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The seventh transport revolution and the new challenges for sustainable mobility

Ennio Cascetta [a], Ilaria Henke [b,*]

[a] Universitas Mercatorum, Italy
[b] University of Naples "Federico II", Italy

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ABSTRACT

Over the course of history there have been several and significant changes in the methods and technologies used to move people and things. Innovations typically follow the distributive and social needs of their time but in some cases they drive or at least contribute to the social and economic evolution of human communities. The paper is based on the hypothesis that transport system innovations occur with different speeds and have impacts of different magnitude in different historical moments. Changes can thus be classified as revolutions or as evolutions depending on weather they (contribute to) change societal, economic and/or territorial systems in a relatively short time period or not. In this paper, analysing the history of humanity, six transport revolutions and several evolutions following over time have been identified, extending and re-defining the ideas of Gilbert and Pearl (2010). We suggest that transportation systems are undergoing a seventh revolutionary phase due to the combined effects of three main drivers. These are innovations in energy sources and their transmission, developments of connected and autonomous vehicles for all transportation modes, and new smart mobility services. As for past revolutions it's impossible anticipate the extent of change it will bring about, both in the transportation market and in society at large. According to the "law of unintended consequences" of previous revolutions, the combined effects of the three drivers will likely further amplify the scope of possible changes. These changes can have positive, neutral or negative effects on short to medium term for environmental, social and economic sustainability of freights and passengers transportation. The paper starts with a synthetic description of previous transport revolutions, as proposed by the Authors. The main elements of the seventh transport revolution are then discussed together with some possible interactions among them. Finally the paper analyses some opportunities and risks connected to the ongoing innovation with respect to environmental, social ed economic sustainability. The perception of the current time as a revolutionary phase should change the approach of researchers and practitioners in the wide field of transportation system analysis with respect to the last evolutionary decades. Future research, in addition to sector specific evolutions, should focus on the actual holistic deployment of the seventh revolution trying to continuously update its combined effects and anticipate as much as possible its trajectory in order to reduce undesirable ones while boasting desirable ones. Future transport policies, especially in urban areas, will have to take into account the opportunities and risks deriving from the ongoing transport revolution as well as the resulting level of uncertainty.

1. Introduction

Over the course of history there have been numerous and significant changes in the technologies and their use to move people and things. Methods and technologies follow the distributive needs and economies of their time but frequently also drive or at least contribute to the social and economic evolution of human communities. In the pre-industrial age, transport modes were functional to an agricultural economy based on local production and consumption with limited long range commerce. Progress in agriculture, industrialization and the consequent increase in medium and long-distance traffic led to the need for faster and cheaper transport modes.

The analysis proposed in this paper is based on the hypothesis that innovations in transport systems take place at different speeds and have impacts of different magnitude in different historical moments, similar to what is assumed in the so-called punctuated equilibria theory of

* Corresponding author.
E-mail address: ilaria.henke@unina.it (I. Henke).

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evolution of the species (Gould & Eldredge, 1977) or the theory of scientific revolutions (Kuhn, 1970). Innovations in transportation systems include changes in traction power sources and vehicles, infrastructures, and service organization, all which may bring about significant changes in the availability of transportation services in space and/ or time, reliability, commercial speed and costs.

Changes can be classified as revolutions or evolutions. Generalizing the definition proposed in the literature (Gilbert & Pearl, 2010), a transport revolution can be defined as innovations in transportation systems that produce and/or allow significant societal changes, occur in a limited time span with respect to the previous evolutionary period and give rise to subsequent evolutions over an extended period of time. Societal changes can be relative to dimension and structure of human settlements, tradable goods and routes, production and distribution of goods, personal and societal lifestyles, and the physical environment. Technology innovations, however large, alone are not enough to be considered revolutions. To qualify as a revolution, the adoption of new technology should significantly modify one or more fundamental transport parameters (such as speed, cost, power, availability, etc.) in such a way as to significantly change the travel characteristics/ performance and/or create new mobility needs/markets, in a relatively short period of time.

In the literature, some authors see the possibility that ongoing innovations can significantly impact society at large, (e.g. Cugurullo et al., 2021, Gaio & Cugurullo, 2022) while others recognize the historical nature of revolutionary innovations but see the ongoing one as driven only by the change in energetic vectors (Gilbert & Pearl, 2010).

Taking into account the definitions of revolution and evolution in the first part of this paper, six transport revolutions that have occurred over the course of human history, followed by evolutionary phases are proposed (Section 2). The main contribution of this first part is in the identification of six revolutionary transport innovations occurred in history as well as some elements common to the phases of "revolutionary innovation" that can be useful for understanding what may happen in the near future. In Section 3 the three main transport technological innovations, that could lead to a seventh revolution, will be analysed. Decarbonization of traction energy, autonomous guidance of vehicles and smart mobility services are currently being developed together with some interactions among them. The system-level changes that will follow from the seventh revolution can have positive, neutral or negative effects on short to medium term for environmental, social and economic sustainability of freights and passengers transportation. These effects, however unpredictable in the long term, are discussed, as far as we can anticipate, in Section 4 while Section 5 draws some conclusions and propose some further research themes.

The original contribution of this paper is twofold. One is putting the set of disruptive changes in a historical perspective, thus anticipating some possible features of past revolutions, namely the unintended consequences and super additivity, both increasing the uncertainty about the effects of the current one. The other is recognizing that there are at least three divers of the potential current revolution with their multiple interactions defining what is going to be the possible mobility of the future and that they are opportunities but also risks for what will be sustainable development.

2. The first six revolutions

Our species, the "homo sapiens", evolved in Africa around 250,000 years ago and until the end of the last glaciation (about 10,000 years ago), only moved by foot in groups of tens or hundreds of hunter-gatherer individuals (Harari, 2014). For a long time, despite many evolutions in the technologies of production of tools, weapons and artifacts, nothing changed in relation to their mobility. Homo sapiens literally walked out of Africa and reached all major landmasses over several millennia. In the last Eocene era the so-called agricultural revolution took place, apparently in three different areas of the world, and this set up a number of changes in the way men moved themselves and their goods. These transport innovations can be classified as revolutions or evolutions as defined in Section 1. We argue that in the course of human history six transport revolutions took place as shown in Fig. 1 each revolution gave rise to subsequent evolutions that in some cases are continuing to our days.

The first revolution started around the year 8000 b.C. (Fig. 1) when animals were domesticated and there is a transition from human traction to animal traction. Persons and goods were moved using animals as the source of traction power. Animal traction allowed the expansion of cultivated land, the transport for produces and the first urban agglomerations. The following evolutions are related to the expansion of the number of domesticated animals suitable for traction.

The second revolution can be documented from 4000 b.C. when the first Egyptian papyrus sailing boats were represented. This is the first technology innovation that uses a traction force other than the muscular, allowing longer and faster trips. Sail evolutions took place over centuries improving their performances (e.g.their ability to go upwind) until the second half of the 19th century when steamships take over and there is the beginning of what will be the rapid decline of commercial sailing. Sailing ships allowed travel over extended sea and river distances, allowing the exchange of people and goods, as well as the birth of Mediterranean civilizations. Sails are still evolving for sporting and are facing a possible come-back to reduce CO_2 emissions also for commercial use.

In 3500 b.C. in Mesopotamia, the Sumerians started the third revolution by inventing the wheel thus substantially reducing the traction effort needed to move the same weight on land. Since then, wheels became increasingly differentiated and allowed the introduction of new transport modes. The wagon was the first wheel-based transport mode as documented in Mesopotamia from the 4th mill. b.C. (Enciclopedia Zanichelli, 1995). The combination of wagon and animals has evolved over the millennia allowing land transportation over extended distances starting the growth of cities and other larger and larger polities. Among the evolutions relating to the wheel, it is worth mentioning the introduction of two-wheeled vehicles with human traction force in 1791. The "celerifero" was invented in France, evolving to the modern (muscular) bicycle.

It is interesting to note that from the dawn of civilization until the beginning of the nineteenth century, humans have used successive evolutions of the same three technologies. For about 5000 years, while cities, social rules, writing, mathematics, philosophy, physics, literature, printing, guns and steal (Diamond & Ordunio, 2001) were introduced and developed, people continued to move with animal-drawn wagons and sailing boats and ships like their ancestors of the early Mesopotamian civilizations. The fourth transport revolution started during the first decades of the19th century the steam engine was invented to increase the productivity of mechanical looms at the dawn of the first industrial revolution, soon it was used to tow trolleys of material extracted from coal mines. In 1804 the locomotive train suitable for transporting goods and travellers, appeared (Burton, 2000). In 1807, the first steamboat invented by James Watt, sailed along the Hudson River (Brown, 1991). The steam engine introduced chemical energy from coal combustion, a new energy source w.r.t. muscular and wind energy. This greatly increased the traction power and therefore the speed of land and sea transport and, consequently changed the relations between cities, ports and countries. The steam engine revolution brought about a series of evolutions, for example the steam engine trains have gone from a 3 km/h speed (with the first steam locomotive, invented by the English R. Trevithick, in 1804 capable of carrying 70 people and 10 tons of iron) at a speed of 175 km/h (German locomotive, in 1936) (Bergsteiner, 2005). The development of steam railways and ships allowed the extension of cities, the growth of industry, the beginning of transoceanic personal travel and stronger land and sea commercial routes. The diffusion of electricity has certainly revolutionized very important sectors of society such as communications (telegraph, telephone, radio, etc.) but its

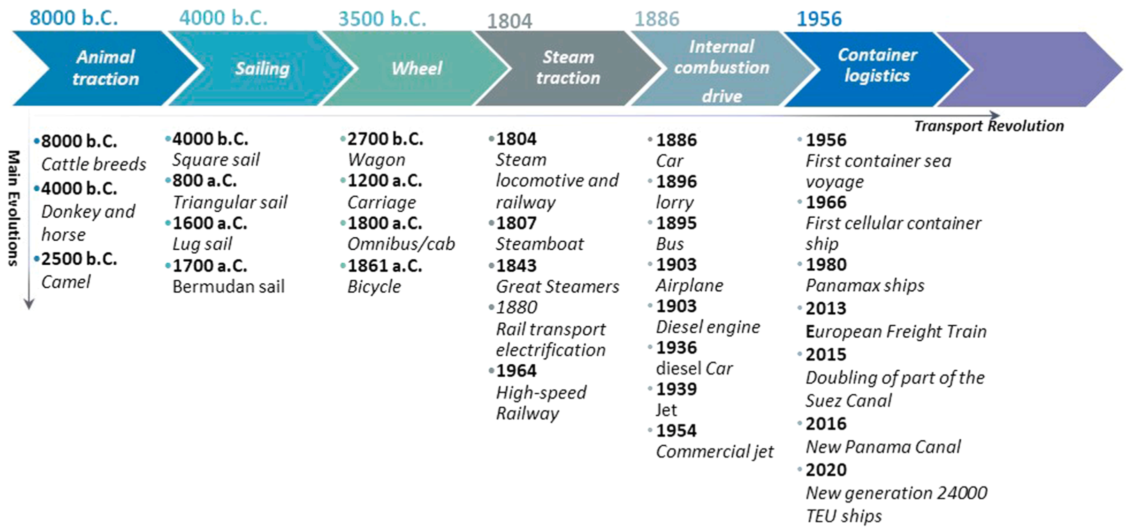

Fig. 1. The first six revolution and their main evolutions (sources: elaboration starting Cascetta et al., 2021b).

application to electric traction does not meet the definition of revolution proposed in this paper. Functionally, electric trains did not provide significantly different performances from steam trains and the two traction energy production technologies coexisted for many decades and still coexist with internal combustion rail traction. Among the most significant evolutions of electric railway is the development of High Speed Railways that started in Japan in the '60 s (Cascetta et al., 2020).

