Future mobility as a bio-inspired collaborative system

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ABSTRACT

The current trends towards vehicle-sharing, electrification, and autonomy are predicted to transform mobility. Combined appropriately, they have the potential of significantly improving urban mobility. However, what will come after most vehicles are shared, electric, and autonomous remains an open question, especially regarding the interactions between vehicles and how these interactions will impact system-level behaviour. Inspired by nature and supported by swarm robotics and vehicle platooning models, this paper proposes a future mobility in which shared, electric, and autonomous vehicles behave as a *bio-inspired collaborative system*. The collaboration between vehicles will lead to a system-level behaviour analogous to natural swarms. Natural swarms can divide tasks, cluster, build together, or transport cooperatively. In this future mobility, vehicles will *cluster* by connecting either physically or virtually, which will enable the possibility of sharing energy, data or computational power, provide services or transfer cargo, among others. Vehicles will collaborate either with vehicles that are part of the same fleet, or with any other vehicle on the road, by finding mutualistic relationships that benefit both parties. The field of swarm robotics has already translated some of the behaviours from natural swarms to artificial systems and, if we further translate these concepts into urban mobility, exciting ideas emerge. Within mobility-related research, the coordinated movement proposed in vehicle platooning models can be seen as a first step towards collaborative mobility. This paper contributes with the proposal of a framework for future mobility that integrates current research and mobility trends in a novel and unique way.

KEYWORDS

Future mobility; Collaboration; Micro-mobility; Autonomous vehicles; Swarms; Platooning

1. Introduction

For more than ten years, the need for rethinking mobility has been regarded as a critical aspect in fighting climate change (Chapman, 2007). In 2018 the transportation sector accounted for 28.3% of the greenhouse gas emissions in the US (United States Environmental Protection Agency, 2020). Predicted global urbanization and population growth rates further increase the urgency of finding mobility solutions that provide an

efficient and ecological service in our cities (United Nations Department of Economic and Social Affairs Population Division, 2019).

Current trends in new urban mobility such as vehicle sharing, electrification, and autonomy are expected to revolutionise the urban mobility landscape (Möller, Padhi, Pinner, & Tschiesner, 2019). These trends have the potential to alleviate many of the urban mobility-related problems if they are wisely combined (Cervero, 2017; Greenblatt & Saxena, 2015; Jones & Leibowicz, 2019; Sanchez, Pastor, & Larson, 2020).

Vehicle-sharing allows the convenience of private vehicles with the efficiency of public transportation (He, Mak, Rong, & Shen, 2017). Research shows that sharing can reduce the number of vehicles on the roads (Martin, Shaheen, & Lidicker, 2010; Martinez & Crist, 2015; Millard-Ball, 2005). Since the cost of ownership is shared, it can also promote the use of electric vehicles, which have a high purchasing cost but low operating costs (He et al., 2017; Jones & Leibowicz, 2019).

Electric vehicles (EV) have less lifecycle greenhouse gas (GHG) emissions for both the vehicle and fuel than conventional internal-combustion-engine vehicles (ICEV), according to Miotti et al. (Miotti, Supran, Kim, & Trancik, 2016). Lombardi et al. (Lombardi, Tribioli, Cozzolino, & Bella, 2017) argue that while some environmental indicators improve when shifting from ICEV to hybrid and electric vehicles, there are some other indicators, such as human toxicity and terrestrial acidification, that are worsened and should be taken into consideration in the vehicle electrification process. However, as the energy mix shifts towards renewable energy sources, these results might vary in the future (Lombardi et al., 2017). Another environmental benefit related to electric vehicles is that the batteries installed in electric vehicles can compensate for the supply irregularities of some renewable energy sources and help balance the supply and demand of the electric grid (Mitchell, Borroni-Bird, & Burns, 2010).

Regarding autonomous driving technology, the potential impact of autonomous vehicles in cities is still being studied. Some indicators point towards the need to combine autonomy and vehicle sharing in order for them to have a positive impact (Narayanan, Chaniotakis, & Antoniou, 2020). According to Cervero (Cervero, 2017), the combination of autonomy and car sharing could be the next paradigm shift for mobility in the US. In the case of shared autonomous vehicles, overall emissions would be reduced through increased efficiency and vehicle utilization rates—which would lead to smaller fleet sizes—even if there might be a slight increase in the total vehicle miles traveled due to rebalancing and induced demand (Narayanan et al., 2020).

In light of the above, combining vehicle sharing, electrification, and autonomy can greatly improve urban mobility. According to Greenblatt and Saxena (Greenblatt & Saxena, 2015), as a result of sustainable power generation, fleet size reduction and more cost-effective high-performance EVs, by 2030, the GHG emission per mile traveled in the US would be reduced 87-94% below ICEV per each autonomous taxi implemented.

However, what will come after most vehicles are shared, electric, and autonomous remains an open question, especially regarding the interactions between vehicles and how these interactions will impact system-level behaviour.

Autonomous vehicles can communicate with other vehicles, humans, and the infrastructure and have the intelligence to make decisions based on this communication (Harding et al., 2014). Having vehicles with communications skills opens the door to a future in which mobility would work as a collaborative system. From this perspective, vehicle platooning can be seen as the first step towards joint mobility. The field of vehicle platooning studies the coordinated movement of autonomous vehicles to improve safety and reduce congestion and fuel consumption (Maiti, Winter, & Kulik, 2017), but we imagine a future in which the interaction between vehicles is much richer than

communicating to coordinate.

