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Reducing road congestion and air pollution with ICT-based platooning

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Abstract

Platooning connects a fleet of (normally heavy) vehicles, allowing them to travel close together in a coordinated and synchronized manner. The use of Information and Communication Technology (ICT) can contribute to make this solution more effective. The reduction of road congestion and air pollution emerges as potential benefits of this solution. Yet, the actual impacts on congestion remain a contentious subject, with outcomes heavily dependent on the specific indicators under examination, such as travel time, average speed, or delays, and the type of vehicles involved. Through a concept-centric approach, this study aims to investigate the impacts on both traffic congestion and polluting emissions deriving from the implementation of ICT-based platooning. Key research areas encompass route optimization, scheduling, and trajectory planning. Anticipated positive outcomes include improved fuel efficiency, reduced greenhouse gas and air pollution, and alleviation of traffic congestion. Notably, this paper expands the platooning concept beyond heavy goods vehicles to include passenger and public transport. The article identifies potential gaps in knowledge and highlights areas requiring further exploration. More structured approaches may better capture the potential long-term effects of platooning, considering factors like demand fluctuations, change in modal share and the influence on traffic patterns.

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Keywords: Congestion; Air pollution; Platooning; Impacts.

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1. Introduction

Platooning is a technical solution which uses advanced vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies to allow groups of vehicles to drive in close proximity to each other in a coordinated and synchronized way, at close intervals between vehicles (Maiti et al., 2017). Platooning lowers aerodynamic drag and fuel consumption of following vehicles through minimal spacing, leading to lower operating costs and emissions. In addition, it can improve traffic flow and relieve congested roads, thus providing economic and social advantages. As a consequence of the digitalisation of transport, ICT-based platooning is gaining increasing attention in the transportation industry (Alam et al., 2015).

While there are many potential benefits of platooning, several challenges and impacts need also to be addressed. For instance, there are concerns about cybersecurity and data privacy, as the implementation of platooning requires significant investment in technology and infrastructure. Regulations and standards are needed to ensure safety and interoperability, and questions have been raised about the impact of platooning on the labour market. Some limitation of platooning concern legal, regulatory, and technical constraints in real-life scenarios. Overall impacts of platooning can only be fully understood when automation is in a more advanced phase of implementation (Antonissen et al., 2013). In this paper, we intend to summarise key messages related to transport externalities, focusing on road congestion and air pollutant emissions, by examining the current state of research.

Platooning is a well-established research topic. One of the earliest studies has been conducted by Hallè et al. (2003). More recently, was proposed a decentralised approach using a leader-follower strategy with communication based on an ad-hoc wireless network (Kavathekar and Chen, 2011). To facilitate platooning, several technologies, such as adaptive cruise control, cooperative adaptive cruise control, and V2V communication systems have been considered. Platooning can be classified into four categories based on the level of technology, automation, and communication: manual, semi-automated, fully automated, and connected and automated platooning. This work focuses on the last two groups, which are considered solutions part of the digitalisation process that transport is undertaking.

One advantage that is highlighted in the literature is a positive correlation between platooning and traffic density, although showing how driver behaviour greatly influences the stability of platooning. However, the benefits of platooning increased as traffic density increased, and driver behaviour played a critical role in determining the stability of platooning formations (Jiang et al., 2021). The hierarchical control architecture of this system is a combination of perception, control, and communication. There are a lot of challenges related to the implementation of platooning, some of these concerns of traffic reduction and the advanced technologies. Discussions on traffic control concepts, including centralised and distributed systems, but also disruptive technologies such as autonomous vehicles, are numerous, but one conclusion is that platooning can reduce traffic (Baskar et al., 2021).

