest number of 307 published documents in 2021. These values show that the topic of platooning has gained relevance and is now an actively studied topic. The most studied topic during this period was Traffic Flow and Road Capacity, closely followed by the topic of Global Objectives, starting in 2011. During this period, the topic of Energy Efficiency started to be investigated, with the number of published documents approaching that of the Global Safety topic.

Within the topic of platooning, the previously identified areas of work experienced different progress rates during the last 49 years of available data. To better illustrate this phenomenon, Figure 5 shows the evolution of the percentage that each area of work—Energy Efficiency, Global Safety, Traffic Flow and Road Capacity, and Global Objectives—contributed to overall platooning development. From 1973 to 1994, the small number of articles made it difficult to establish clear trends regarding the relative contribution of each research grouping. Only from 1995 onwards was there a stabilization in the topics covered. Initially, three research sub-areas were explored including Global Safety, Traffic Flow and Road Capacity, and Global Objectives. Later, in 2007, the additional sub-area of Energy Efficiency appeared, becoming a permanent area of research in 2009.

A clear interest in the area of Energy Efficiency was evident after 2008, which may be related to the growing public awareness of the climate crisis and the introduction of
more ambitious policy instruments. For example, the Energy and Security Act, signed in December 2007, increased the fuel economy standards in the United States by 40% [36]. Since platooning is seen as a tool that promotes safer and less energy-demanding transport, this would be a helpful tool in achieving the aforementioned fuel economy standards. Alongside this act, 2006 saw the premiere of An Inconvenient Truth, which contributed to raising awareness about climate change in the general population [37]. In 2007, the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) was published, which attributed climate warming to human activity [38]. There was also pressure from the European Union regarding air pollution, as seen by the Euro 4 emissions standard launch in 2006, which came with vehicle pollutant reduction for CO, HCs, NOx, and PM. All these actions contributed to changes in policy and helped strengthen the need for further research in the Energy Efficiency area of platooning.

The Global Safety category showed a decrease in the percentage of dedicated work after 2010. Since 1993, the average percentage of work dedicated to Global Safety was around 30%, but, starting in 2010, it dropped to below that value. This does not mean a decrease in interest in the subject, as the number of documents on the topic still increased. The exponential growth of works within platooning means that even if Figure 5 shows a decreased percentage of documents published, the absolute number of papers published on safety still increased yearly. This category included documents related to the safety of driving vehicles, such as in the work of Best [39], as well as the security of systems that allow platooning to function, such as in the work of Sawade et al. [40].

The categories of Traffic Flow and Road Capacity and Global Objectives account for more than half of the works published on the platooning theme. The exception was in 1985 and 1993 when Global Safety took precedence. As the number of vehicles on roads kept increasing, so did the problem of lack of usable road space and congestion. It should be noted that the works that focused on more than one aspect of platooning were categorized as Global Objectives. This means, for example, that even if a document’s main work was on traffic flow, if it referred to a reduction in fuel consumption by the vehicles related to driving in an optimized way, it was classified as a work in Global Objectives and not in Traffic Flow and Road Capacity. Therefore, the Global Objectives category contains works from all the other categories that employed a holistic approach, enriching the works and changing their category in the scope of the current work. In essence, these two categories dominate the research areas of platooning.