The fifth revolution started in 1886 with the invention of internal combustion engine (ICE). The internal combustion engine, which generates motion power by the chemical energy produced by the controlled explosion of air and refined petrol blends, allowed the development of innovative transport means due to the high energy content for unit weight of refined oil. The availability of engines with high power and fuels with a very high energy content allowed the diffusion of the car, which after about 5000 years replaced the wagon and the carriage as a transport means for few or individual travellers. The history of the car begins in 1886, with the first car patented by the mechanical engineer Karl Benz. After a few years, in 1892, Rudolf Diesel patented the "Diesel" engine, similar to the internal combustion engine but without spark plugs. Thanks to their extraordinary power, these engines, were mounted on large trucks and installed on heavy machinery. The internal combustion engine revolution has also brought important evolutions in public transport. The first bus, the De Dion-Bouton, dates back to 1897, while in Italy the first bus was built by Fiat in 1906. The revolution of the internal combustion engine allowed also the development of the airplane and the consequent evolutions from the first biplane of the Wright brothers (1903) to modern jet airliners. Also in maritime transport, the availability of diesel engines with great powers triggered a very rapid evolution in the transport of people and goods.

In conclusion, society has been profoundly changed by the internal combustion engine revolution, everything was profoundly and quickly changed. It can be said that the last century was the oil century.

In the second half of the 20th century, the sixth revolution of freight transport and logistics based on the container began in maritime transport. A revolution with "low technological content", which, by reducing the cost of maritime freight transport by a factor of ten, consequently changed the economic and geopolitical assets of the world, giving way to the phenomenon we know as globalization (Donovan & Bonney, 2006) where supply chains of several products could be stretched over thousands of miles to save on labor and/or raw materials and intermediate products.

The analysis of the six past transport revolutions shows that they share two common elements (Cascetta et al., 2021a): the "law of unintended consequences" and "super additivity" compared to previous technologies. By "law of unintended consequences" we mean that the innovation is generated by needs different from transport and/or leads to forms of transport that are not foreseen in the early stages of adoption of that innovation. For example, steam traction is based on technology, the steam engine, conceived for operating weaving looms. Furthermore, almost all revolutions use innovative combinations of new technologies and technologies developed in previous revolutions. The phenomenon by which the combined effect exceeds the "sum" of individual ones is defined here as "super additivity". For example, the car combines pre-existing technology (the carriage) with an internal combustion engine that replaces animal traction giving rise to completely different performances and possibilities, such as mass production. Evolutions are innovations in transportation systems improving the performances of existing transportation services, even significantly so, without producing significant societal changes. In the case of evolutions, there is no "law of unintended consequences", changes arise explicitly to improve technology or an organization of transport forms that already exist.

3. The three drivers of the possible seventh revolution and their interactions

From the analysis of the six revolutions, it emerges that modern trains, cars, ships and planes and the infrastructures and organization they require are evolutions of technologies available seventy or a hundred years ago. Nothing comparable, for example, to what happened in the information, and telecommunication sectors (ICT) in the last few decades (Sapolsky et al., 2018; Jorgenson & Vu, 2016; Groumpos, 2021; Seel, 2022). In 1982, in the iconic film "Blade Runner", the future (2018) was imagined with flying cars but with prehistoric computers and without smartphones. The flying car is not the only example of a revolution expected for at least seventy years that has not occurred. Today, the mobility of the future is imagined as a system that allows the traveler to choose the trip program from a menu of options with alternatives that include electric autonomous vehicles, exclusive or shared with other travellers, different pricing depending on the specific trip as well as on different on board services and facilities, exchanging information with each other and with the infrastructure to optimize the network.

Like any other complex socioeconomic system, the transport system is internally complex, made up of many elements influencing each other both directly and indirectly, often nonlinearly, and with many feedback cycles (e.g. number of travellers that use the infrastructure is influenced by the performances of physical elements, the performance of these elements and the impacts of their use, are strictly connected to travel demand and users' behavior) (Cascetta, 2009). Apart from their internal complexity, transportation systems are closely interrelated with other systems that are external to them, for example, environment, the quality of life, and social cohesion (Cascetta, 2009). The changes of the transport system, therefore, are influenced by the evolutions that take place in several different areas, such as technology, the economy, institutions, behavior, culture, ecology and belief systems (Rotmans et al., 2001).

In the first half of this century, some strands of technological and organizational innovation are visible that will most likely lead to the next transport revolution. Gilbert and Pearl (2010) anticipated the next transport revolution, as essentially driven by decarbonization and the change in energy production and use in transportation. We propose a wider approach driven by three concurring areas of technologic innovations: i) decarbonization of transport, ii) self-driving vehicles connected to each other and to infrastructures, iii) transformations in mobility services (Cascetta et al., 2021b). These three drivers are already underway, and they will continue to develop and interact in the next decades

3.1. Decarbonization and new energetic vectors

Climate change is the biggest challenge for humanity. It is no longer an exclusive problem of the scientific community, but rather a global problem. In this context, European climate law will become a key element of future EU regulation and the legislative process. The Green European Deal as an EU climate and energy strategy has become an important basis for climate legislation and is, among other things, the result of the Paris agreements concluded during Conference Of the Parties-COP21 (*XXI Conference of the Parties of United Nations Framework Convention on Climate Change)*. Since then other COP took place, up to the last COP27 (*XXVII Conference of the Parties of United Nations Framework Convention on Climate Change)* in Egypt progressively defining targets and economic tools to reach them without penalizing Countries with different development levels.

Sustainable development is defined by the united nations environment programme (UNEP) as the capacity to satisfy current needs without compromising future generations (FAO, 2020), managing the earth's resources and minimizing climate change's negative impacts (Session S.W., 1987). This concept is so important that, in 2015, the United Nations endorsed the 2030 Agenda for Sustainable Development and 17 Sustainable Development Goals (SDGs), reaffirming the World Community commitment to Sustainable Development (Nations, U. 2015). Through this Agenda, 193 member states in a big action plan with 169 targets seek to achieve the Millennium Development Goals (Cartenì et al., 2020a). Among the 17 goals, the transport sector can contribute significantly to two aims: to reduce CO_2 emissions and increase energy efficiency.

On 14 July 2021, the European, Commission presented the 'Fit for 55′ package (EU Commission, 2021), its purpose is the implementation of the European Union's (EU) Green Deal in general and the climate neutrality objective for 2050. As a first step on the path to climate neutrality, the 2030 GHG reduction objective has been raised to 55% (with respect to 1990)—a binding commitment for the EU and all Member States (Schlacke et al., 2022). On 14 July 2021, the European Commission submitted a proposal: sectors covered by the Effort-sharing Regulation (ESR) should achieve a collective reduction of 40% in their emissions by 2030 compared to 2005 (European parliament (07/2022), Revising the Effort-sharing Regulation for 2021–2030: "Fit for 55″ package).

In this context is important to stress that in the European Union (EU), the transport sector was responsible for 25% of greenhouse gas emissions (GHG) in 2020. The emission of GHG within the agriculture sector contributes 10.30%, industrial processes and use of products contributes 8.80%, and waste management contributes 3.27%. Moreover from 1990 to 2020 the transport sector experienced a slow decrease in its emissions from fuel combustion in contrast to other major energy sectors (e.g. Industry), therefore the incidence of transport has increased (from 20% in 1990 to 25% in 2019).

Among the fields of action, most encouraged in the transport sector to reduce its GHG footprint include electric vehicles and greater use of energy-efficient appliances instead of conventional Internal Combustion Engines (ICE) (Masson-Delmotte et al., 2018).

The main long-term strategies of European Member States agree on the need to leverage a plurality of technologies to achieve the international target of limiting global warming to below 1.5 °C compared to preindustrial levels. In a recent study (The European House - Ambrosetti, 2022), a total of 100 decarbonisation technologies have been identifed that need to be analyzed and/ or promoted in order to optimize investments following a principle of technological neutrality.

In Fig. 2 Production and usage of carbon neutral energy vectors.

In the transport fields, electric mobility seems to be one of the best options to achieve both the sustainability goals and mobility needs at least for passengers and Light duty vehicles (e.g. Gilbert & Pearl, 2010; Prata et al., 2015; Cartenì et al., 2020a; Tsoi et al., 2022). Since the 2000s, opportunities and limitations of electric mobility are also widely discussed among scientists and politicians (Carteni et al., 2020b).

The current main weaknesses of e-mobility concern the following: (i) the high purchasing price (23–100% higher than a traditional vehicle) (Table 1); (ii) the autonomy of the battery, which limits the maximum distance travelled without recharging (despite the kms of a fully charged electric vehicle being comparable to a traditional one, the limitation is due to the recharging time not being immediate, which is different to the other vehicles) (Plananska, 2020); (iii) the limited re-charging infrastructure network (not enough to satisfy the demands of future potential users) (Pavić et al., 2020); (iv) the "no zero" carbon footprint related to Life Cycle emission (for production, consumption and disposal) (Dang et al., 2014); v) the electric vehicle has zero local impacts since it does not pollute while it circulates, but the impacts deriving from the production of electricity necessary to power the vehicle are anything but zero (Carteni et al., 2020b) except in the case of production of renewable energy for recharging the battery (e.g., wind energy, solar energy) (Cartenì et al., 2020a, Fondazione Caracciolo, 2022).

Clearly "zero local emissions" is a not negligible advantage, especially referring to their usage in cities with high population density, where the reduction of the local emissions could significantly reduce pollution and improve the quality of life (Cartenì et al., 2020a).