Moreover, in nature, there are many great examples of collaboration; for instance, in insect colonies local and simple interactions lead to complex system-level behaviours (Bonabeau et al., 1999). The behaviour of these natural swarms has been transferred to artificial systems by researchers working in the field of swarm robotics (Sahin, 2004). In this sense, nature and swarm robotics can serve as an inspiration to design how vehicles will interact.

Therefore, inspired by nature and supported by models such as swarm robotics and vehicle platooning, this paper proposes a future mobility in which shared, electric and autonomous vehicles behave as a *bio-inspired collaborative system*. We have named the interaction between vehicles in this scenario as *vehicle clustering*. When vehicles *cluster*, they connect either physically or virtually, which will enable the possibility of sharing energy, data or computational power, provide services or transfer cargo, among others.

This paper does not intend to provide all the answers to how future mobility will operate, but rather contribute with a framework for future mobility based on current research and mobility trends. While the presented proposal borrows from current research, to the best of our knowledge, it is the first time that such concepts are integrated this way.

The remainder of the paper is organised as follows. Section 2 provides a description of the three key ingredients of the future that is proposed in this paper: system behaviour, bio-inspiration, and collaboration. Section 3 provides an overview of the fields of swarm-robotics and vehicle platooning, explaining how these concepts might be transferred to collaborative mobility as well as giving an outline of the potential benefits. Section 4 aims to convey our interpretation of the future mobility framework presented in this paper and how these concepts can be applied to the main urban mobility needs: the movement of people, movement of goods, and utility services. Finally, the main conclusions of this work are highlighted in Section 5.

2. Future mobility as a bio-inspired collaborative system

At the MIT Media Lab City Science group, we envision a future mobility in which shared, electric, and autonomous vehicles behave as a *bio-inspired collaborative system*. In this future, vehicles are regarded as parts of a system rather than as individual entities. Within the system, the relationships and interactions between vehicles are based on collaboration. We have named these interactions as *vehicle clustering*. When vehicles *cluster*, they connect either physically or virtually, which will enable the possibility of sharing energy, data or computational power, provide services or transfer cargo, among others.

This section describes the three key ingredients for this future: system behaviour, bio-inspiration, and collaboration.

2.1. System behaviour

Urban mobility is a complex system composed of many layers. If we think of commuting trips, mobility systems solve the need of transporting people to and from home to work in the city. However, people also travel for leisure, emergencies, or just to run errands. In addition to this, depending on their age and ability (e.g., children, elderly, or disabled), people have different mobility needs. Moreover, there is also the need

to transport goods, which can vary in shapes, sizes, and urgency levels. Goods are sometimes delivered between people, from a business to a person and vice versa, or between businesses. Lastly, urban mobility is also needed to fulfill utility services such as street cleaning, trash pickup, gardening, or infrastructure maintenance.

As expressed by Cascetta, "[Transportation systems] are, indeed, internally complex systems, made up of many elements influencing each other both directly and indirectly, often nonlinearly, and with many feedback cycles." (Cascetta, 2009, p. v). Due to the increasing complexity and dynamic nature of mobility, traditional planning falls short on the necessary flexibility and adaptability, and developing analytical optimization methods for transportation is no longer straightforward (Dorer & Calisti, 2005).

A successful design and planning of urban mobility require understanding all of its layers and their interactions. Therefore, mobility - and future mobility - should not be regarded from an individualistic point of view but rather as a system. All the vehicles that are part of the urban mobility landscape, companies, citizens, and the urban infrastructure are part of this collective system.

2.2. Bio-inspiration

The cardiovascular system is an excellent semantic figurative metaphor for urban mobility (Cruz, 2015), and metaphors can provide us of new ways of thinking about old problems. As described by Stefanovska and Bracic:

In the course of evolution, individual cells organised into cellular systems of increasing complexity... At this level of organization, cells were no longer capable of individually sustaining autonomous life. A collective system that provides and distributes oxygen and nutrient materials to each cell and takes away the products of their metabolism became essential... (Stefanovska, 1999, p. 31).

Similarly, as our cities become increasingly complex, individuals are no longer autonomous, and there is a need for a collective system, that in the case of cities, is urban mobility. This parallelism inspires us to think of urban mobility as a collective system instead of a group of agents that follow their own preferences and priorities.

Another interesting parallelism arises when analysing the goals of the cardiovascular system and urban mobility. The main goal of the cardiovascular system is to transport oxygen and metabolites through the body while collecting carbon dioxide and other wastes for removal (Quarteroni, Tuveri, & Veneziani, 2000). In urban mobility, there is also a need to transport people and goods and remove waste. However, in urban mobility, these tasks are carried out separately. The cardiovascular system inspires us to think of multi-functional systems that can perform these tasks simultaneously.