3.2. Platooning from the Environmental Perspective

The environmental impact of platooning is assessed in this section. In the available literature, the environmental dimension is addressed by three main parameters as follows: a reduction in the aerodynamic drag coefficient (C_d), air pollutant emissions, and energy consumption. Since this work aims to provide a quantitative analysis of the environmental impact of platooning, only the documents that presented a quantitative evaluation of these parameters were analyzed. This means that from the initial 44 identified documents in the second phase of this literature review, only 15 documents fulfilled these criteria. The contents of these 15 documents are summarized in Table 2, following the entry points described in the Section 2. For the documents that did not provide information on the data entries, the corresponding cells in Table 2 are greyed out.
Table 2. Case study characteristics, modeling setup, and environmental implications found within the documents identified during the second phase of this literature review.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Case Study Characteristics</th>
<th>$C_d$ Reduction [%]</th>
<th>Emission Reduction [%]</th>
<th>Fuel/Energy Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hu and Bauer [41]</td>
<td>Platoon with three identical electric HDVs driving at 70 mph with a 10 m inter-vehicle gap</td>
<td>40</td>
<td></td>
<td>33.4</td>
</tr>
<tr>
<td>Validi and Olaverri-Monreal [42]</td>
<td>Platoon with three connected delivery vans (HDVs) with a 5 m inter-vehicle gap</td>
<td></td>
<td>79 18 85 51</td>
<td></td>
</tr>
<tr>
<td>Ye et al. [43]</td>
<td>Platoon with eight LDVs in a network with 150 other vehicles simulated with data from real cars with a 3 m inter-vehicle gap</td>
<td>20</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Gao et al. [44]</td>
<td>Platoon with eight LDVs traveling on the freeway joined by another LDV through an on-ramp with a 0.9 s inter-vehicle gap</td>
<td>Up to 1.63</td>
<td>Up to 4.77</td>
<td></td>
</tr>
<tr>
<td>Bibeka et al. [45]</td>
<td>Three-lane corridor with five HDVs platooning when possible, driving at 65 mph with a different market penetration rate of connected vehicles with 5.49 and 17.37 m inter-vehicle gap</td>
<td>Up to 25</td>
<td>Up to 25</td>
<td></td>
</tr>
<tr>
<td>Bichiou and Rakha [46]</td>
<td>Platoon with five vehicles (LDVs and HDVs in different scenarios) travelling at 100 km/h with a 0.6 s inter-vehicle gap</td>
<td></td>
<td>4 for LDV and 11–14 for HDV</td>
<td></td>
</tr>
<tr>
<td>Zhai et al. [47]</td>
<td>Platoon with three LDVs traveling a virtual 8 km freeway with varying slopes with a variable inter-vehicle gap</td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Muratori et al. [48]</td>
<td>Platoon with two HDVs traveling at 50 mph with 30 ft inter-vehicle gap</td>
<td>6.4</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Bishop et al. [49]</td>
<td>Platoon with two HDVs driving at 65 mph with 30 to 150 ft inter-vehicle gap</td>
<td>Up to 21 for the platoon</td>
<td>Up to 6.96 for the platoon</td>
<td></td>
</tr>
<tr>
<td>Koller et al. [50]</td>
<td>Platoon with three HDVs that form if it is beneficiary</td>
<td>50</td>
<td></td>
<td>Up to 13</td>
</tr>
<tr>
<td>Hardy and Fenner [51]</td>
<td>Platoon with LDV driving in traffic at 20 mph in a steady state instead of start and stop traffic with a 24.46 m inter-vehicle gap</td>
<td></td>
<td>43 43</td>
<td></td>
</tr>
<tr>
<td>Deng and Ma [52]</td>
<td>Platoon with two HDVs accelerating to 25 m/s and decelerating to 5 m/s with a 5 m inter-vehicle gap</td>
<td></td>
<td>29.8 for deceleration and 3.5 for acceleration</td>
<td></td>
</tr>
</tbody>
</table>
With the above aspects in mind, truck hauling companies would be interested in research platooning, where the most studied platoon composition is three HDVs. The remaining studies platoon would greatly benefit the industry and drive research further for this type of primary routes connected by highways [48]. Considering that the number of truck drivers provides an overview of the type of vehicles mostly studied in platooning and how many vehicles are considered each time. There is a clear dominance of documents related to heavy-duty vehicles (HDVs), with 57% of the works focusing on these. This could be explained by heavy-duty vehicles (trucks) often having long hauls, usually on the same primary routes connected by highways [48]. Considering that the number of truck drivers is projected to not be enough to fulfill future demand [34], having only one driver per platoon would greatly benefit the industry and drive research further for this type of vehicle. Another aspect that could increase research efforts focusing on truck platooning is the possibility for a driver not leading a platoon to benefit from not having to drive the truck for certain periods. In this situation, the truck is expected to maintain course and drive safely in an automated manner within the constraints of a platooning formation. With the above aspects in mind, truck hauling companies would be interested in research efforts focused on truck platooning, as this could lower their operating costs. Within HDV platooning, the most studied platoon composition is three HDVs. The remaining studies used two vehicles and five vehicles in their composition, with the five-vehicle platoon composition being the least present in studies.