In the last decade, battery-powered electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), started to enter the market in significant numbers (Fig. 3) and are expected to grow exponentially in the next future due to reductions in capacity and costs of batteries. Indeed, in 2021, around 16 million electric cars (BEV and PHEV) were on the street in worldwide (Fig. 3). In 2021, the share of Electric Vehicles (EV) for light commercial vehicles (LCV), Buses and Trucks is negligible (Fig. 4). The search for sustainable mobility pushes car manufacturers to offer electric vehicles with higher performance standards and at the same time countries promote policies to encourage the use of this transport mode. Moreover, during the last five-ten years several car manufacturers like Peugeot, and Mercedes started to produce just EV or Hybrid cars, spreading electric production into the global car market. In fact, some conventional ICE city cars like Smart ForFour or Smart ForTwo are no longer produced and will be replaced with their electric model version. According to IEA (International Energy Agency) the existing policies and measures, which have been legislated by governments around the world, will bring the global EV stock to expand rapidly. Total EV will reach 200 million in 2030 (Fig. 4), with a significant increase of LCV-BEV since 2025.

Also the urban electric public transport fleet can play an important role in e-mobility being a solution to reduce Particulate Matter (PM) pollution (Carteni, 2018¸ Di Pace et al., 2022). Indeed, most of the buses circulating in European cities are powered by diesel (Acea, 2019) and significantly contribute to increasing polluting substances in the air such as particulate matter and nitrogen oxides (ACI, 2020). Indeed, a bus that travels one km damages human health like 20 cars that travel one km

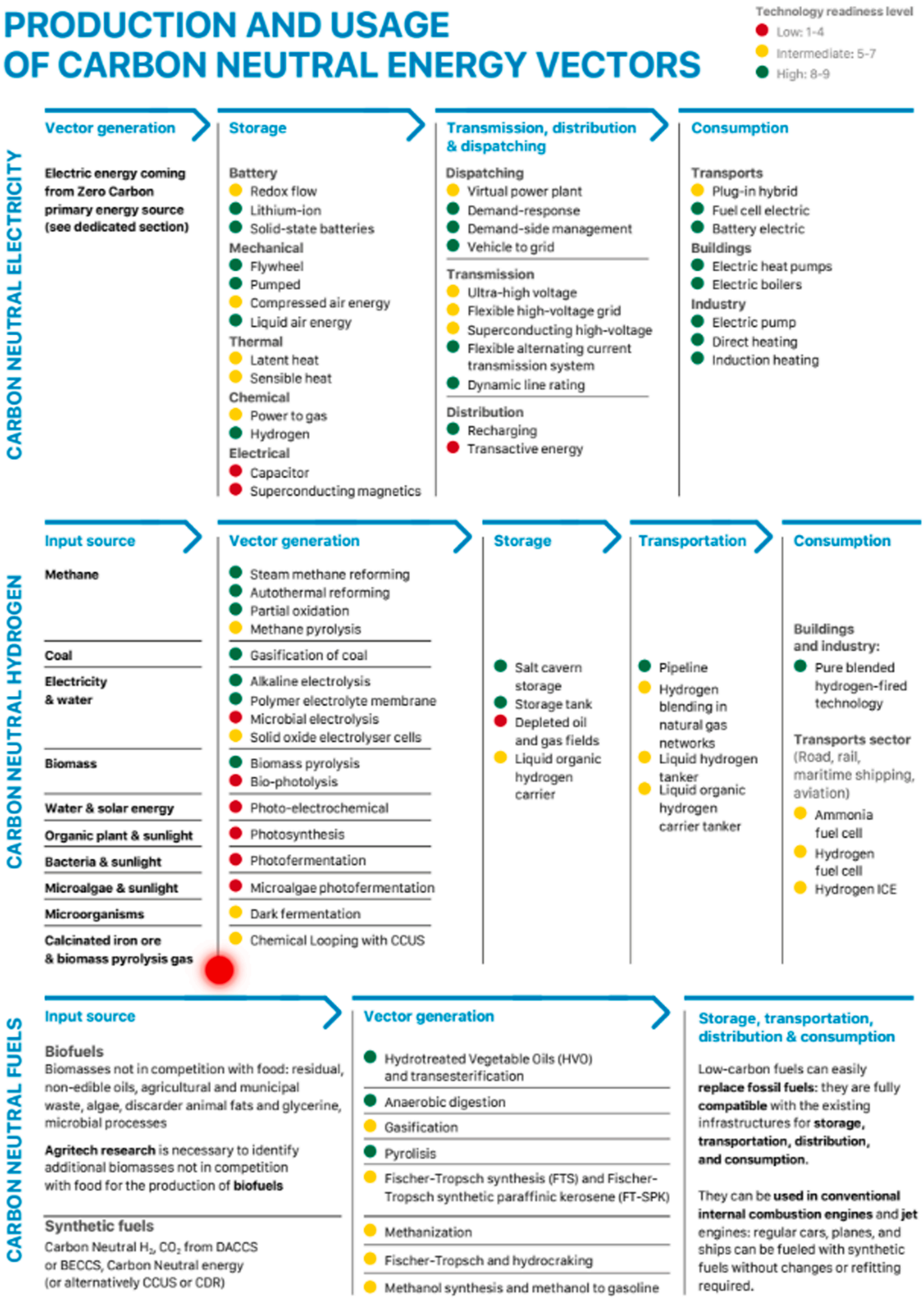

Fig. 2. Production and usage of carbon neutral energy vector (sources: The European House - Ambrosetti, 2022).

(Carteni et al., 2020b). Electric bus systems are defined as environmentally friendly, powerful energy-saving systems that are easily integrated into high-quality sustainable urban transport (Kühne, 2010).

The Finnish government created a test platform used by several electric bus manufacturers worldwide and this test platform became a center for the assessment of manufactured prototypes (Erkkilä et al., 2013). Germany is working on silent and low-emission transport systems, which are also able to regenerate braking energy and store this energy with ultra-capacitors with electric buses (Cartenì et al., 2020a).

In addition to electric mobility, hydrogen-powering fuel cells and

Table 1
Comparison between the average purchase price of private electric/traditional (diesel/ gasoline) car (source: elaborations on www.quattroruore.it, last access February 2023).

Tipology	Segment	Model	Price (€)	% var. (electric-traditional)
Sport Utility Vehicle	F	Jaguar I-Pace (Electric)	83,690	23%
		JAGUAR F-Pace	68,100	
Crossover Utility Vehicle	B	Peugeot e-2008 (Electric)	40,980	65%
		Peugeot 2008	24,900	
Sedan (Berlina)	B	Peugeot e-208	36,180	103%
		Peugeot 208	17,820	

electric engines have emerged as a solution for climate change, air pollution and energy security (Körner et al., 2015). Although hydrogen is the most abundant element on earth, it cannot be found by itself in nature. Hydrogen can be produced from a variety of processes associated with a wide range of emissions depending on the technology and energy source used (European Commission, 2020).

Hydrogen generation technologies are increasingly being codified by referring to a scheme based on different colors (Newborough & Cooley, 2020; Ivanenko, 2020; Noussan et al., 2020). The main colors that are being considered are the following:

- gray (or brown/black) hydrogen, produced by fossil fuels (mostly natural gas and coal), and causing the emission of carbon dioxide in the process;
- blue hydrogen, through the combination of gray hydrogen and carbon capture and storage (CCS), to avoid most of the GHG emissions of the process. While this approach seems to be less costly than shifting towards green hydrogen, it is important to remember that CCS implementation may involve technical barriers, in additions to problems related to social acceptability. Blue hydrogen pathways have currently technology readiness levels (TRL) between 7 (coal gasification + CCS) and 8 (SMR + CCS) (Thomas, 2018);
- turquoise hydrogen, via the pyrolysis of a fossil fuel, where the by-product is solid carbon;
- green hydrogen, when produced by electrolyzers supplied by renewable electricity (and in some cases through other pathways based on bioenergy, such as biomethane reforming or solid biomass gasification). The green hydrogen pathway is defined as the combination of power generation from renewable sources and water electrolysis. By supplying electricity and pure water to an electrolyzer, output flows of hydrogen and oxygen are produced;
- yellow (or purple) hydrogen, when produced by electrolyzes supplied by electricity from nuclear power plants.

Blue hydrogen pathways have the advantage of building on existing industrial experience from gray hydrogen, and in some cases retrofitting of existing plants could be performed by adding CCS systems. However, specific conditions need to be met to ensure effective and durable storage of CO_2.

A widespread and effective development of green hydrogen requires a notable amount of renewable electricity, which may be a problem in the short term, since RES (renewable energy sources) are already needed to decarbonize existing electricity demand. For this reason, blue hydrogen can represent a useful option in the short and medium term, by helping in paving the way for green hydrogen at a later stage (Dickel, 2020).

Germany is among the most active nations on this issue, in fact, hydrogen transportation and infrastructure in Germany are currently

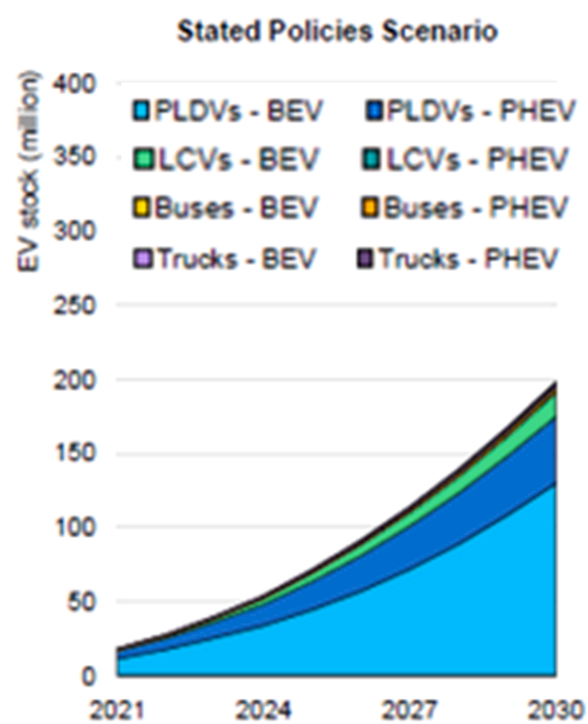

Fig. 4. Global EV stocks by mode, 2021–2030 (source: Global EV Outlook 2022, International Energy agency, 2022).