Moreover, insects that live in colonies, such as ants, termites or honeybees, or other animals such as fish, show a collective behaviour named natural swarms (Groß, Dorigo, & Yamakita, 2006). Natural swarms can divide tasks, cluster, build together, or transport cooperatively, among others (Bonabeau et al., 1999). Taking ants as an example, ants can coordinate in colonies of hundreds of thousands of members with only local tactile and chemical communication (Deneubourg, Goss, Franks, & Pasteels, 1989). In some ant species, ants can find the food sources that are closest to the nest, as well as finding the minimum path between the nest and the food as a combination of the actions of many ants (Bonabeau et al., 1999). Ants are also able to transport large prey collaboratively; when working together, ants can move 5,000 times the weight and 10,000 times the volume of a single ant (Hölldobler & Wilson, 1978) (Feinerman, Pinkoviezky, Gelblum, Fonio, & Gov, 2018). The African weaver ants (*Oecophylla*

longinoda) chain their bodies forming bridges over large gaps so that other ants can walk over (Hölldobler & Wilson, 1978). In the species *Pheidole*, colonies are formed by ants of two different sizes; the smaller ones take care of the most quotidian tasks such as brooding or cleaning the nest, while the larger ones are specialised in milling seeds or defending the nest among others (Bonabeau et al., 1999; Wilson, 1984).

Some of these behaviours have been adopted by the field of swarm robotics and, if we translate these concepts from the behaviour of ants into urban mobility, exciting ideas start to emerge. To name a few examples, large fleets of vehicles might be able to cooperate based on only local communication, vehicles might be able to find the shortest paths through collective behaviour without previous knowledge of the environment, vehicles might also be able to transport large objects collaboratively or specialise and divide tasks.

The reader will recognise some of these ideas throughout the remainder of the document; behaviours found in nature, such as those described in this section, have largely inspired some of the proposals presented in this paper.

2.3. Collaboration

Collaboration, the third ingredient in this proposal, aims to describe how future vehicles will interact in order to build a collective system. In the previous sections, there are examples of animals from the same species collaborating, such as ants coordinating to optimise foraging efforts (Bonabeau et al., 1999) or birds flocking to gain aerodynamic efficiency (Wallraff & Wallraff, 2005). This could be compared to vehicles belonging to the same owner collaborating, for example to create structures and reduce energy consumption (Alam, Gattami, & Johansson, 2010). Besides, we want to extend this concept to the collaboration of fleets of vehicles belonging to different owners, as well as belonging to different individuals, which would be the equivalent to considering animals from different species. This would enable all vehicles on the roads to be part of the same collaborative system, that could have the goal of increasing global efficiency.

Symbiosis, the term which encompasses these interactions in nature, is defined as "the living together of two or more organisms in close association" (Margulis, 1971, p. 49). The different types of symbiotic relationships are shown in Figure 1. Amongst all of them, mutualism is specially interesting, since it benefits both parts involved, making it an important incentive for agents to collaborate. The equivalent to symbiotic relationships, and more concretely mutualistic, are not new in human society; they have been part of social interactions since ancient times, when humans started to trade and exchange resources (Chertow, 2007). Throughout history, businesses have learnt how exchanging energy, materials or information can bring further benefits than those coming from the sum of each company acting alone (Chertow, 2000).

We would argue that current mobility is mainly based on competition or neutralism, which lie at the opposite side of the spectrum from win-win mutualistic relationships. The individualistic behaviours of drivers on the road – who mostly compete for their own interests – result in inefficient and unsafe conditions. We believe that transitioning from these interactions to mutualistic relationships that create benefit-benefit situations would radically transform urban mobility for the better.

While it can be intuitive to imagine vehicles from the same company collaborating as part of a system, it may be more challenging to imagine vehicles from different companies trying to build mutualistic relationships. However, industrial firms have already found ways to collaborate by means of the appropriate business models (Fraccascia,

Giannoccaro, & Albino, 2019), and we believe that this could also be the case in urban mobility. Based on these collaborative relationships, urban mobility would behave in a more similar way to a natural system that transports people and goods through the city in the most efficient and balanced way.

Figure 1. Diagram of the six possible types of symbiotic relationship, from mutual benefit to mutual harm, adapted from Ian Alexander (Alexander, 2018).

3. From swarms and platooning to future mobility

The concept of future mobility as a bio-inspired collaborative system combines, expands, and translates ideas from nature, swarm robotics, and vehicle platooning. Natural swarm behaviours have served as an inspiration for researchers in robotics, leading to the field of swarm robotics (Sahin, 2004). While the application is different from mobility, there are excellent examples of translating these behaviours from natural systems to artificial systems. In the field of mobility, research in vehicle platooning studies how vehicles can travel in coordination (Maiti et al., 2017) and thus can be seen as a first step towards collaborative mobility. However, our view of future mobility extends the possible interactions between vehicles from coordination to various ways of collaboration.

This section explains how some of the concepts of swarm robotics might be transferred into the field of mobility and combined with vehicle platooning. Therefore, the potential benefits would include those of swarm robotics and vehicle platooning among others. This section also explains how the concepts from vehicle platooning can be extended to micro-mobility systems and heterogeneous mixes of vehicles. In doing so, it provides details on the characteristics of the future mobility proposed in this paper, as well as some of its potential benefits.

3.1. From swarm robotics to mobility

The 'swarm' concept in the context of robotics is applied for the first time by Fukuda et al. (Fukuda & Nakagawa, 1988) and G. Beni (Beni, 1988) in 1988. Fukuda studies how to design a robotic system that, having an intelligence analogous to the biological gene, would be able to dynamically reorganise its shape and structure for a given task by employing limited available resources (Fukuda & Nakagawa, 1988). G. Beni,

instead, defines what he named as Cellular Robotic System (CRS).