Based on the data entries from the case study characteristics column in Table 2, Figure 6 provides an overview of the type of vehicles mostly studied in platooning and how many vehicles are considered each time. There is a clear dominance of documents related to heavy-duty vehicles (HDVs), with 57% of the works focusing on these. This could be explained by heavy-duty vehicles (trucks) often having long hauls, usually on the same primary routes connected by highways [48]. Considering that the number of truck drivers is projected to not be enough to fulfill future demand [34], having only one driver per platoon would greatly benefit the industry and drive research further for this type of vehicle. Another aspect that could increase research efforts focusing on truck platooning is the possibility for a driver not leading a platoon to benefit from not having to drive the truck for certain periods. In this situation, the truck is expected to maintain course and drive safely in an automated manner within the constraints of a platooning formation. With the above aspects in mind, truck hauling companies would be interested in research efforts focused on truck platooning, as this could lower their operating costs. Within HDV platooning, the most studied platoon composition is three HDVs. The remaining studies used two vehicles and five vehicles in their composition, with the five-vehicle platoon composition being the least present in studies.

### Table 2. Cont.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Case Study Characteristics</th>
<th>CO₂ Reduction [%]</th>
<th>CO₂ Emission Reduction [%]</th>
<th>Fuel/Energy Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davila and Ferrer [53]</td>
<td>Platoon with five vehicles (two HDVs and three LDVs) driving at 85 km/h in two 2 km straights with an 8 m inter-vehicle gap</td>
<td>11 for HDV and 15 for LDV</td>
<td>11 for HDV and 15 for LDV</td>
<td>11 for HDV and 15 for LDV</td>
</tr>
<tr>
<td>Davila et al. [3]</td>
<td>Platoon with five vehicles (two HDVs and three LDVs) driving at 85 km/h in two 2 km straights with an 8 m inter-vehicle gap</td>
<td>Up to 80, depending on the vehicle and scenario</td>
<td>11 for HDV and 15 for LDV</td>
<td>11 for HDV and 15 for LDV</td>
</tr>
<tr>
<td>Suzuki et al. [54]</td>
<td>Platoon with three HDVs driving at 80 km/h while in an overtaking situation with other LDVs with a 4 m inter-vehicle gap</td>
<td></td>
<td>7.72</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Type and number of vehicles in a platoon.
The remaining studies are equally divided between those studying only light vehicles and those considering a mix of light and heavy-duty vehicles. Within each platooning composition considered in this literature review, a different number of vehicles was found to compose each platoon. For the mixed platooning composition, only platoons with five vehicles per platoon were found, and all of these used the same composition of two HDVs and three LDVs. For the LDV exclusive composition, two different approaches in the number of vehicles per platoon were previously studied. Most of the LDV-only documents used a platoon with eight vehicles, while the remaining documents considered a platoon with three vehicles.

In terms of the modeling aspect, the methodology employed in each study was examined with respect to vehicle dynamics, followed by the evaluation of energy consumption and emissions. For the assessment of vehicle dynamics, most studies implemented mathematical models to simulate the driving behavior of vehicles within the platoon. Examples include the discrete-time model [46], the hybrid optimal control algorithm [49], and kinematic equations [50]. Authors utilizing specific mathematical models have generally aimed to enhance fuel efficiency by applying various optimization algorithms, as demonstrated in the works of Zhai et al. [47], Koller et al. [50], and Deng and Ma [52]. These investigations primarily focus on understanding the behavior of physical or kinematic variables, examining their influence on vehicle dynamics, engine performance, and consequently, on the vehicle’s Energy Efficiency or environmental footprint.

However, a significant portion of the studies also utilized commercial traffic simulation software. These studies primarily focus on analyzing the effects of infrastructure or specific singularities of the network on the performance of the platoon, as well as the impact of the platoon on the overall traffic network’s efficiency from various perspectives. Both software and mathematical modeling approaches were employed in all the papers listed in Table 2 that incorporate traffic flow analyses, as depicted in Figure 7. Within the software approach, VISSIM was used by the works of Bibeka et al. [45], Gao et al. [44], and Suzuki et al. [54] and was applied in conjunction with other software. The other software then specified values for pollutant emission and for fuel or energy consumption that enhanced the use of VISSIM. By contrast, SUMO was not used along with other software but was still capable of providing traffic information and emission data, as shown by the work of Validi and Olaverri-Monreal [42].