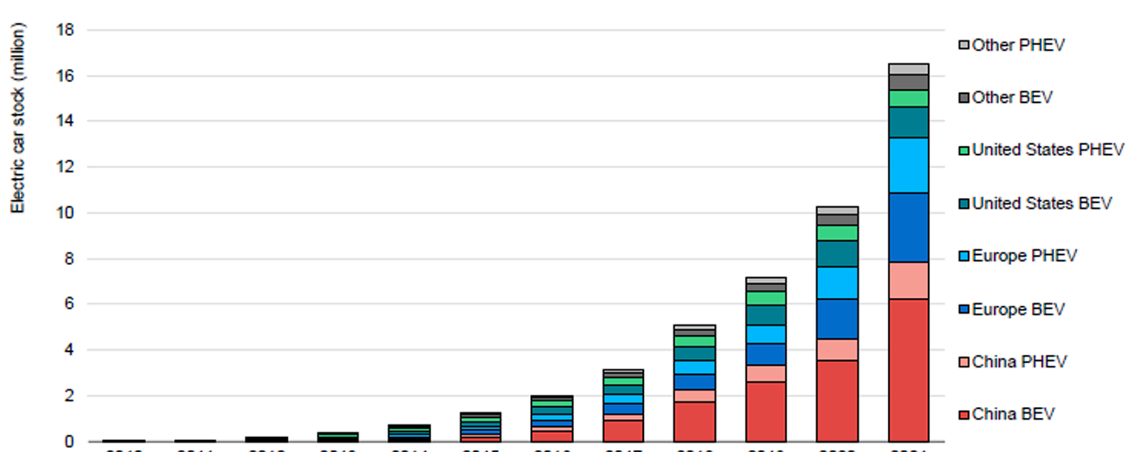

Fig. 3. Global electric passenger car stocks, 2010–2021 (source: Global EV Outlook 2022, International Energy agency, 2022).

developing (Herwartz et al., 2021). As of June 2020, there have been 89 hydrogen refueling stations (HRS) in operation mode for road vehicles in Germany. The government's aim is to establish 400 HRSs by 2023. Additionally, about 54% of the German rail network is not electrified. On those non- or partly electrified tracks, diesel-fueled trains (diesel multiple units e DMU) are being operated. Those could potentially be replaced with hydrogen-powered trains (fuelcell electric multiple units e FCEMU) (Pagenkopf et al., 2020). In 2018 the world's first two FCEMU were put in scheduled passenger service in Germany.

Regarding the freight and logistics sector, in urban areas the policies most common regarding the adoption of electric freight vehicles (EFVs) instead of conventional Diesel-fueled trucks in urban pickup/delivery operations (Fiori & Marzano, 2018). On the other hand, BEV heavy freight vehicles (HFV) are currently seen as a noncompetitive solution given the battery weight needed for long-haul trips. Hydrogen fuel cells and bio-methane are considered more competitive solutions due to their higher energy density. Hydrogen and bio-methane have energy densities of about 33 kWh/kg and 14 kWh/kg, respectively; while electric batteries reach 0.4 kWh/kg. BEV HFVs for long-haul trips would weigh much more than fuel cells or bio-methane HFVs, losing the advantage of exploiting a more efficient powertrain. Indeed, the greater the weight, the more energy must be expended to move the truck. Similar considerations are being made for bio-diesel (HVO) powered vehicles. Recently bio-fuels are emerging as candidates to power last generation diesel engines (Euro 6) with reduced or null CO_2 emissions on the WTW cycle (e.g. Lilja et al., 2020; Mantziaris et al., 2020). In fact, the biomasses used as a source for the production of biofuels subtract CO_2 from the environment during their life cycle. To produce, transport, and distribute a biofuel energy unit (WTT), CO_2 is released into the atmosphere. A "bio credit" equivalent to the CO_{2eq} emission given by the combustion of the energy unit produced and corresponding to the quantity of CO_2 removed from the environment by the biomass must be subtracted from this contribution. Given that the biomasses used for second-generation biofuels exploit agricultural waste or ad hoc crops, the "recovered" CO_2, counted in the "bio credit", would be "lost" if not used to produce biofuels. In fact, the natural decomposition would still cause the emission of CO_2 captured by the biomass during the life cycle. The value of the "bio credit" depends on the biomass used as an energy source(Prussi et al., 2020). The TTW contribution depends on the vehicle analyzed and is always considered positive. The WTT contribution will be conditioned by the "bio-credit". In the Fig. 5, a simplified chart for the case of bioethanol, where the emission contributions are shown in blue; in green are reported the "bio-credit" accumulated by the specific type of biomass used. A positive sign is attributed to climate-altering emissions, a negative sign to "bio credit" since it is considered as a quantity of CO_2 subtracted from the environment.

The HVOs (Hydrotreated Vegetable Oils) are advanced biofuels produced by refining vegetable oils or animal fats through a hydrogenation process. HVOs are considered less polluting than other biofuels such as biodiesel, as the hydrogenation process removes almost completely nitrogen oxides (NOx) and volatile organic compounds (VOC), which are air pollutants that can have negative impacts on human health and the environment. HVOs can be used as direct substitutes for fossil diesel without the need to modify the engine of vehicles, and therefore represent a more immediate solution for reducing CO_2 emissions in the transport sector (Lilja et al., 2020). A study published in Nature Energy in 2021 (Blanco et al., 2021) highlighted that the use of advanced biofuels produced from non-food biomass could contribute to more efficiently reducing greenhouse gas emissions in the transportation sector compared to complete electrification of the vehicle fleet. Another research (Larsen et al., 2020) concluded that, in some parts of the United States, advanced biofuels may be more effective in addressing greenhouse gas emissions in the transportation sector than a full conversion to electric vehicles. However, it is important to note that biofuels also have some environmental limitations and issues, such as the need for land and water resources for biomass cultivation and greenhouse gas emissions associated with biofuel production and transportation (e.g. Gopalakrishnan et al., 2019; Singh et al., 2021; Li et al., 2022).

The electrification of maritime transport is progressing but is currently limited to ferries and other short-haul ships. The low energy density provided by the electric batteries excludes the complete electrification of ships. At the moment the more promising solutions for regular ships are uncertain and connected to Hydrogen, but due to cost and problems related to storage and energy demand for compression/ liquefaction, it is not yet clear whether it will become the main energy carrier in the sea transportation sector (Zhou, 2005; Machaj et al., 2022). However, second-generation biofuels might represent an interesting solution since they offer similar energy densities of traditional fuels and would be able to supply ICE engines, requesting no redesign of powertrains (Napolitano et al., 2022). In alternative fuel experimented for regular ships are based on Ammonia, which is an excellent hydrogen carrier (Dimitriou & Javaid, 2020) and is favored by the maritime sector (e.g. Al-Breiki & Bicer, 2020; Baldi et al., 2019, Laval et al., 2020). Ammonia is one of the most widely produced inorganic chemicals, in 2019, approximately 240 million tons of ammonia were produced and it is predicted that in 2030 production will increase to approximately 300 million tons (Laval et al., 2020; Machaj et al., 2022). Most of it is produced in four countries: China, India, Russia, and the United States, but is traded worldwide (Machaj et al., 2022).

In the last decade, there are different port operating policies with the aim to reduce emissions from shipping during the berthing phase; however, their efficacy varies for different ports. Cold ironing (CI) or alternative maritime power (AMP) defines the procedure of providing

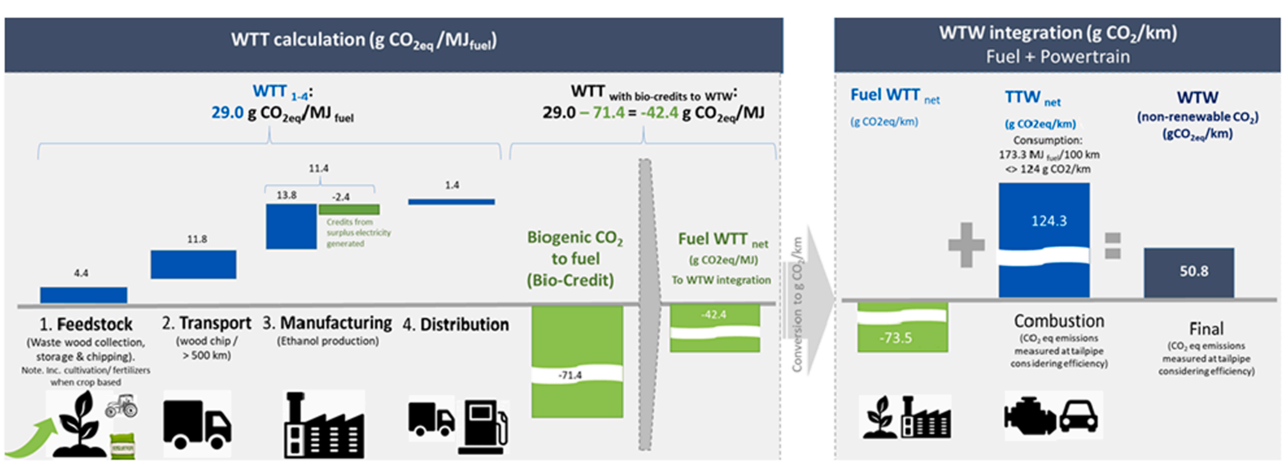

Fig. 5. CO_2 equivalent- WTW calculations- simplified chart (sources: Prussi et al., 2020).

electrical power to a ship at berth to meet the ship's energy demands while the ship's main and auxiliary engines are switched off. This technological solution can eliminate local emissions as the ships' funnels do not release pollutants in port. Global GHG reductions will depend on the origin of the energy providing the shore power (with increased emissions locally near the power supplier) (Zis, 2019).

3.2. Autonomous and connected vehicles

All transport vehicles have been driven by humans since the first revolution. This is going not to be the case in a few decades.

Road mobility at the moment is almost entirely controlled by drivers perceptions, reactions and errors. Road vehicles are undergoing a transformation in their control and driving systems through a combination of advanced sensor technology; on-board and remote processing capabilities; GPS and telecommunications (5 G) systems (e.g. Connected and Autonomous vehicles). The main innovations are expected from the automotive world up to the Autonomous Car (or robot car), a self-driving car that uses a combination of sensors, cameras, radars and artificial intelligence (AI). This technology allows moving between different destinations without the need for human intervention, even on roads that have not been pre-adapted for the purpose. The Society of Automotive Engineers (SAE, 2014) has classified automated vehicles into six levels of driving automation, ranging from Level 0 (no automation) to Level 5 (full automation) Fig. 6. In the literature road autonomous vehicles are referred to as AV (autonomous vehicle), CAV (connected AV) and CCAV (cooperative connected autonomous vehicles).