The systems considered consist of a large (but finite) number of relatively simple robotic units capable of accomplishing, collectively, relatively complex tasks. ... The system formed by the autonomous robotic units (called Cellular Robotic System or CRS) is characterised by its reliability and its ability to self-organise and self-repair. (Beni, 1988, p. 57).

In 1993, G. Beni and J. Wang (Beni & Wang, 1993) argued the unpredictability in the behaviour of systems that are capable of producing order can result in a non-trivial, different form of intelligence, which was named as 'swarm intelligence'. Swarm intelligence is a form of artificial intelligence inspired by insect colonies, emerging from the collective association of individual agents behaving in a way that goes beyond the aggregation of the individual capabilities of each agent (Innocente & Grasso, 2019).

Swarm robotics implements swarm intelligence to multi-robot systems (Innocente & Grasso, 2019). Trying to emulate the natural behaviour of social insects, researchers have pursued imitating behaviours like foraging, flocking, sorting, stigmergy, or cooperation (Groß et al., 2006). These behaviours enable social insects to guide themselves individually and without any reference to a global pattern, using only local information to make decisions (Groß, O'Grady, Christensen, Dorigo, & Kernbach, 2013). Based on the same principle, swarm robotics aim to construct robust, flexible, and scalable systems by using simple robots and local interactions (Groß, Bonani, Mondada, & Dorigo, 2005).

Swarm robots are characterised by some interesting properties, defined by G. Beni (Beni, 2004) and completed by others (Sahin, 2004; Tan & Zheng, 2013; Zakiev, Tsoy, & Magid, 2018a). As will be discussed in the next sections, we believe that most of these characteristics remain of interest when applied to urban mobility systems:

3.1.1. Robustness

The number of elements is large enough to provide redundancy and robustness. That way, swarms can continue working even after the failure of some individuals (Beni, 2004). Robustness is also fundamental in transportation. Numerous studies have shown the relevance of reliability in mobility mode choice behaviour (Carrion & Levinson, 2012; Cherif, Senouci, & Ducourthial, 2009). It has been shown that unreliability results in a negative effect in mode choice for commute trips, even for those who have flexible work schedules (Bhat & Sardesai, 2006). In addition, in the event of disasters, transportation provides access to emergency supplies and services (Al-Deek & Emam, 2006) and it is also critical in order to restore other services such as water, electricity, or communications (Du & Nicholson, 1997).

3.1.2. Flexibility

Robotic swarms act as a massive parallel computing system that, being able to create various solutions through task division between robots (Cheraghi, Shahzad, & Graffi, 2021), can carry out more complex tasks than the individual itself (Tan & Zheng, 2013). This improves efficiency and performance in task completion as compared to single robotic systems (Arkin, 1998). Task division provides either optimization eliminating redundant efforts or extra security through redundancy (Sahin, 2004). For instance, a cluster of autonomous vehicles traveling together can share the navigation tasks required for autonomous driving (e.g., localization, obstacle detection, path planning), provide redundancy in the tasks that are more critical, or enable the vehicles to increase

their performance thanks to the combined computational and physical capabilities.

3.1.3. Local Interactions

As mentioned in (Zakiev et al., 2018a), inter-robot communications and sensing are limited to be only local. This property is directly inherited from natural swarms, which heavily rely on local interactions for cooperation (Tan & Zheng, 2013). Their local interactions lead to some other properties such as scalability, flexibility, and robustness (Brambilla, Ferrante, Birattari, & Dorigo, 2012). In addition to these benefits, as a system based on local interactions, it could dynamically adapt to different fleet sizes without any change in the software or hardware, which is very relevant for real-world applications (Tan & Zheng, 2013) such as urban mobility.

3.1.4. Self-Organization

In the same way that biological swarms self-organise into patterns, robotic swarms show intelligence by producing ordered structures in an unpredictable way (Beni, 2004; Brambilla et al., 2012). Self-organization could be a good solution for some challenges inherent to vehicle networks such as high mobility, large scale, and network partitioning (Cherif et al., 2009).

3.1.5. Scalability

Thanks to local interactions and self-organization, robotic swarms could theoretically count on an unlimited number of members (Zakiev, Tsoy, & Magid, 2018b). In practice, robotic swarms could be composed of thousands, or even millions of units (Beni, 2004). While clusters of vehicles might be formed by a smaller number of vehicles, collaborative systems of two or a few agents could already show many of the characteristics and potential benefits seen in larger swarms, such as task division, decentralization, or local interactions (Dorigo et al., 2013). In mobility, scalability would make the system able to handle different numbers of vehicles without altering the performance (Ashraf, Bilal, Khan, & Ahmad, 2016).

3.1.6. Decentralization

Robots act by themselves when performing tasks with a distributed control topology and, consequently, any swarm member can make decisions independently (Tan & Zheng, 2013). In connected mobility, decentralization can be critical to increase security and robustness, decreasing delays in communication, and solving the problem of a single node failure, as has been proved in research about network topologies (Dorri, Kanhere, & Jurdak, 2016). Decentralization could also improve scalability; having self-coordinating agents without a centralised communication allows having a greater number of agents (Innocente & Grasso, 2019).