Several studies have investigated the safety of platooning. The need to improve safety measures in platooning of heavy goods vehicles is crucial, especially in challenging weather conditions (Xiaoxiang et al., 2022). Platooning can also improve road safety by reducing human errors that can lead to accidents, and by addressing the shortage of qualified truck drivers. Beyond technical issues, the social and economic impacts of platooning were also investigated. Sivanandham et al. (2020) analysed the benefits and challenges of introducing platoons and their impact on fuel economy, reducing pollution and congestion. Optimised route planning and scheduling can improve companies' financial and operative performances. Although platooning research typically focuses on freight transport, these premises could also be applied to passenger vehicles such as buses. The aim of our research is to present a thorough review of the current literature on the effects of platooning on externalities, emphasizing the potential of large-scale application to heavy-duty vehicles. This is particularly important in the context of transport policy, given the impact that external costs of transport, such as road congestion and air emissions, have on modern societies and the significant efforts that are being made to mitigate them (EU et al., 2020; Cavallaro and Nocera, 2022, 2024; Cavallaro et al., 2024). The contribution is structured as follows: Section II presents the methodology used to review the literature, followed by a summary of the main quantitative results in Section III. Ultimately, Section IV concludes the article by including a discussion of the results.

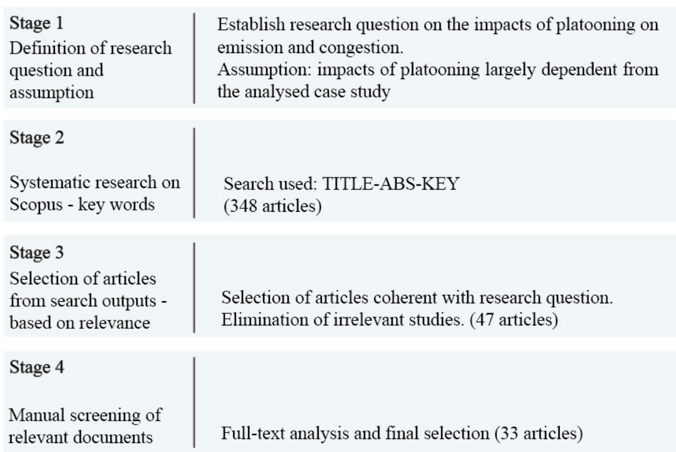
2. Methodology

The literature review follows a concept-centred approach. This approach is useful for investigating interdisciplinary issues that involve several interrelated aspects not typically analysed together. By considering the interrelationships of different concepts, the review gives an overall view of the issue and highlights insights which might be obscured by unilateral analysis. This approach can be used when combining qualitative and quantitative research, theoretical models, and empirical research to explore issues at an early/limited stage of research. Gaps in existing research can be identified, as well as areas for future research**.** As shown in Figure 1, the methodology comprises four sequential stages. First, appropriate research questions are defined to highlight key challenges and to provide an organised framework for future research (stage 1). In this specific case, the focus is on the impacts of platooning on air emissions and road congestion.

Hence, we conducted a search of the Scopus database (stage 2) using the keywords 'platooning' AND 'emissions' OR 'congestion' to explore the intersection of these three issues. Keywords were deliberately kept general to avoid missing relevant contributions that did not use the exact search terms in our query. This search resulted in 348 contributions. The third step (stage 3) is to screen the documents identified during the previous steps, by selecting only the relevant documents based on their abstracts, titles, and subject headings. In this case, relevance is defined as the ability to estimate the impact of platooning on either road congestion or emissions from road transport, while other aspects of platooning are not considered. This limited the initial research to 47 papers. Five main reasons justify the significant reduction in the number of papers. First, platooning was mentioned as a potential solution to improve the performance of the road transport sector, together with other measures. Second, no quantitative insights on the actual impacts on emissions and congestion were provided in the articles, despite many containing at least two of the three keywords in the title and/or abstract. Instead, they simply provided generic sentences about the potential effects of introducing platooning.

Third, platooning is sometimes conceived in manual or semi-automated terms, as noted by Hallé et al. (2003). These studies are not relevant for our purposes, since we are interested in the implication of ICT-based innovation of the vehicular fleet and flows. Fourth, platooning at urban intersections is considered, which is something else than a measure to optimize the vehicle circulation along roads. Fifth, in most cases it is written that platooning can contribute to reducing fuel consumption or emissions, but this is only a general and initial statement, which is not addressed in the rest of the paper. Once identified those articles that fit to our analysis, Stage 4 involves reading the full text of selected articles for further refinement. Contributions with unclear methodology or contradictory/unclear results are excluded. To complement the semi-automatic search, further articles not identified by the previous analysis are searched for in the references of the selected documents. The final number of analyses was then determined.