To date, most current vehicles have acquired Level 1 or Level 2 since these vehicles are equipped with ADAS technologies such as cruise control, hazard warning, and automated parallel parking. The automotive industry requires several years of development, testing, and approval to completely reach Level 5 of self-driving vehicles. Currently, carmakers are competing to acquire fully autonomous features for their vehicle design. Some Companies already sell Level 3 cars such as Mercedes and Honda allowing automated driving in some Driving Traffic Domains, typically motorways. Other have been implementing Level 4 pilot projects to test AVs under certain circumstances such as specific road types, areas, and weather (Ahmed et al., 2022). For example, Waymo (Google's company for the development of self-driving, one of the pioneering companies in the development of the level 5 driverless car, such as to have covered, to date, over 32 million km and recently collected an external investment of 2.25 billion dollars), robotaxi designed for the transport of people compliant with level 5 of self-driving, is available in the city of Phoenix, Arizona (see Section 3.4). However, today, it would seem Level 4 does not appear to be designed for use in the private car market (but mostly for taxis), but some level 4 features are useful for private cars, such as Intelligent Park Pilot. Intelligent Park Pilot (level 4) (Mercedes-Benz is developing this technology) allows a fully automated parking activity, the driver has the possibility to leave the car, which will park autonomously. The Volvo company is investing in the level of automation by focusing on *Ride Pilot* technology based on the high redundancy of cameras and sensors (including the LiDAR of Luminar) and on the constant updating of the software in OTA (over-the-air) mode. The car can park (with autonomous driving) even in parking lots distant from the place where the driver has abandoned

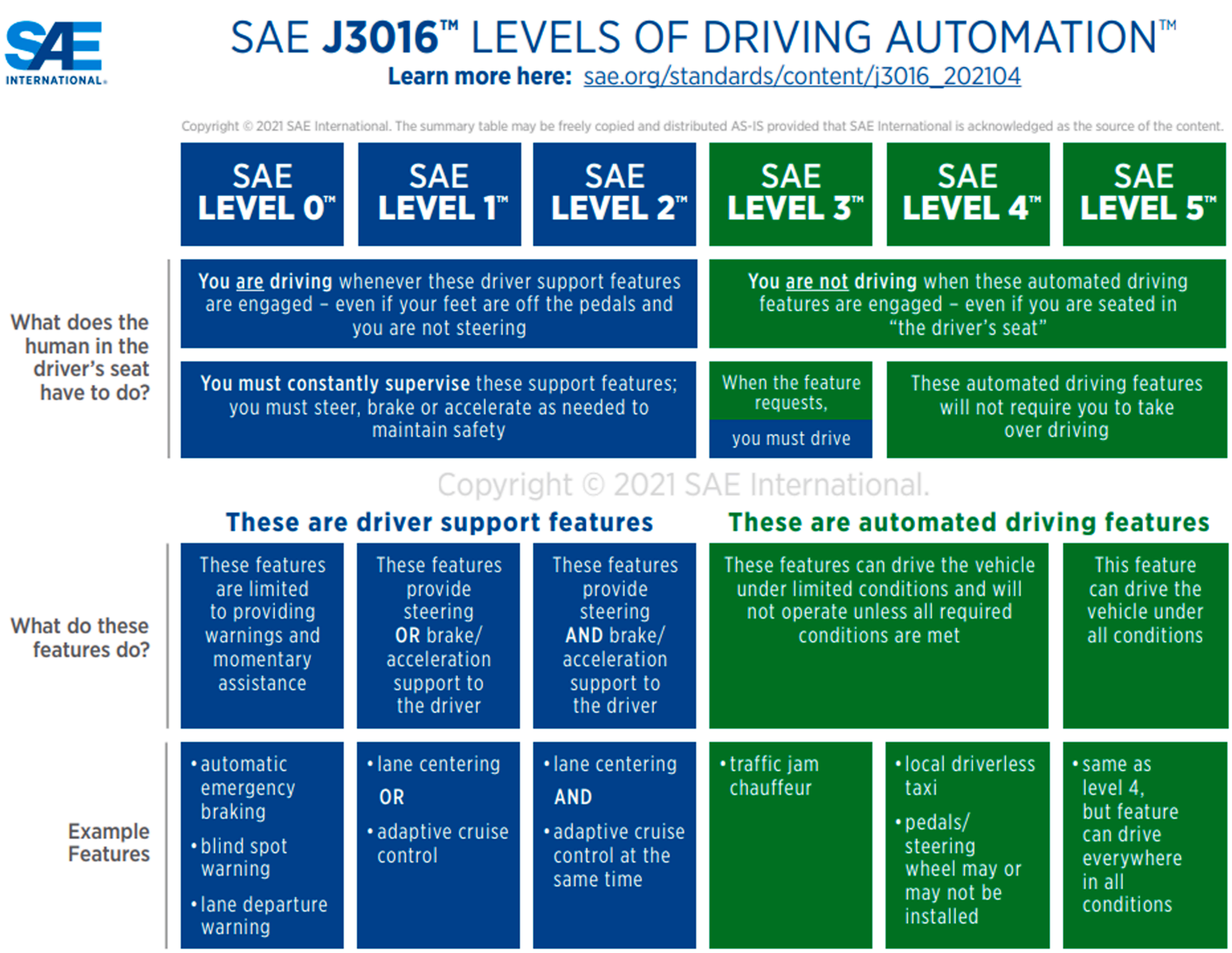

Fig. 6. The six levels of driving automation (sources: Society of Automotive Engineers).

the vehicle (Stein, 2020). This will lead to a change in urban areas and in particular in city centers, in fact, if in the peripheral areas will be built special parking lots for autonomous vehicles, the central areas will be freed from parking areas and those areas can be used for other purposes. Cruise (of General Motors) also announced its plans: 1 million autonomous cars by 2030 used for public and private taxis services. Cugurullo et al. (2021) assumed that AV_S will be the dominant form of urban transport by 2040, especially in cities like San Francisco, London, Pittsburgh, Gothenburg, and Singapore, where today this new technology is tested in real-life environments.

The automation level SAE 4 seems to have a short term higher adoption potentiality for local public transport in urban contexts, as shown by some pilot experiences. Some prototype versions of Level 4 and 5 vehicles are starting to be applied for airport shuttle services and minibus lines, such as in the UK (Lo, 2012), France (E. NAVYA, 2016) and Germany (EasyMile, 2021), where vehicles run at very low speeds ranging from 15 to 20 km/h (e.g. Hagenzieker et al., 2020) in pedestrian areas and/or along enclosed and restricted routes limiting their movements and interactions with other vehicles and people. However, such technological limitations are widely expected to end in the foreseeable future, allowing automated vehicles (AVs) unlimited movement on roads jointly with both traditional vehicles and pedestrians (Hulse et al., 2018). Recently traffic flow model able to support the implementation of traffic management strategies in the presence of human-driven and connected vehicles are proposed (e.g. Storani et al., 2021; Storani et al., 2022a; 2022b)

The spread of self-driving vehicles in the market is linked to two main problems: 1) technological, 2) regulatory. The main technological problems concern safety issues related to driving automation (Levels 4 and 5), especially in urban areas where there are both traditional vehicles and pedestrians (e.g. Martinho et al., 2021, Nyholm & Smids, 2016, Ethik-Kommission, 2017). Ordinary traffic situations are the day-to-day interactions with pedestrians, cyclists, animals, that require some flexibility, such as crossroads, highway entrances, or crosswalks with limited visibility. These interactions are challenging for AVs not only because these systems lack human intuition and flexibility but also because of the large scale fleet programming that is needed (Martinho et al., 2021). If on one hand, self-driving car technology reduces/eliminated accidents for human error (Ethik-Kommission, 2017), furthmore, in dangerous situations, algorithms are able to decide within a fraction of a second, whereas human drivers become panicked and act on their instinct (Nyholm & Smids, 2016), the ethical issues are an issue to be resolved (Ethik-Kommission, 2017).

From a regulatory point of view, the European Union has recently approved UN Regulation No. 157, (2022) which provides uniform guidance to EU member countries on the safety certification of autonomous vehicles. The Regulation sets out clear performance-based requirements that must be complied with by car manufacturers before equipped vehicles can be sold. The new functionalities must also comply with the strict cybersecurity and software update requirements outlined in the relevant UN Regulations. The directive holds motor vehicle manufacturers responsible for the safety of their products. This means that if a motor vehicle is involved in an accident and does not meet the safety requirements set forth by the directive, the manufacturer may be held responsible for the accident and may be required to pay for any resulting damages. In the near future, important legal decisions will need to be made regarding criminal responsibility, for example, if an autonomous vehicle (level 5, without human intervention) collides and causes the death of a nearby pedestrian (Imai, 2019). Additionally, UN Directive No. 157 includes among its main innovations the allowance of level 3 vehicle driving on motorways, where pedestrians and cyclists are prohibited and the traffic moving in opposite directions is separated by physical barriers. Level 3 driving is allowed at speeds of up to 130 km/h, and automated lane changes are also permitted.

Furthermore, the spread of AV will be determined also by social attitudes, and how individuals feel about autonomous vehicles.The research carried out by Cugurullo et al. (2021) has empirically shown that, in Dublin, people are generally concerned with the safety of autonomous vehicles and, yet, inclined to use them once available.

As mentioned, the innovation of self- and connected driving on the road does not only concern vehicles, but also the infrastructure and interactions among vehicles. Allowing communication and connection with the vehicles that travel is one of the goals of smart roads (Decreto number 90, 2018 on Smart Road). The smart road is a synthesis of automatic data detection technologies such as cameras, radars, sensors in the pavement, of fast and bidirectional communication technologies (Vehicle to infrastructure V2I vehicle to infrastructure and vehicles V2X) between sensors, vehicles and control center, platforms for analysis, traffic forecasting and management of control interventions in ordinary and emergency flow conditions. There are several examples of smart roads in Europe, among these the pilot project C-ROADS, in Austria, can be mentioned that started in February 2016 and ended becoming operational in 2019 which affects the motorways connecting Vienna and Salzburg, the Brenner corridor and the surroundings of Graz. The project consists of equipping 300 km of motorways with C-ITS (Connected Intelligent Transportation Systems). It resorts to the support of the ITS-G5 mobile network to provide C-ITS services such as accident notifications, roadworks alerts and in-vehicle weather reporting. Mayor smart road projects are currently under way in Italy (ASPI, CAV, ANAS).

Self-driving is a technology already widely used for other modes of transport, such as driverless rail systems. The world's first automated driverless Railway opened in Kobe (Port Island Line) in 1981, Japan. The second in the world (and the first such driverless system in Europe) was the Lille Metro in northern France in 1983. In this system, trains can operate automatically all times, including door closing, obstacle detection and emergency situations. All vehicles are continuously managed from a centralised control center and on-board staff may be provided for other purposes, for example customer service, but are not required for safe operation.

In october 2021, a driverless train makes its first trips on the urban network in Hamburg. The train was developed by Siemens and Deutsche Bahn and is part of 'Digital Rail Germany'. Hitachi Rail and Rio Tinto have build a self-driving freight train in Pilbara region in western Australia. This system, operating by the end of 2018, is the world's first and only fully automated rail system for long-distance heavy freight transport. It enables 220 trains, monitored remotely from an operations center in Perth, to safely and efficiently across more than 1866 km of track.

A fully autonomous freight train will be ready on Finnish tracks by the end of 2023. Led by Finnish technology company Proxion, the freight train will have Automatic Train Operation (ATO) over the European system ETCS (European Train Control System).

About freight digital transformation there is the possibility of connecting more trucks to form a train (Truck platooning).A truck platoon includes a lead truck (leader) and one or more trailing trucks (followers) and is defined by the European Automobile Manufacturing Association (ACEA) as "the linking of two or more trucks in convoy, using connectivity technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey, for instance on motorways.