3.1.7. Simplicity

Simplicity has been defined as agents having a limited capability relative to the global task (Innocente & Grasso, 2019). Additionally, the robots are usually quasi-identical, which allows for standardization and cost efficiency (Sahin, 2004). Autonomous vehicles might be less simple and more capable relative to the task than swarm robots. With more intelligent vehicles, as long as scalability is maintained (Sahin, 2004), we

believe that fewer vehicles might be needed to benefit from collaboration.

In light of the above, there seems to be great potential in extending these concepts from swarm systems to mobility. Synergies created in a collaborative mobility ecosystem would bring human behaviour closer to natural systems, which have been developed for millions of years and are clear evidence of the power of collaboration (Ahmed & Glasgow, 2012).

3.2. From vehicle platooning to collaboration

Autonomous vehicles can communicate with other vehicles, humans, and the infrastructure and have the intelligence to make decisions based on this communication (Harding et al., 2014). These communication skills open the possibility for autonomous vehicles to a more cooperative way of acting, giving birth to concepts as vehicle platooning (Kavathekar & Chen, 2011). Maiti et al. define vehicle platooning as a closely following mechanism that allows vehicles to travel in a coordinated way, without any mechanical linkage, while maintaining a safety distance (Maiti et al., 2017).

The concept of vehicle platooning has its origins in the 1960's (Hanson, 1966). It started to gain attention when, in 1995, a research report related to the California PATH project showed promising results related to drag force reduction (Zabat, Stabile, Farascaroli, & Browand, 1995). One of the most striking early demonstrations of these concepts took place in the 2011 Grand Cooperative Driving Challenge (GCDC) (Ploeg, Shladover, Nijmeijer, & Wouw, 2012), where there was a demonstration of a number of vehicles dynamically cooperating both in urban and highway scenarios.

Vehicle platooning has three fundamental elements: Vehicle to Vehicle (V2V) communication, distributed control, and Vehicle to Infrastructure (V2I) communication. V2V communication was early shown in 1997 at the National Automated Highway System Consortium (NAHSC) (Shladover, 2006). In this event, the PATH research showed an eight-car automated platoon based on V2V communication (Shladover, 2006). Among other concepts and technologies, they also demonstrated the few resources needed for vehicles to coordinate (Bergenheim, Shladover, Coelingh, Englund, & Tsugawa, 2012). Distributed control proposes a framework for creating a robust system that also decreases the control required downstream in the platoon (Alam, 2011). The main underlying idea is that each vehicle decides how to act, based on not only on-board sensors but also on the information received via V2V communications (Bergenheim et al., 2012). Finally, V2I communications provide a solution for vehicles to interact with the infrastructure in a variety of scenarios such as finding a charging spot, navigating to attach to a platoon, and many others (Bergenheim, 2010).

Platooning has multiple potential benefits, some of which are summarised in this section. Provided that we see platooning (i.e., coordinated travel) as a first step towards collaboration, the benefits of collaboration would also include the benefits of platooning. Even if platooning research has mainly focused on heavy vehicles, extending this concept for lighter vehicles could lead to similar benefits (Shladover, 2006).

3.2.1. Fuel Consumption

The main research line in vehicle platooning is related to heavy vehicles due to direct benefits in fuel consumption associated with drag reductions (Alam, 2011; Tsugawa, Kato, & Aoki, 2011). Drag reductions lead to environmental and financial gains, which is very relevant as fuel is the highest cost for a heavy vehicle fleet owner (Bergenheim et al., 2012). For example, Assad Alam et al. (Alam et al., 2010) show a fuel consumption

study for a platoon of heavy-duty vehicles. This research estimates that thanks to air drag reduction and suitable automatic control, two vehicles with a constant speed of 70 km/h could reduce: 4.7-7.7% of fuel consumption if the vehicles are identical, 3.8-7.4% if the lead vehicle is 10t lighter, and 4.3-6.9% if the lead vehicle is 10t heavier.

3.2.2. Traffic flow efficiency

Traffic flow efficiency is characterised by macro parameters that determine the number of vehicles moving and their speeds (Darbha & Rajagopal, 1998). The quantitative strategy to increase efficiency in traffic flow determined in (Darbha & Rajagopal, 1998) proposes an Intelligent Cruise Control System (ICC) based on velocity and space regulation that eases traffic congestion. Michael et al. (Michael, Godbole, Lygeros, & Sengupta, 1998) quantified the increase in traffic flow efficiency, concluding that platoons formed by up to ten light-duty passenger vehicles could double or even triple highway capacity. However, there are some limitations and requirements for vehicle platooning; for instance, cooperative control strategies require a substantial number of vehicles and are especially beneficial in conditions of high traffic volume (Arem, Driel, & Visser, 2006).

3.2.3. Safety

Among all traffic accidents, human error is involved in 50% to 90% of them (Peters & Peters, 2002), and it is predicted that autonomous vehicle platooning will contribute to road safety (Axelsson, 2017). One of the systems that have been proposed to improve driving safety is Cooperative Adaptive Cruise Control (CAAC), a system in which vehicles constantly communicate and measure distances to their predecessors (Arem et al., 2006). CAAC will be complemented with low-cost, high-performance distance sensors to implement active and predictive safety systems that are under development (Xiao & Gao, 2010).

Our proposal for future mobility takes vehicle platooning as a first step towards collaboration; by integrating concepts from swarms, we envision that, when vehicles cluster as proposed in this paper, the collaboration possibilities between vehicles will be much richer than simply communicating to coordinate.