Fig. 1. Four-stage approach for investigating the links between platooning, emissions, and congestion.



3. Results

While most authors agree that platooning can have positive effects on the transport sector, the magnitude of these impacts varies significantly. The methodological assumptions made by the researchers, the boundaries of the analysis and the unit of measurement chosen contribute to a significant variation of research outcomes (Cappelli and Nocera, 2006). Table 1 summarizes, based on studies carried out in different parts of the world, the impact of platooning on congestion and emissions. The table contains a description of each study, the type and length of road, as well as an indication of the units of measure used to quantify the impacts.

Contributions to platooning and their approach to determining effects have several salient features. Notably, there is a lack of clarity in terms of the indicators by which congestion is measured. Some studies are based on average speed and delays, whereas others refer to traffic flow. Therefore, it is important to interpret the impact's sign as positive or negative accordingly. A noteworthy difference between studies is the type of vehicles considered in the analysis. While most studies consider only the vehicles directly involved in platooning, typically trucks, others provide a more comprehensive evaluation of system performance including all vehicles in circulation (Davila and Ferrer, 2014; Bichiou et al., 2021; Massar et al., 2021). Simulations are often conducted with varying levels of penetration of platooned and automated vehicles, expressed either as the number of vehicles in a platoon or as a percentage of the vehicle fleet or road capacity. Yet, the results of these simulations are often not clear cut. In some cases, the performance of the vehicles is improved, leading to a reduction in the average travel time or in the delay (Mahama and Chen, 2019; Shynkar at al., 2022; Lin at al., 2022). Lin et al. (2022) consider average values for the entire vehicular fleet, including light vehicles along off-ramps. In some cases, platoons can be a source of traffic congestion and longer travel times, especially if they are large or if there is high demand for road use (Zhao et al., 2021). Also, regarding traffic flows, there is no clear consensus. While Hardwood and Reed (2014) report an increase of traffic flows, other studies show a decrease (Mahama and Chen, 2019; Singh and Santhakumar, 2022). Sometimes platooning is combined with innovative fuel solutions, such as heavy-duty electric vehicles (Hu and Bauer, 2021) or electric cars (Validi et al., 2022). The impact on road safety is another aspect related to congestion. The efficiency and safety of traffic varies with the characteristics of truck platoons in a critical traffic condition: longer platoons can improve traffic efficiency, but short platoons improve safety (Mahama and Chen, 2019).

Interestingly, most studies on air pollutants focuses on greenhouse gases, while such pollutants like particulate matter (PM_x) or nitrogen dioxide (NO_x), which are the main products of heavy-duty diesel combustion, have been given less attention or treated as global indices (Hwang et al., 2020; Shynkar et al., 2022). However, Validi and Olaverri-Monreal (2021) provided an exception by calculating the expected impact in terms of emissions of CO, CO_2, NOx, HC and PM_x separately. Studies on CO_2 emissions, due to changes in aerodynamic drag and the associated fuel savings, indicate a reduction after the introduction of platooning. The reductions in CO_2 emissions vary from -0.5% (Paddeu and Denby, 2021) to -49% (Hu and Bauer, 2021). The most significant reductions have been achieved by the combination of platooning with speed reductions. Generally, CO_2 savings are found to be below 10%. For example, Tsugawa (2013) found reductions in the range between 2% and 5% (depending on the driving speed), while Bibeka et al. (2021) reported a reduction of 5%. Gawron et al. (2018) found slightly better results (up to -10%). However, they suggested that platooning seems to be less effective and less profitable for the participating companies compared to other measures (e.g. use of alternative fuels or optimisation of vehicle design). The results of the studies included in this review are generally comparable, based on Antonissen et al. (2013) who reported values between -5% and -10%. These results are also consistent with the figures presented in Schroten et al. (2020).