The energy and emissions model section in Table 2 is the most diverse. The primary method for evaluating energy and emissions is through mathematical models that calculate values based on factors like time, vehicle mass, drag coefficient, and speed. The second most common method is empirical assessment, which focuses on valuing energy (fuel). The third most common method involves accountability of emissions, with each document using its own method or following a previously published one. This diversity in modeling and software usage reflects the multifaceted nature of energy and emissions evaluation in the context of platooning environmental analysis.
Few values for drag coefficient (C_d) reduction were found within this review. Only values for HDVs were identified, with two concrete values that include an average 45% drag coefficient reduction rate and two works with a more complete analysis. The most complete works offered different C_d values for different vehicle gaps. Focusing on the more complete works, Davila et al. [3] provided values for each vehicle in a mixed platoon with two HDVs followed by three LDVs, while Bishop et al. [49] provided a platoon with only two HDVs. These works were not included in the aforementioned 45% drag coefficient reduction. This was because the drag coefficient values presented in these documents varied with the distance between vehicles and the type and order of vehicle analyzed in the platoon. Only the work of Hu and Bauer [41] had a fixed inter-vehicle gap of 10 m, which made it comparable to the other works of gap-based drag coefficient reduction, with a value of 50%, similar to the value for the following HDV in the Davila’s platoon. The more complete works presented values of the drag coefficient or drag coefficient reduction for each vehicle in the platoon with different inter-vehicle gaps. The inter-vehicle gaps analyzed by Davila et al. [3] were 3, 4, 6, 8, 10, and 15 m, while Bishop et al. [49] analyzed gaps of 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 ft. These two works found analogous values for C_d or C_d reduction at the 3 m or 10-foot vehicle gap. At higher vehicle gaps, the similarity in the values between works disappeared. The bigger platoon of two HDVs and three LDVs consistently performed better than the platoon with only two HDVs. In the work by Davila et al. [3], at 90 km/h, the drag coefficient values of the HDVs varied from almost 0.6 to just below 0.3, depending on the distance between vehicles and the HDVs analyzed (the leading vehicle or the following vehicle). This translates to a C_d reduction of up to 50%. For the LDVs, the drag coefficient was reduced by up to 90%, from approximately 0.45 to 0.05, depending on the vehicle and the inter-vehicle gap. In this work, the between-platoon distance that led to the best results of lower aerodynamic drag resistance was the 6 m gap. In the work by Bishop et al. [49], only two HDVs were considered in the platoon. When looking at the vehicles separately, the C_d reduction varied from 0 to 46% at a speed of 65 mph (approximately 105 km/h). The best result was found at the smallest gap of 5 ft with a 46% drag coefficient reduction for the following vehicle and 24% for the leading vehicle. At the highest vehicle gap, the following HDV experienced a 29% drag coefficient reduction, while the leading HDV did not experience any drag coefficient reduction. After the 60 ft vehicle gap, the change in the drag coefficient for a higher vehicle gap was negligible. Their work also added another aspect to platooning, where the vehicles were not aligned but instead travel with a 2 ft side offset. In this scenario, the leading vehicle did not experience a significant change in the drag coefficient, while the following vehicle experienced a significant difference in the drag coefficient that was reduced with an increase in the vehicle gap.

Regarding the overall emission reduction, only three values for each vehicle type were available in the analyzed literature. All vehicular formations experienced emission reduction while traveling in a platoon formation, with HDVs reducing emissions by an average of 9.5% and LDVs by 24.3%. The range of emission reduction was small for HDVs, while for LDVs, it varied from 15 to 43%. This reduction was justified by reducing the distance between vehicles in the platoon [3,53] and by driving in a steady state instead of stop-and-go traffic [51].

CO_2 emission reduction values were more common in this review than the overall emission reduction values, allowing for a statistical data analysis. A box plot was the method selected for this analysis (Figure 7). These values show a higher CO_2 emission reduction for LDVs than for HDVs. This is supported by Davila et al. [3], who compared LDVs and HDVs traveling at the same speed in a platoon and found that the LDVs showed a higher drag reduction and thus emitted less CO_2. The mean values are 23.3% for LDVs and 14.5% for HDVs, as indicated by the x in the box plot graph. The data intervals for HDVs are smaller than for those of LDVs.

The fuel/energy reduction column has the most available data. Figure 8 shows that the values for HDVs have a higher range than those for LDVs, which is the opposite of
the CO₂ emission reduction values. However, these values are quite far from the average values for reducing HDV fuel consumption. Here, the mean values for the reduction in fuel or energy consumption are similar, with a 14.3% reduction for LDVs and a 13.2% reduction for HDVs, as marked with an x in the graph. The highest value for fuel/energy reduction is around 33% for HDVs, and the lowest values are around 4% for both groups of vehicles. Most analyzed documents had a value or range of values for each platoon type, with an average value for the entire platoon, such as in the work by Bichiou and Rakha [46], which also included an electric vehicle. The works by Bishop et al. [49] and Deng and Ma [52] were the only ones with a different approach. The first differentiated values for leader and follower vehicles, and the latter had different values for accelerating and decelerating instead of the usual value for vehicles traveling at a constant speed.