Another key difference lies in how the platoons would be formed. While most platooning research considers centralised planning approaches, it has been argued that platoons might be formed ad hoc between drivers who do not necessarily know each other (Khan & Boloni, 2005). We imagine that other types of collaboration between vehicles would also happen spontaneously and without previous planning, based on local interactions.

Lastly, while most platooning research considers that all the agents are identical or at least very similar (Alam et al., 2010), we believe that collaboration will happen between vehicles of different types and sizes -including micro-mobility solutions- forming heterogeneous clusters. Some vehicles could have specific duties such as charging vehicles or maintenance vehicles that could provide services to other vehicles. Some vehicles could also have a higher level of autonomy than others; for instance, vehicles with outdoor driving capabilities could guide vehicles that can only navigate indoors from one building to another. Taking this idea even a step further, collaboration could happen between autonomous and non-autonomous vehicles; autonomous vehicles could guide and "share" intelligence with non-autonomous vehicles.

Our proposal for future mobility builds on top of the research in vehicle platooning

by bringing concepts from swarm robotics that expand interactions between vehicles from communication to a much larger and richer set of interactions that imitate the behaviour found in natural swarms. Consequently, the potential benefits would include those of swarm robotics and vehicle platooning, among others. In addition to expanding the possible interactions between vehicles, this proposal introduces the possibility of collaborating across scales and vehicle types.

4. Evolving towards this future

The previous sections have provided a definition and a framework for future mobility mainly from the perspective of an academic contribution. We have defined our view of a *bio-inspired collaborative system*, as well as the interactions between vehicles in this future, which we have named as vehicle *clustering*. This section aims to convey our interpretation of this framework by including how we imagine that these concepts can be applied to the main urban mobility needs - the movement of people, the movement of goods, and utility services - showing some of the benefits that the system proposed in this paper could bring in addition to the benefits inherited from vehicle platooning and swarms.

4.1. Movement of people

Traditional transport is not well suited to provide coverage of all regions, mobility needs, and population groups in an efficient and affordable way (Papanikolaou, Basbas, Mintsis, & Taxiltaris, 2017). To solve this issue, demand-responsive transport (DRT) has been regarded as an alternative to conventional services such as buses and taxis for more than three decades (Mageean & Nelson, 2003). The main goal of DRT is to provide an efficient solution by combining the capacity of regular fixed transport services with the flexibility of on-demand services (Papanikolaou et al., 2017).

In terms of on-demand services, the introduction of vehicle sharing has led to solutions such as Uber and Lyft, and it is expected that these systems will further evolve into autonomous on-demand services (Pavone, Smith, Frazzoli, & Rus, 2012). However, we believe that the aforementioned mobility-on-demand services have not yet achieved the goal of DRT of combining the flexibility of on-demand services with the capacity of traditional transport; while they do provide great flexibility, they are still very limited in terms of capacity.

Another very relevant proposal in the field of urban mobility in recent years is the concept of Mobility as a Service (MaaS) (Jittrapirom et al., 2017). MaaS proposes shifting from an ownership-based model to an access-based model by offering customised multi-modal mobility packages through an integrated interface that provides services such as trip planning, reservations, and payment (Nikitas, Michalakopoulou, Njoya, & Karampatzakis, 2020). One of the central aspects of MaaS is to provide a 'seamless' experience for multi-modal transportation (Chowdhury & Ceder, 2016).

In the framework of mobility as a bio-inspired collaborative system, the movement of people could occur as follows. Vehicles that shared some path could cluster for part of their trip and collaborate by, for instance, sharing battery, data, or computational power. Being a distributed collaborative system, this future way of moving people would also inherit the benefits of swarm systems such as flexibility, scalability, or robustness. Thanks to reduced aerodynamic drag forces, vehicles could save energy or travel faster, similarly to vehicle platoons (Tsugawa et al., 2011). Then, when their

paths diverged, vehicles would simply detach and continue on their own.

Such a system could simultaneously offer the advantages of MaaS and mobility on-demand. Clustering individual mobility modes with other vehicles could create a seamless connection between a single-person mobility mode and a new collective transportation method. The commuting experience would be seamless in a much higher degree than in MaaS, since there would be no need for intermodality, and therefore, of transitioning between mobility modes.

In addition, the way that this collective transportation would be generated is intrinsically demand-responsive since it would organically appear where vehicles are, as opposed to fixed-schedule and fixed-route services. As a demand-responsive solution for collective transportation, it could address the yet unmet goal of DRT of combining the flexibility of on-demand services with the capacity of traditional systems.

Figure 2. Trip length coverage of different mobility modes including autonomous personal mobility devices (PMDs) and autonomous pods, illustrating how clustering could extend the trip lengths covered. Adapted from (Curran, 2008)

For example, if we look at the characteristics of the trips that would be covered by new mobility systems such as autonomous personal mobility devices (PMDs) and autonomous pods in Figure 2, PMDs would provide a service in between shared bikes and private bikes and autonomous pods, instead, would provide a service in between transit, taxis, and private vehicles. However, these systems are limited in capacity and the trip lengths that they cover.

Clustering could extend the trip lengths that vehicles serve, as well as their capacity, due to the clustering of many vehicles, while maintaining the price in the same range, potentially even covering all the trip lengths in a city. As a consequence, clusters of vehicles would provide a service that is more flexible than public transportation, without the need of heavy infrastructure, and with a capacity that is higher than the one offered by PMDs, which are single-person vehicles, and pods, which are typically four- or six-seaters.