Platooning is also an innovative system in public transport. A study conducted by Sethuraman et al. (2019) shows that synchronising the timetables of different routes, so that buses reach stops at the same time and travel using the platooning system, helps to reduce traffic and energy consumption. The application of this system to public transport in an urban environment reduces the energy used in a 3-metre platoon by 13.7%, while at the same time increasing the speed of vehicles from an average of 28.9 km/h to 34 km/h and reducing the speed of private vehicles. A recent research niche stresses that combining platooning and automation offer future interesting perspectives for passenger transport, approaching the concept of modularity (Liu et al., 2021), of which some examples (e.g., the Next concept in Italy) are already in a test phase.

Table 1. Review of the impacts of platooning on congestion and emissions.

Author	Area	Type of road	Length [km]	Congestion			Emissions			
				Indicator	Unit of measure	Variation	Indicator	Unit of measure	Variation	Notes
Barth et al. (2014)	United States	Highway	NA	x	x	x	CO2	%	[-10%; -15%]	
Besselink et al. (2016)	Sweden	Highway	NA	x	x	X	CO2	Kg	-2770	
Bibeka et al. (2021)	United States	Freeway	42	x	x	x	CO2/h	%	-5%	
Bichiou et al. (2021)	United States	Highway	123	Travel time	%	-5%	x	x	x	
	United States	Highway	123	Travel delay	%	-9.4%	x	x	x	
Brummit et al. (2022)	United States	Highway	NA	x	x	x	CO2	t	-37.9 million	
Calvert et al. (2019)	Netherlands	Motorway	57	Travel delay	%	-2.9%	x	x	x	Assuming 50% of vehicles
Čičić et al. (2022)	NA	Highway	5	Travel delay	%	-52.7%	x	x	x	
Davila and Ferrer (2014)	United Kingdom	Highway	7.5	x	x	x	CO2eq/y	t	[-0.1; -2.85]	0.1 for gasoline cars; 2.85 for diesel trucks
Dvorkin et al. (2019)	USA	Highway	--	x	x	x	GHG	%	[-3%; -9%]	Depends on vehicle speed
Faber et al. (2020)	Netherlands	Motorway	3.3	Maximum Flow	%	-10.7%	x	x	x	
Gao et al. (2022)	NA	Freeway	NA	x	x	x	CO	%	[-1.33%; +1.63%]	Depends on initial speeds
	China	Highway	NA	x	x	x	CO2	%	[-6.7%; -9.4%]	
Gawron et al. (2018)	United States	Highway	NA	x	x	X	CO2eq	%	-9%	
Han et al. (2022)	Japan	Expressway	0.6	x	x	x	CO2	%	-5.7%	
Harwood (2014)	United Kingdom	Motorway	10	Maximum Flow	%	3%	x	x	x	
Hota et al. (2023)										
Hu and Bauer (2021)	United States	Highway	NA	Travel time	%	+22.2%	CO2	%	-49.3%	
Hwang et al. (2020)	Korea	Motorway	NA	x	x	x	Overall emissions	%	-30%	
Lin et al. (2022)	NA	Freeway	4	Travel delay	%	-22%	x	x	X	
Mahma et al. (2019)	NA	Highway	NA	Speed variation	%	[135%; 156%]	x	x	x	
	NA	Highway	NA	Travel delay	%	[39%; 43.5%]	x	x	x	
Massar et al. (2021)	NA	NA	NA	x	x	x	GHG	%	-35%	
Mena-Oreja (2018)	NA	NA	110	Traffic flow	%	22%	x	x	x	
	NA	NA	110	Traffic speed	%	71.5%	x	x	x	
Paddeu et al. (2022)	United Kingdom	Highway	NA	x	x	x	CO2eq	%	-0.54%	