**Figure 8.** Reduction in fuel or energy consumption for light and heavy-duty vehicles from Table 2.

### 4. Discussion

Previous analyses have demonstrated the potential of platooning to reduce emissions and energy use, with an average 14% reduction in fuel or energy use for light-duty vehicles (LDVs) and a 13.2% reduction for heavy-duty vehicles (HDVs). While electric rail solutions continue to offer superior efficiency for large-volume, long-haul transport, platooning provides crucial flexibility and adaptability to complement traditional freight methods. To fully leverage platooning’s benefits, several areas require further exploration. Below we describe four areas of future interest and development in the field of platooning and the environment:

#### 4.1. Platoon, Drag Coefficient, and Operational Conditions

The drag coefficient (Cd) plays a pivotal role in platooning, accounting for 70% of resistive force at 110 km/h [3]. Therefore, it should be a focal point in future research. Understanding the relationship among Cd, speed, and the gap between vehicles is crucial for optimizing platoon efficiency. Mixed platoons have shown the potential to reduce C_d, leading to increased efficiency and lower emissions [55]. However, the concept of mixed platoons involving light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) is largely underexplored. Further research is still needed involving different types of vehicles and inter-vehicle distances at fluctuating speeds to provide additional knowledge on determining optimal platooning formations under different contexts. Furthermore, most studies focus on platooning at constant speeds [29]. However, real-world traffic conditions often require vehicles to accelerate and decelerate. Understanding how these variable speeds impact the fuel or energy savings and emission reductions from platooning is indispensable. Field studies under diverse traffic conditions could support and validate simulation models and provide practical insights for real-world implementation.
4.2. Platooning and Air Quality

Even though some studies calculated potential reductions in CO$_2$ equivalent emissions [3,42,43,45,51,53,54], there is a significant lack of research focusing on the potential impact of platooning on air quality and human health. This gap is particularly relevant in urban environments where air quality is a major concern. The implementation of platooning systems might present trade-offs, potentially improving Energy Efficiency but exacerbating local pollutant concentrations. The optimal configuration of platooning for reducing energy consumption might not necessarily be the best for improving air quality because of the non-linear behavior of emissions with power or pollutant dispersion. Vehicle speed, inter-vehicle distance, and overall platooning configuration could vary depending on whether the priority is Energy Efficiency or air quality. For instance, in certain traffic contexts or when air quality is a primary concern (e.g., an urban ring or freeway), it might be necessary to adjust the platooning configuration. Similarly, the optimal speed might need to be lowered to reduce emission rates. A holistic approach to platooning research, incorporating traffic, emissions, and fuel/energy considerations, as highlighted by Lammert et al. in 2014 [56], is still needed. This should not only examine its impact on fuel or energy consumption but also its effect on air pollutant emissions. Moreover, life cycle analysis and traffic flow modeling methodologies could be instrumental in achieving this comprehensive perspective.

Finally, we must be aware that advancements in electric and hydrogen-powered vehicles are transforming the transportation sector. However, platooning technology still offers potential benefits. The adoption of electric and hydrogen technologies will take time, and optimizing current fossil-fueled vehicle usage during this period with platooning could reduce harmful emissions in the short and medium terms (decades). Additionally, platooning strategies could improve the efficiency of electric and hydrogen vehicles, extending their range and facilitating their widespread adoption.

4.3. Environmental Optima vs. Technological Advancements and Regulation

It is important to acknowledge that the most desirable environmental solution may not always be in harmony with technological feasibility or public acceptance. This is a crucial consideration in the context of platooning and vehicle electrification. From a technological perspective, platooning and electrification have shown significant potential to generate environmental benefits over multiple traffic contexts, as outlined in Table 2. However, they also introduce considerable challenges. To ensure safety, these systems must be equipped to manage complex driving scenarios and respond in real time, implying that further research is required in areas such as communication latency, system reliability, and robustness [17]. Future advancements in communication technology could potentially facilitate shorter gaps among vehicles in a platoon, thereby reducing aerodynamic drag and enhancing fuel efficiency. Addressing these challenges and exploring how advancements in communication technology can be utilized to optimize platooning and its environmental benefits should be a key focus of future research.