Moreover, it could help to reduce the use of private cars. Since the introduction of the automobile, cities have been designed for cars and no longer for humans; at the City Science group, we envision future cities to shift back to a human scale, putting people - and not cars - at the centre of urban design (President’s Council of Advisors on Science and Technology, 2016).

There are many other possibilities that would be enabled by vehicle clustering in a collaborative system. For example, clusters could be heterogeneous; some vehicles

could have specialised tasks such as charging the vehicles, doing maintenance operations, or providing services to the passengers such as in-transit food or beverages. Additionally, clustering could also provide a way for travelling in groups of family or friends using micro-mobility systems even when sharing just part of the trip and even if each person preferred to use different vehicles.

All in all, a future in which vehicles would behave as a collaborative system would offer a mobility solution that combines the convenience of door-to-door transportation with the efficiency of mass transit.

4.2. Movement of goods

Freight transport is an important source of economic growth and, at the same time, responsible for a substantial amount of CO2 emissions, traffic congestion, and road accidents (M. Piecyk & McKinnon, 2010). While it has been demonstrated that longer trailers lead to fuel savings and increased efficiency, platooning can offer similar advantages with smaller trucks (Elbert, Knigge, & Friedrich, 2020). Similarly, clusters of even smaller vehicles could replace trucks or trailers for goods delivery.

A cluster of smaller vehicles provides much greater flexibility than fixed-sized trucks. The capacity could be adapted to the need at each moment by just having more or fewer units, consequently optimizing resources (Wang & Kopfer, 2014). For example, instead of having a truck deliver the cargo from the central warehouse to smaller warehouses, a van to transport it to a neighborhood scale, and a delivery person with a cart for the last metres, the entire process could be served by the same vehicles. These smaller vehicles would be clustered in a big number to move cargo in the metropolitan or even inter-metropolitan scale, then divide in smaller clusters to travel in the intrametropolitan scale, and finally separate into individual vehicles for the last-mile delivery in the neighborhood scale. The use of smaller vehicles could reduce fatalities since collisions with trucks are especially deadly (George, Athanasios, & George, 2017). Moreover, these smaller vehicles would provide the necessary agility for narrow streets with limited accessibility and maneuvering space, solving one of the most common issues of last-mile delivery (Alessandrini, Campagna, Delle Site, Filippi, & Persia, 2015).

In the case of different logistic agents collaborating, collaborative transport (CT) is a field that has already attracted a lot of research interest (Pan, Trentesaux, Ballot, & Huang, 2019). Understood as the collaboration between companies to optimise the global supply chain network to reduce costs (Gonzalez-Feliu & Salanova, 2012), CT it is considered to be a very efficient approach to make transport more efficient and improve problems such as CO2 emissions or congestion (M. I. Piecyk & McKinnon, 2010). In this context, collaboration is not only a new way of moving goods based on short-term partnership for operations management, but also a way for establishing long-term commercial strategies (Pan et al., 2019) that can lead to new business models (Chan & Zhang, 2010). Two main types of CT have been proposed so far: vertical collaborative transport (VCT), where partners serve distinct parts of the network (e.g., first leg of the city covered by conventional trucks from one company and last mile by vans from another company) and horizontal collaborative transport (HCT), in which partners cover the same - or at least overlapping - segments of the supply chain (e.g., two van companies working together in the same section of the supply chain, sharing orders and infrastructure) (Cleophas, Cottrill, Ehmke, & Tierney, 2019).

Clustering can be an interesting complement for both types of CT. Thanks to the

flexibility in capacity, vehicle clustering could extend the possibilities of creating HCT models that simultaneously cover more segments of the supply chain. These additional possibilities, combined with the increased efficiency of collaboration between vehicles proposed in this paper, would bring these systems closer to the maximum achievable global efficiency in logistics, which is the main objective in collaborative transport (Pan et al., 2019). In terms of privacy, CT needs to ensure the protection of companies’ sensitive information and decision-making competencies (Wang & Kopfer, 2014). As clustering would have decentralised planning, it could work even with limited exchange of information (Elbert et al., 2020) and, therefore, comply with the privacy protection requirements of CT. In addition, clustering with physical attachment could allow vehicles to transfer cargo on the go, opening up another great set of opportunities in the design of collaborative transportation systems.

The resulting system would be composed of small and agile vehicles which, together, could have enough loading capacity to cover the city’s needs substituting heavy vehicles that, in addition to their lack of flexibility and maneuverability, pose a threat to pedestrians.

4.3. Utility services

Due to the increasing speed at which cities grow, the management of utility services is becoming increasingly important (Zhang et al., 2014). In fact, it is estimated that the global investment needed in infrastructure will be 3.7 trillion USD per year through 2035, and 1 trillion USD per year more to meet the United Nations Sustainable Development Goals (Woetzel, Garemo, Mischke, Kamra, & Palter, 2017). This indicates very clearly the need for rethinking urban infrastructure, and, therefore, how utility services are carried out.

Currently, companies are developing autonomous robots for utility services such as surveillance, snow removal, and gardening (e.g., SMP Security robot, Snowbot, Yardroid). We believe that, in the future, swarm systems of these smaller robots will complete utility services collaboratively and replace traditional approaches such as large trucks or vans.