There are different levels of automation here as well. The characteristics of level 1 are: leaders and followers with driver on board, possibility of opportunistic platooning (on the fly) or by appointment and only V2V communications are required. The characteristics of level 2 are: leader with driver on board, followers with autonomous driving or with driver at rest (change of rules), need for truck platooning stations on portions of the network (highways) and need for V2V and V2I communications (smart road). Finally, the characteristics of level 3 are: leaders and followers with autonomous driving, the need for truck platooning stations on portions of the network (highways) and the need for V2V and V2I communications (smart road). Studies (e.g. Marzano et al. 2022) have shown that truck platooning has a significant potential market share in medium to long distance journeys, increasing with the level of automation, and cost reduction.

Truck platooning is not the only step toward autonomous trucks. ADAS functionalities such as adaptive cruise control (ACC), automatic emergency braking (AEB) and lane keeping assist (LKA) are accelerating for commercial vehicles (). In the near future, attention will be directed towards accelerating Level 4 in order to offer autonomous capabilities in last-mile delivery. Several car manufactures (e.g. Tesla,Volkswagen, Volvo) are investing in new technology with the aims to roll-out L4 autonomous capabilities in the near future. Volvo Autonomous Solutions have constituted a new business area as of January 1, 2020, Tesla plans to market with Autopilot capabilities and offer at least 500 miles of range (Future Bridge, ADAS in commercial vehicles, Q2'20 Pulse). As with AVs, for autonomous commercial vehicles technological challenges and regulatory barriers still exist. Adoption of standard legal and insurance framework will help to accelerate the testing and faster commercialization of autonomous trucks. There are also logistics groups, such as FedEx, which is ready to launch an autonomous Heavy Goods Vehicles service in 2023 in the US.

3.3. Smart mobility services

The development towards smart mobility is being led by the technology sector, use of new ICT, IoT and RFiD technologies in the field of transport services. It has and will change users' mobility in different markets. In the last twenty years, the mass adoption of the world wide web, and the diffusion of the smartphone have transformed many aspects of everyday life, modifying, in less than a generation, the ways people communicate, organize patterns of work, shopping, and socializing and transforming the idea of mobility (Docherty et al., 2018).

The use of these telecommunication technologies in mobility services involves (Curtis & Lehner, 2019):

- Improving access to information (Kim & Yoon, 2016; Pisano et al., 2015)
- Facilitating intermediation between providers and users (Bálint & Trócsányi, 2016; Schor et al., 2016)
- Facilitating payments (Cartwright, 2016)
- Increasing trip convenience (Butenko, 2016)

New technology based mobility services have several declinations and also different names for similar instances. In this paper we define "Smart mobility" as the set of new mobility-related services made possible by ICT technologies. This definition is general enough to include very different services that have been proposed over the last few years as well as some that will be proposed in the next. The services proposed so far can be grouped in four classes and their combinations:

- Info mobility
- Sharing mobility
- Vehicle Sharing
- Ride Sharing
- Smart pricing
- Mobility as a Service (MaaS)

Info-mobility refers to systems that allow travellers and companies to access trip related information before the trip (to allow for decision-making on the options to choose based on several factors including prices, speed and timeliness) and during the trip (to be informed in real-time on the variation of the trip characteristic) (Peprah et al., 2019). Different platforms suggest routes for road networks based on real time travel times estimated through all service users,Google Maps and WAZe are among the most used. For the time being, route information and suggestions are based on travel times and possibly tolls, but is possible to anticipate more sophisticated predictions/ suggestions based on other users' specified attributes such as reliability, type of roads, number of stops, driving stress and so for. With Google map it is possible to choose "eco-friendly routing" (available from October 2021 in U.S. and from October 2022 in Europe). Several platforms provide real time information in Public Urban Transportation services, regional and intercity rail services, flights etc.

The sharing mobility is linked the terms "sharing economy", "collaborative consumption", "peer to peer economy", all terms to describe the phenomenon as peer to peer sharing of access to underutilized goods and services, which prioritizes utilization and accessibility over ownership (e.g. Cheng, 2016; Schor & Fitzmaurice, 2015). The sharing economy is largely promoted in academic literature as offering access over ownership (Martin, 2016; Light & Miskelly, 2015), by leveraging the idling capacity of goods and services (e.g. Harmaala, 2015; Heinrichs et al.,;, 2017), in order to reduce our overall consumption and subsequent resource use (e.g. Ala-Mantila et al., 2016; de Leeuw & Gössling, 2016) Different economic model could be used in sharing economy, the most popular for sharing mobility are:

- Peer-to-peer (or consumer-to-consumer) model implies that the fleet of vehicles (cars, bikes, moto) is owned by a community. The marketplace then matches cars that are available by the owners with the prospective drivers willing to rent them. In this model, private individuals rent their vehicles in exchange for financial compensation. Companies such as Turo (formerly RelayRides), Getaround, and JustShareIt offer examples of peer-to-peer car sharing.
- Business-to-consumer model means that a company owns a fleet of vehicles (cars, bikes, moto) and facilitates the sharing among members. Multiple drivers have access to the same vehicle, owned by companies that rent by the hour or by the day (e.g. car-sharing, bike sharing) Auto manufacturers (e.g., BMW, Peugeot, Daimler), rental brands (e.g., Hertz, WeCar), and car-sharing brands (e.g., Zipcar, StattAuto, GoGet) offer examples

Sharing mobility has grown rapidly in recent years, probably because of great recession of 2007–2008 (e.g. Aptekar, 2016; Cohen et al., 2016; Morgan & Kuch, 2015; Posen, 2015), health emergency for COVID-19 (e.g. Lukasiewicz et al., 2022), increased environmental awareness (e. g. Ala-Mantila, 2016; Butenko, 2016, Cohen & Kietzmann, 2014; Matzler et al., 2014) and proliferation of ICT applications (e.g. Tussyadiah, 2016; Hamari et al., 2016). According to the analysis conducted by Statista (E. Statista, 2022b) the revenue in the Shared Mobility segment is projected to reach US$1.18tn in 2022. Revenue is expected to show an annual growth rate (CAGR 2022–2026) of 10.38%, resulting in a projected market volume of US$1.74tn by 2026 (Fig. 7). In global comparison, most revenue will be generated in China (US$312.50bn in 2022).

The market's largest segment is Shared Vehicles with a projected market volume of US$0.80tn in 2022. The number of business-to-consumer (B2C) car sharing users worldwide has increased, by 2025 carsharing users will reach 36 million, maintaining an annual growth rate of 16.4% (Fig. 8). In Europe, the number of vehicles in car sharing programs went from 7.500 in 2006 to around 61.000 in 2018 with an increase of 710% and the growth in the number of car sharing users in Europe from 2011 to 2020 is equally significant, from about 700.000 to about 15 million. In Italy, car sharing services began to take hold at the beginning of the 2000s thanks to some "local" experiments; but the real boom was recorded in 2013, with an increase of 330% compared to 2012 in the number of users, which went from 30.000 in 2012 to 130.000 in 2013. In 2019, car sharing in Italy counted over 2,2 million users and about 8.300 vehicles and 12 million rentals of which 3% employed in station-based car sharing and the remaining 97% in free floating, testifying to the significant importance that the latter type has been hiring in our country in recent years.

Another case of sharing economy is ride sharing, people sharing the same vehicle for travel (Novikova, 2017). Various dynamic ride-share

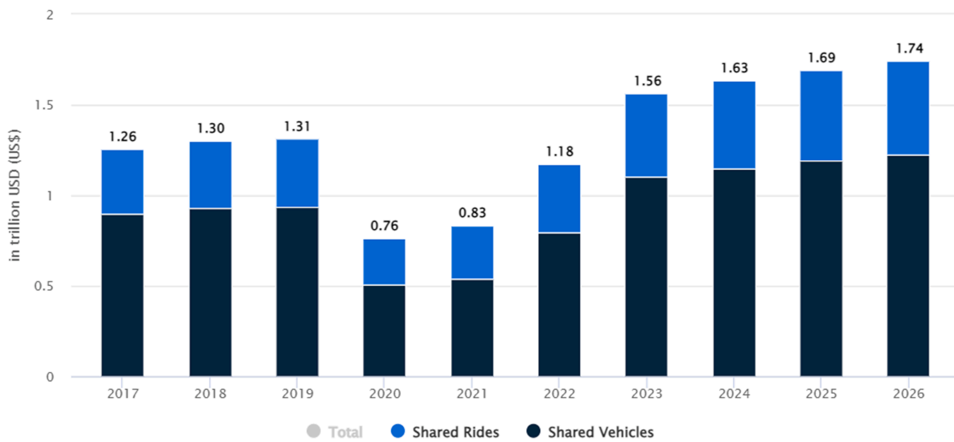

Fig. 7. REVENUE in shared mobility in worldwide. (sources: E. Statista, 2022b).

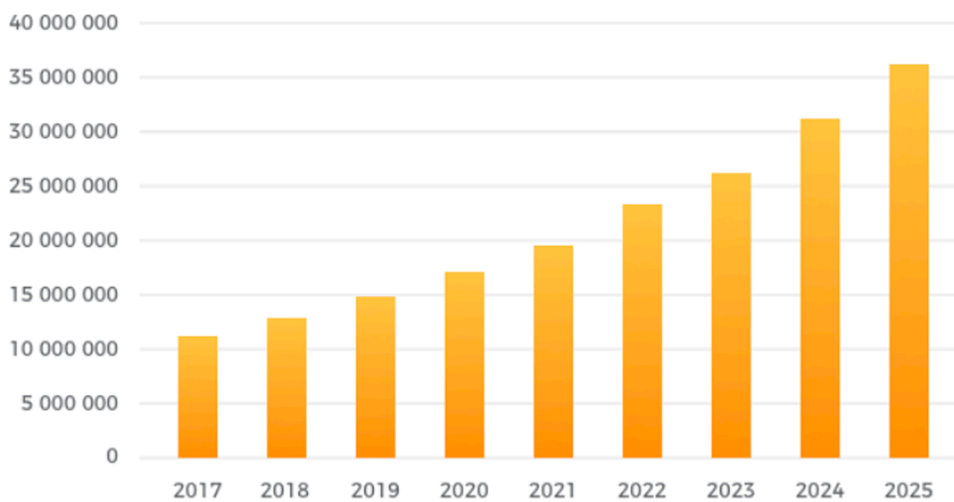

Fig. 8. Number of carsharing users worldwide (Source: Frost & Sullivan, Future of Car Sharing Market to 2025).