Moreover, automated platooning must comply with existing traffic laws, including states’ following-too-closely (FTC) statutes. Some jurisdictions may need to update or modify these laws to allow for the closer proximities among vehicles that platooning entails, as highlighted in [57].

4.4. Environmental Optima vs. Public Acceptance

Simultaneously, as vehicle spacing could become narrower because of technological advancements, the psychological comfort and perceived safety of vehicle occupants could be the new dominant constraints. Generally, people feel safer maintaining a certain distance between vehicles, representing a comfort zone that may be challenging to overcome even with assurances from advanced safety systems. Indeed, the successful implementation of new technologies heavily relies on public acceptance. Therefore, future research and development efforts in making more efficient platooning systems need to account for not
only the technical aspects but also the human factors. The public acceptance of platooning technologies can be influenced by concerns about safety, privacy, reliability, and convenience. Therefore, it is crucial to consider these factors when evaluating the potential of these technologies as environmental solutions. Additionally, it is important to integrate these solutions into a comprehensive approach and control operation model that considers broader transportation and environmental policy goals. For instance, developing dynamic mechanisms to adapt platooning behavior to address strategic environmental challenges unique to each network segment.

Being a literature review, this work reflects the outcomes of the available works. In addition, the obtained results are subject to some limitations; so, it is important to interpret them properly. These limitations are mostly related to three aspects. First, only one database was used to gather documents for this literature review. The database used has some of the most relevant journals and publishers indexed but it can still be a limiting factor for this study. Second, the identified keywords for each classified area of work within the topic of platooning played a deciding role in all the analyses made. This approach, being quick, may incur classification errors that would not be present if the documents were read individually. Finally, a thorough analysis of the proposed environmental aspects of platooning was limited by the small number of eligible works that were analyzed. In addition to this limitation, the information found within each document was insufficient to complete all the cells in Table 2. Because of the limited data available, it was not possible to make strong conclusions about how $C_d$ influences fuel consumption and pollutant emissions, as few documents provided values for $C_d$ or $C_d$ reduction.

5. Conclusions

This paper provides an overview of the evolution and potential environmental impacts of platooning within the transportation field. It emphasizes the methodological approaches to traffic and emission assessment, impacts on $C_d$ and emissions, and energy savings. This paper’s primary contributions include identifying simulation methods for platooning and pollutant emission and systematically and critically assessing the available literature on vehicle pollutant emission and fuel and energy savings. It also highlights the limitations of these previous works and identifies three major research gaps that point towards possible research directions.

The performed review showed that the topic of platooning has gained exponential interest in the last two decades. The different areas researched stabilized their distribution in the percentage of work for each area in the last years, with Global Objectives and Traffic Flow and Road Capacity being the most common.

The focus of this work was on the environmental effects of platooning. Within this area, the most common results presented in the literature were for fuel or energy savings. The tools used in the studies usually relied on mathematical models for traffic, energy, and emissions modeling. The choice of approach seemed to depend on the objective of each work, as mathematical models were mostly used in works related to improving fuel efficiency. Data on the drag coefficient and emissions are scarce in the literature, which leaves space for future works with a holistic approach. Emissions are not directly dependent on fuel economy in all the analyzed cases but are both important for the decarbonization of the transport sector. Reducing emissions is also a critical aspect of the future of transport as air pollution becomes a leading cause of death in the world.

While platooning presents promising benefits in terms of increased road capacity, safety, energy use reduction, and pollutant emissions reduction, there are still research gaps that need to be addressed. These research gaps and potential directions for optimizing platooning efficiency and emission reductions were discussed. It was established that while platooning presents opportunities for reducing emissions and energy use, more research is needed to harness its potential fully.

Areas such as understanding the drag coefficient ($C_d$) and its relationship with speed and inter-vehicle gaps, exploring mixed platooning involving light-duty and heavy-duty
vehicles, and studying the impact of variable speeds on fuel savings and emission reductions were identified as crucial. The need for a holistic approach to platooning research, incorporating traffic, emissions, and fuel/energy considerations was emphasized.

Additionally, the importance of considering air quality and health impacts in urban environments was highlighted, suggesting the need for adaptable platooning strategies. Finally, we underscored the importance of balancing environmental solutions with technological feasibility and public acceptance, advocating for future research to address both technical aspects and human factors.

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