Taking waste collection as an example, the City Science group has participated in a research simulating a fleet of lightweight autonomous tricycles behaving like a swarm system that picked up the trash in the area of Kendall, Cambridge (USA) (Alfeo et al., 2019). The vehicles modeled in the simulation were Persuasive Electric Vehicles (PEVs) (Yao, 2019). The PEV is an autonomous tricycle developed by the City Science group that aims to provide a lightweight solution for the delivery of people and goods. In this case, the PEV was modeled to be carrying waste from trash bins on the street to a central deposit. The PEVs worked as a bio-inspired swarm, using methods such as multi-place foraging and stigmergy, with pheromones saved in RFID tags located at road intersections. The study showed that this self-organised system outperformed the current approach that uses traditional garbage trucks, reducing both the average amount of trash on the trash bins and the average number of full trash bins.

We believe that the same approach could be applied for other utility services, replacing traditional systems with fleets of smaller vehicles that would provide a more efficient service by working collaboratively.

These sections present the potential benefits that clustering could bring into solving the problems of transporting people and goods and doing utility services. However, these functions should necessarily be separated. Having lightweight electric vehicles

that could transport people and goods at the same time has already been proposed for the PEV (Yao, 2019). Additionally, in (Alfeo et al., 2019) the PEVs are proposed for garbage collection. In a similar way to how the cardiovascular system transports oxygen and metabolites while removing waste (Quarteroni et al., 2000), we believe that multi-functional vehicles will be essential for efficient transport. Today cars are stationary during 95% of their lifetime (Hudda et al., 2013) and, while it is estimated that sharing and autonomy will increase vehicle utilization rates, there will still be a representative percentage of the time (up to 50% or more) when the vehicles are not in use (Vosooghi, Puchinger, Jankovic, & Vouillon, 2019). During these periods, vehicles could be used for other purposes such as transporting goods or doing utility services, which could further increase the efficiency in the use of the vehicles and, consequently, reduce the number of vehicles in the streets.

5. Conclusions

In the current trend towards sharing, electrification, and autonomy, little attention is being paid to what will come after these trends are settled, specially from the perspective of interactions between vehicles and how these interactions might affect the system-level behaviour.

This paper proposes a future in which urban mobility works as a bio-inspired collaborative system of shared, electric, and autonomous vehicles. Mobility is an increasingly complex system, and, in nature, there are various examples of complex systems with similarities to mobility that have evolved to be collaborative. Collaboration brings benefits that could never be achieved with an individualistic behaviour.

This proposal combines, expands, and translates ideas from nature, swarm robotics, and vehicle platooning. Research in swarm robotics has demonstrated the potential benefits of translating these natural behaviours into artificial systems. It studies how self-organised agents collaborating with local interactions in a decentralised manner can lead to robust, scalable, and flexible systems. The collective capabilities of swarms exceed by far the aggregation of the individual abilities of each agent. Moreover, there is also research in platooning demonstrating how coordination between vehicles can lead to more efficient traffic, reduced energy consumption, and increased safety. While we imagine a future in which the interaction between vehicles is much richer than communicating to coordinate, vehicle platooning can be seen as a first step towards collaboration.

Therefore, expanding vehicle platooning by combining and translating ideas found in nature and swarm robotics, this paper proposes a future mobility based on three key ingredients: system behaviour, bio-inspiration, and collaboration. In this future, vehicles will be able to cluster by connecting either physically or virtually, which will enable the possibility of sharing energy, data, or computational power, provide services or transfer cargo, among others.

In addition to inheriting the benefits of vehicle platooning and swarms, this proposal can radically transform the way cities address the three main mobility needs: the movement of people, movement of goods, and utility services. When moving people, clusters of vehicles will allow for individual vehicles to attach to other vehicles, creating a seamless connection between single-person mobility modes and a new way of collective transportation. Vehicle clustering would also extend the trip lengths that are covered by each vehicle, as well as increasing capacity and adding flexibility. This will provide a responsive solution to cover the many different mobility needs, combin-

ing the convenience of door-to-door transportation with the efficiency of mass transit. Regarding the movement of goods, trucks and trailers will be replaced by smaller vehicles that collaborate in clusters that will cover a wide range of trip distances. Vehicles will be able to attach and detach from the cluster on the go, dynamically adapting the cluster's capacity. This will create a versatile system where clusters of vehicles will collaborate and dynamically adapt their size, acting either as a single and agile lightweight vehicle or as a cluster of many vehicles substituting a truck, which would improve the efficiency in every segment of the supply chain. Finally, utility services will also be performed by smaller vehicles which, through collaboration, will provide a much more responsive and efficient system than traditional solutions.

All in all, thinking of urban mobility as a bio-inspired collaborative system of shared, electric, and autonomous vehicles could revolutionise transportation. This contribution opens many new paths for future research that we will continue to pursue at the City Science group, further defining the details of how this future could work.

The presented concepts will be validated through simulations, prototypes, and, potentially, real-world testing. The framework proposed in this paper points towards a future in which mobility would work more similarly to how natural systems behave. Since natural processes have been tailored by millions of years of evolution, natural systems are more efficient, sustainable, and resilient, which are characteristics that we want our future transportation systems to have.

Disclosure statement

No potential competing interest was reported by the authors.

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