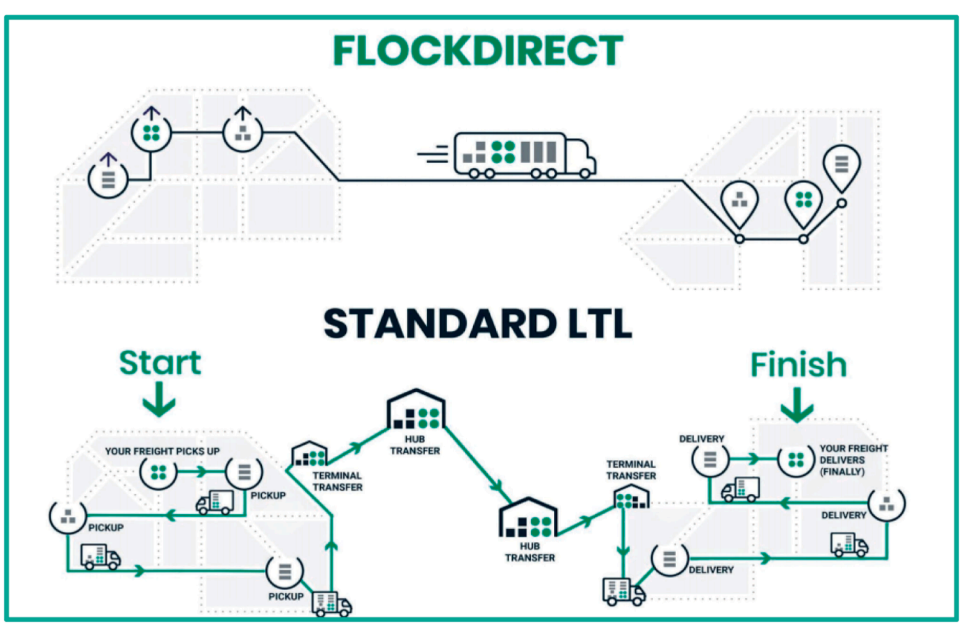

Fig. 9. The sharing in freight sector: "Flock Freight's shipping solution for the aim of carbon neutral" (sources:https://www.flockfreight.com/blog/what-is-flockdirect/).

systems aim to bring together travellers with similar schedules and itineraries on short notice, this is the case of Car-pooling(or ride hailing – vehicle owners allowing other passengers to ride in the same vehicle to and from the same or similar destinations). Other scheme of ride sharing is on-demand ride service, the driver owns the vehicle and picks up people, offering a flexible door-to-door service, with Uber being the most prominent example of a platform enabling peer-to-peer transactions (Cohen & Kietzmann, 2014).

Also, the freight sector is developing the concept of sharing, even though at a slower pace. For example, Flock Freight is a shared truckload service (Fig. 9), which enables several businesses to share trailer space in one multi-stop full truckload. This is a hubless shipping mode that uses advanced algorithms to pool midsize freight (between four to 22 pallets) from multiple shippers when it's moving in the same direction with the aim of lower the shipping carbon footprint.

New technologies can be useful for designing congestion pricing (crediting) schemes more equitable and acceptable for users. The road-pricing is a well-established policy option with the aim to reduce congestion in central areas and to reduce environmental impacts (Cascetta et al., 2017). It could be possible to group the main pricing schemes into:

- toll pricing, for which the user pays for crossing a road infrastructure;
- cordon pricing, for which the user pays for crossing a cordon (e.g. for entering in a city);
- area pricing, for which the user pays for entering into a specific restricted area (e.g. for moving within an Historical area in the city center).

The development of the Intelligent Transportation System (ITS) technologies allow and will allow in the next years to extend and apply these pricing schemes (both for passenger and for freight) in several different and most rational (sustainable) ways, connecting the price both to the individual characteristics of the trip and to the type of vehicle used, as for example (Cascetta et al., 2017; Cascetta & Montanino, 2022):

- distance-based, where the price is defined in function of the distance travelled;
- time-based, function of the hour of the day/season of the trip (e.g. peak vs. off-peak hours; summer vs. winter months);
- congestion-based, function of the congestion level of the path/road used;
- vehicle-based, function of the vehicle typology used for the trip (e.g. electric vehicle vs. traditional vehicle; old vehicle vs. new vehicle, light goods vehicle vs. heavy goods vehicle) and/or to the loading factor (e.g. 1 user/car vs. 2–5 users/car).

The set of all smart mobility services can be collected in a MaaS system (Mobility As A Services). MaaS is a new concept of mobility that provides for the integration of multiple public and private transport services, generally belonging to multiple modes of transport and operated by a variety of operators, accessible to the end user through a single digital channel (e.g. Jittrapirom et al., 2017; Kamargianni et al., 2018). The MaaS concept promotes a digital future, simple, accessible and multimodal, which will allow users to move more easily and plan their trips directly from a mobile app, which will allow them to perform all the operations: from choosing the best route (and pedestrian path) to checking the availability of vehicles, booking them, paying for the entire route, consulting their movements, for a new and complete "mobility experience". Depending on the service offered (e.g. buying a ticket with the app, allowing the integrated ticket relating to the entire trip) and integration with other transport modes (planning integration), different MaaS can be defined and different impact can be observed (e.g. Rantasila, 2015; Karlsson et al., 2016; Jittrapirom et al., 2017; Sochor et al., 2018; Storme et al., 2021).

3.4. Some possible interactions among innovation streams

The three drivers of the seventh revolution are being developed by separate industry segments but they have a very high potential for interactions defining what is going to be the possible mobility of the future. For example, the decarbonisation of transport can be facilitated by the development of sharing mobility. Sharing mobility, the use of the electric vehicle combined with the sharing mobility service, on one hand, will produce benefits for the human being and the environment, and on the other, it will also push vehicle manufacturers, rental companies, and those who deal with charging infrastructure management to start new projects in favor of increasingly sustainable mobility (Mounce & Nelson, 2019). Furthermore, through sharing mobility, the problem of the initial purchase cost of an electric vehicle could be overcome (which, as highlighted in Section 3.2., is one of the weaknesses of electric mobility) and the diffusion of electric vehicle circulation in urban areas could be increased (which are also those with more congestion problems and consequently emissions).

Sharing mobility could be accompanied by the adoption of connected and automated vehicles (CAVs) (see e.g. Fagnant & Kockelman, 2015, Docherty et al., 2018). There are several examples in the world of prototype services of shared automated vehicles. In Singapore, in 2016 a field trial of self-driving taxis began. The service is limited to an area of 2.5 square kilometers and requires the presence of a driver for emergency situations in the initial phase. Waymo, (Google company) has decided to bring its automated vehicles (AVs) on the road, with ride-sharing services (service comparable to UBER with the difference that the cars are self-driving). The services started in the city of Phoenix, Arizona, where a fleet of 500 new Chrysler Pacifica equipped with the autonomous system is available 24 h a day and 7 days, in a restricted area of the territory (Fig. 10). The vehicle is booked online through the pages of the official website where the user will write the desired destination. A centralized system will receive user requests, including the position where the car must go to pick up the passenger, will check if the route to be taken is completely safe for self-driving mode, possibly suggest a starting point or different arrival, and will choose the best path to take. However, current legislation does not yet allow self-driving cars to drive in complete autonomy. And that's why Chrysler Pacifica plug-in hybrids will have engineers able to take manual control of the vehicle at any time if necessary.

Cruise, the General Motors-backed autonomous vehicle company, currently offers its driverless cars to the public in San Francisco, even if only for trips between 11 p.m. and 5 a.m., and mostly on the west side of the city. Waymo will soon be offering service in San Francisco as well (The New York Times, 2023).

Sharing automated vehicles (AVs) will bring huge gains in safety, and the costs of transport to the user, the potential for automated vehicles to reduce end-to-end travel times will have profound impacts on society and the economy (Wadud et al., 2016).

Furthermore, AVs plus smart mobility will allow the capital stock of the mobility system, primarily infrastructure and vehicles, to be used

Fig. 10. Waymo service in Arizona (sources: https://www.reuters.com/article/us-waymo-autonomous-phoenix-idUSKBN26T2Y3).

much more efficiently (Docherty et al., 2018).

The three drivers of the seventy revolution outline a vision of the future in which mobility will be framed as a personalized 'service' available 'on demand', with individuals and firms having instant access to a seamless system of clean, green, that takes advantage of new technologies for efficient and flexible transport to meet all of their needs (e.g. Wockatz & Schartau, 2015; Docherty et al., 2018). The interaction of the 3 innovation drivers could lead to "Sharing with Self-driving electric vehicles": self-driving and 100% electric cars, booked with smartphones, picking up the costumer anywhere in the territory, used and left wherever the users want and optimizing their recharging by selecting the best station according to expected driving missions and stations availability.

4. Sustainability and the seventh revolution

Sustainable development is defined by the United Nations Environment Programme (UNEP) as the capacity to satisfy current needs without compromising future generations ones (FAO, 2020), managing the earth's resources and minimizing climate change's negative impacts (Session, 1987). Sustainable development is based on three fundamental pillars: social, economic and environmental. In particular, environmental sustainability entails improvement in the quality of the environment and reduction of emissions and energy consumption (greenhouse gasses emission variation; pollutant emission variation; impact variation in other sectors) (Reisi et al., 2014; Shiau & Liu, 2013). By contrast, social sustainability entails improvement in the quality of life and social equity (e.g. easy access to transportation) and improved safety (e.g. reduction in the frequency of accidents) (Reisi et al., 2014; ECMT, 2004; Haughton, 1999). Finally, economic sustainability entails making the mobility of people and goods more efficient and effective and ensuring that the economic benefits produced by the project (for the period under survey) are greater than the costs (Zheng et al., 2015; Reisi et al., 2014; Tien et al., 2020).

Environmental sustainability is arguably the most challenging to meet given the strong dependence of virtually all transportation modes on carbon-based fuels. The objective of net decarbonization by 2050 is particularly difficult to attain in the transportation sector as resulted in several studies (e.g. Kany et al., 2022; Dillman et al., 2021, Beatrice et al., 2023). This led to classifying the transport sector as "hard to abate" using UE terminology (The European House - Ambrosetti, 2022). There is a wide agreement that de-carbonization objectives have to be reached gradually and at different speed by different modes. As found in many recent studies dealing with the decarbonization of the transport sector (e.g., Emodi et al., 2022; Kramer et al., 2021; Kany et al., 2022; Dillman et al., 2021), the ASI framework (Avoid, Shift, Improve) is the most applied and promising approach in scenario building. This framework is based on three principles (Arioli et al., 2020; Wilson et al., 2020):

1. **Avoid**: *reduce unnecessary polluting trips* (fewer vehicle-kilometres travelled for passengers and freights);
2. **Shift**: *use less polluting transport modes* (such as mass transit or railways);
3. **Improve**: *reduce pollution of vehicles within each mode* (low carbon energy technologies and/or emission optimized operations).

The three drivers of the possible seventh revolution are opportunities to promote ASI policies and achieve the decarbonization aims promoted by the EU. The possible contributions of the innovations underway as well as their risks for environmental sustainability are displayed in Table 2.