Shynkar et al. (2021)	NA	Urban	NA	Travel time	%	-44%	Overall emissions	%	-35%	
	NA	Urban	NA	Average speed	%	7%	x	x	x	
Singh et al. (2022)	India	Highway	NA	Maximum flow	%	-22.3%	x	x	X	
Suzuki et al. (2011)	NA	2-lane Highway	1	x	x	x	CO2	%	-8%	Includes overtaking management
Tsai et al. (2022)	NA	Freeway	4	Travel delay	%	Up to -22%	x	x	X	Depending on ability to change lane
Tsugawa (2013)	NA	Expressway	NA	x	x	x	CO2	%	[-2.1%; -4.8%]	Depending on headway
Validi and Olaverri-Monreal (2021)	Austria	Highway	24	x	x	x	CO2	%	-18.2%	.
	Austria	Highway	24	X	x	x	NOx	%	-50.55%	
	Austria	Highway	24	X	x	x	Overall emissions	%	-18.26%	
	Austria	Highway	24	x	x	x	HC	%	-85.1%	
	Austria	Highway	24	x	x	x	CO	%	-78.77%	
	Austria	Highway	24	x	x	x	HC	%		
	NA	Highway	NA	x	x	x	CO2	%	-20%	
Xiao et al. (2020)	United States	Highway	4	Speed variation	%	226%	CO	%	-30%	
	United States	Highway	4	Traffic flow	%	230%	HC	%	-38%	

4. Discussion and Conclusions

Platooning has been proposed as a promising ITS-based technology to improve the efficiency of road transport (Schroten et al., 2020), being theoretically able to lower emissions, decrease congestion and improve logistics operations. In addition, platooning is functionally effective thanks to the V2V and V2I communication infrastructure. This means that it could be ready to become widely deployed in the near future. This paper analyses the scientific contributions on the impacts of platooning on emissions and congestion. Evaluations are mainly based on simulations rather than measurements from field trials. However, there is a lack of quantitative analyses of the impact of ITS applications on interurban transport and logistics, and the results of existing studies are partially contradictory (see section 3). The high context-dependency of quantitative studies underlines the need to understand the initial assumptions. To fully understand the conditions under which platooning can be operationally and socially beneficial, and to what extent it is preferable to other ITS-based or conventional solutions, further efforts are needed by the academic community, decision makers and infrastructure managers. Long-distance interurban transport could be optimised by shifting articulated lorries to trains according to the Rolling Highway scheme (EC, 2017), which would reduce transport externalities.

EU-funded projects and research have addressed this issue, but researchers have mainly focused on corridor-based truck platooning, and system-wide approaches are lacking in the academic literature. The results of the study could be valuable in assessing a more complex and realistic network CCAM (Connected Cooperative Automated Mobility) network, rather than focusing on a single corridor. Besides that, the induced effects in terms of modal share must be evaluated. As pointed out by Schroten et al. (2020), cost-saving innovations such as platooning for heavy vehicles may lead to a modal shift from rail or inland waterway transport to road transport. In addition, the European Commission, while acknowledging that the reduction of headways could increase road capacity, notes that the uneven development of technology, human-like functionality, and overly cautious safety approach of CCAM vehicles (including platooning convoys) may have a negative impact on the consistency of traffic flow(EC, 2019). This is why the interim period (when not all heavy-duty vehicles are technologically ready) is expected to be a critical for road circulation. Once the penetration rate of CCAAM-equipped vehicles reaches about 25%, automation and platooning that are not optimally linked can significantly worsen traffic flow (Wang et al., 2022).

The significance of research and development in the field of Intelligent Transport Systems (ITS) and platooning is evident, and crucial. Research has mainly focused on the automation of trucks and buses. Especially for passenger vehicles, the specific analysis of the externalities associated with the implementation of platooning has been neglected. Future studies, investigations and projects should look at extending the platooning concept to passenger transport, including transit vehicles, and at investigating its potentiality. Modularity and connectivity, combined with other technological advances such as autonomous and shared mobility, may have a significant impact on passenger mobility, relieving congested road and rail junctions, increasing capacity, and creating new opportunities for low-emission, non-private travel (Zhang et al., 2022). Finally, although the technological aspects are now part of the academic discussion, this paper revealed that a significant gap still exists in linking platooning to policy, data and communication management, and transport planning more broadly, including complex systems and time evolution. In particular, macroscopic themes revolving around demand variations due to ITS-driven technological progress, among which platooning is particularly relevant, offer space for further research.

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