Specifically, AVOID policies have the aim to reduce unnecessary polluting kilometyers travelled.. Smart mobility could be an opportunity to reduce vehicle- kilometres by increasing their occupancy. New dynamic ride-sharing systems have the potential to provide significant environmental benefits by reducing the number of cars used for personal travel and improving the utilization of available seat capacity (e.g.Agatz et al., 2012). Some research (e.g. Cepeliauskaite et al., 2021; Sarker et al., 2020; Kanchan et al., 2019; Canales et al., 2017) highlights the positive impact of info-mobility on reducing unnecessary kilometres travelled and so GHG emissions in the area. Specifically, dynamic trip-planning, on-demand mini busses, and real-time location-based shared smart parking systems, produce benefits in terms of reducing kilometres travelled (Sarker et al., 2020; Kanchan et al., 2019) especially in urban areas. The same is true for freight-as-a-service platforms such as Flock Freight whose aim is to reduce truck-kilometres by optimizing Less-than-a-truckload shipments (for details on Flock Freight see paragraph 3.2). Obviously, other innovations have to potential to reduce travel such as smart working, e-banking, e-learning, etc. These however are not part of the transport revolution as defined in this paper.

SHIFTING the travel demand from transport modes with a high environmental impact to more sustainable ones is a possible policy to

Table 2
Environmental sustainability: opportunities and risks.

	OPPORTUNITIES	RISKS
AVOID	**Smart mobility:** **ride-sharing**- increases vehicle occupancy (e.g. carpooling, FAAS), **info mobility**- dynamic trip-planning, on-demand minibuses and real-time location-based shared, smart parking systems, could produce benefits in terms of reducing unnecessary kilometers travelled	• Mobility levels may increase due to the reduction of travel costs and to the increase of travel comfort; • back-shift to individual vehicles due to multitasking possibility, lower driving effort, less congestion, safer trips with CAVs • extra km travelled by repositioning CAVs
SHIFT	**Transport decarbonization ± Smart mobility** electric car/ scooter/ bike in sharing could accelerate the shift from internal combustion cars to electric vehicles **Autonomous and connected vehicles:** lower production costs and more flexibility for unmanned public transportation could increase the shift towards public transport **Smart mobility:** **Maas-** increased the travel quality perception of public transport could increase the shift towards public transport **Smart pricing-** Possibility of travel demand management schemes by smart pricing could increase the shift towards sustainable transport modes	• energetic mix of electricity production.
IMPROVE	**Transport decarbonization:** new technologies could reduce the environmental impact of trips **Autonomous and connected vehicles:** The digital transformation of vehicles and infrastructure will allow • reduction of fuel consumption and pollutant emissions with eco-driving capabilities • possible increases in capacity due to CAV on existing roads and so the reduction of congestion and related emissions **Smart pricing** could promote lower energy consumption routes and/or travel times	

archive environmental sustainability. The new technology could make more attractive and unconventional public transportation. An improvement in the supplied service quality can attract further users and cars would be used less (with effect on environmental sustainability). MaaS has a positive impact on the perceived risk of the trips, on services reliability, and on the perception of travel time, these dimensions have a positive effect on travel satisfaction (e.g. Özer et al., 2013; Dziekan & Kottenhoff, 2007) and so on the number of trips by public transport (Eboli & Mazzulla, 2012). The same could happen as a result of production cost reduction following driverless public transportation (this effect has already been observed in driverless metro systems). Furthermore, new smart mobility services could be implemented in low-density areas. The shift towards greener transport modes can also be observed as a result of a policy of the variation of the travel cost. The possibility of travel demand management schemes by smart pricing and lower prices for unmanned public transportation could affect a modal shift from car to public transport (Cascetta et al., 2017).

Finally, sharing mobility with electric vehicles (electric car, scooter, bike) could lead to increased mileage with low or zero emissions vehicles as users can use electric vehicles, without having to buy one.

The policy of IMPROVE concerns all those policies that encourage the use of new vehicles with low environmental impact and/or with emission-optimized operations. The development of the new energetic vectors (transport decarbonization driver) can contribute to a significant reduction in kilometers traveled in energy-intense vehicles, reducing emissions from the transport sector (e.g. Kany et al., 2022).

Autonomous vehicles, with eco-driving capabilities, can produce a reduction of energy consumption and pollutant emissions (e.g.Ma et al., 2021; Igliński & Babiak, 2017). On this topic, Truck platooning is expected to significantly impact the road freight market and the environment. Some benefits are unanimously acknowledged (Marzano et al., 2022): platooning mitigates fuel consumption and emissions of greenhouse gasses, by improving trucks' aerodynamic performance.

Similarly smart pricing has the potential to promote lower energy consumption routes and/or travel times (Cascetta & Montanino, 2022).

The three drivers of the possible seventh revolution are opportunities to promote ASI policies especially in urban areas. In fact, there are positive experiences around the world of how the transformation of mobility services has quickly spread to urban areas and can be opportunities for sustainable development. For example, free-floating bike sharing in Beijing (Wang & Sun, 2022; Sun & Ertz, 2021), free-floating car sharing in some of European cities (such as Copenhagen, Rome, Hamburg, and London) (Jochem et al., 2020), car sharing in London, Madrid, Paris and Tokyo (Prieto et al., 2017) and in the Netherlands (Nijland & van Meerkerk, 2017), diffusion of on-demand minibus services in Melbourne (Liyanage & Dia, 2020), such as the Kutsuplus in Helsinki (Haglund et al., 2019), autonomous vehicles in Valencia (Zambrano-Martinez et al., 2019); Mobility as services in Helsinki (Jittrapirom et al., 2017) and the positive effects of the congestion pricing in Jakarta (Sugiarto et al., 2020) are some examples of how new forms of mobility can have positive effects in urban areas.

As for **social sustainability**, current innovations also have large potential and pose new challenges, as shown in Table 3.

Technological innovations of the seventh revolution however may also pose risks for environmental sustainability. For example, AVs increase the attractiveness of traveling by car due to the reduction of travel costs (e.g. European Commission, 2011; Bosch et al., 2016) and to the increase in travel comfort (e.g. due to a reduction in driving efforts due to CAV). This could lead to a backshift to individual modes and higher equilibrium-levels of congestion (Gruel & Stanford, 2016). Gaio and Cugurullo (2022) based on historical events and prevailing trends, have identified in the autonomous and connected vehicles the possible risk for the reduction of cycling, of public transportation, and other modes. In fact, the development of AV requires infrastructure design and possible development of urban areas focused on private transport and not on other modes of transport such as the bicycle. Further to this,

Table 3
Social and economic sustainability: opportunities and risks.

IMPACT	OPPORTUNITIES	RISKS
Social	**Transport decarbonization** Reduce air pollution and improve public health **Autonomous and connected vehicles ± Smart mobility** • increase of safety • increase mobility opportunities for social groups now limited • increase new costumer-tailored transportation services • enhance social cohesion in cities • reduce travel times increasing time available for other non-driving/travel activities • increase in public spaces in cities due to the reduction of parking needs	• increase the attractiveness of traveling by car leading to a higher level of congestion and related pollution with negative effects on public health • increases in social inequity due to the higher cost of electric and/or CAVs • reduction of driving jobs related passengers and freight vehicles
Economic	**Transport decarbonization** the reduction of transport costs due to reduced energy costs (e.g. renewable energy costs if the case) **Autonomous and connected vehicles ± Smart mobility** • increase revenues and job opportunities for different sectors (e.g. data services, digital media, electronics, and software) • new business opportunities in the mobility services industry • cost reductions for road transport commercial operations (due to fuel consumption and travel time decreases with truck platooning and cost saving due to driver time restrictions not being applied) • increases of capacity for existing infrastructures and reduced demand for new roads	• possible increases of vehicle production costs due to monopoly of raw materials needed in the transition to electric vehicles

Autonomous Vehicles–cyclist interaction is an important topic that could lead to a reduction in cycling mobility with impacts on environmental sustainability (Gaio & Cugurullo, 2022).

Furthermore, Spieser et al. (2014) and Fagnant and Kockelman (2014) show, in two case studies, that a shared-vehicle mobility system can satisfy the mobility demand of a city with significantly fewer vehicles while causing more vehicle km travelled for rebalancing the fleet.

Similarly, Ride Pilot technology (described in Section 3.2) could have the effect of increasing vehicle km travelled. The car can park (with autonomous driving) in parking lots distant from the place where the driver has abandoned the vehicle with extra miles for the positioning of the vehicles with a trade-off between central parking spaces and kms travelled (Stein, 2020). Finally, the risks to be taken into account in policies to encourage electric vehicles concern the energy mix used to produce electricity, not all of which have the same environmental impacts (The European House - Ambrosetti, 2022).

Transport decarbonization and the reduction of local pollution (e.g. particulate matter, acoustic, etc.) obtained with electric vehicles is a clear advantage for air quality and public health, especially in cities with high population density (Cartenì et al., 2020a).

In general, smart mobility and digital transformation can produce positive societal effects such as : *i)* increase of safety (reduction of road accidents due to human errors- Fagnant & Kockelman, 2015; Kockelman et al., 2016) *ii)* increase mobility opportunities for social groups with now limited access (e.g. providing elderly and handicapped with easily accessible way of moving around by themselves -Imai, 2019); *iii)* enhance social cohesion in cities (e.g. with dedicated services for the suburbs -Kopnina, 2017; Laamanen et al., 2015); i*v)* reduce travel times (due to the reduction of congestion and new mobility services) and so increases in time available for other non-driving/travel activities (Wang et al., 2017; Dresner & Stone; 2004; Fajardo et al., 2011), *v)* increases in public spaces in cities due to the reduction of parking needs (e.g. relocation of parking spaces for autonomous vehicles-Stein, 2020). Also freight transport, truck platooning is expected also to ameliorate traffic safety (Segata et al., 2015; Zheng et al., 2015; Tsugawa et al., 2011).

There are also risks for the social sustainability of the seventh revolution. The performances (social impact) of digital transformation of infrastructures are strongly influenced by the technological development of vehicles which will evolve towards automatic driving and vice versa. The positive effect on road accidents of CAVs will be seen with high penetration rates, while in the transition phase the effect could be marginal given the coexistence with traditional vehicles (e.g. E. Cascetta et al., 2022; IIA, 2021). At the same time, there is a risk that digital transformation will significantly increase the attractiveness of traveling by car and, consequently, traffic volumes will rise significantly, leading to a higher equilibrium-level of congestion (e.g. Gruel & Stanford, 2016). Among the possible social risks there is reduction of the labor force in some sectors due to automated driving and related transition (e.g. Kropp & Dengler, 2019). Furthermore, increasing the use to electric vehicles Section 3.2 and the circulation limitations to older and more polluting vehicles, may involve increases in social inequity. As a matter of fact higher purchasing costs of BEV w.r.t. ICE vehicles, possibly combined with restrictions to the latter, favour higher income groups and regions. This thesis is supported by the results of the regression analysis shown in Fig. 11. In particular, different regression models (e.g. linear, multiple, exponential, logarithmic, polynomial) were tested to evaluate if there is a correlation between BEV penetration on new car sales and GDP per capita. The percentage of new BEV registrations w.r.t. the number of total new registrations was estimated for 20 European

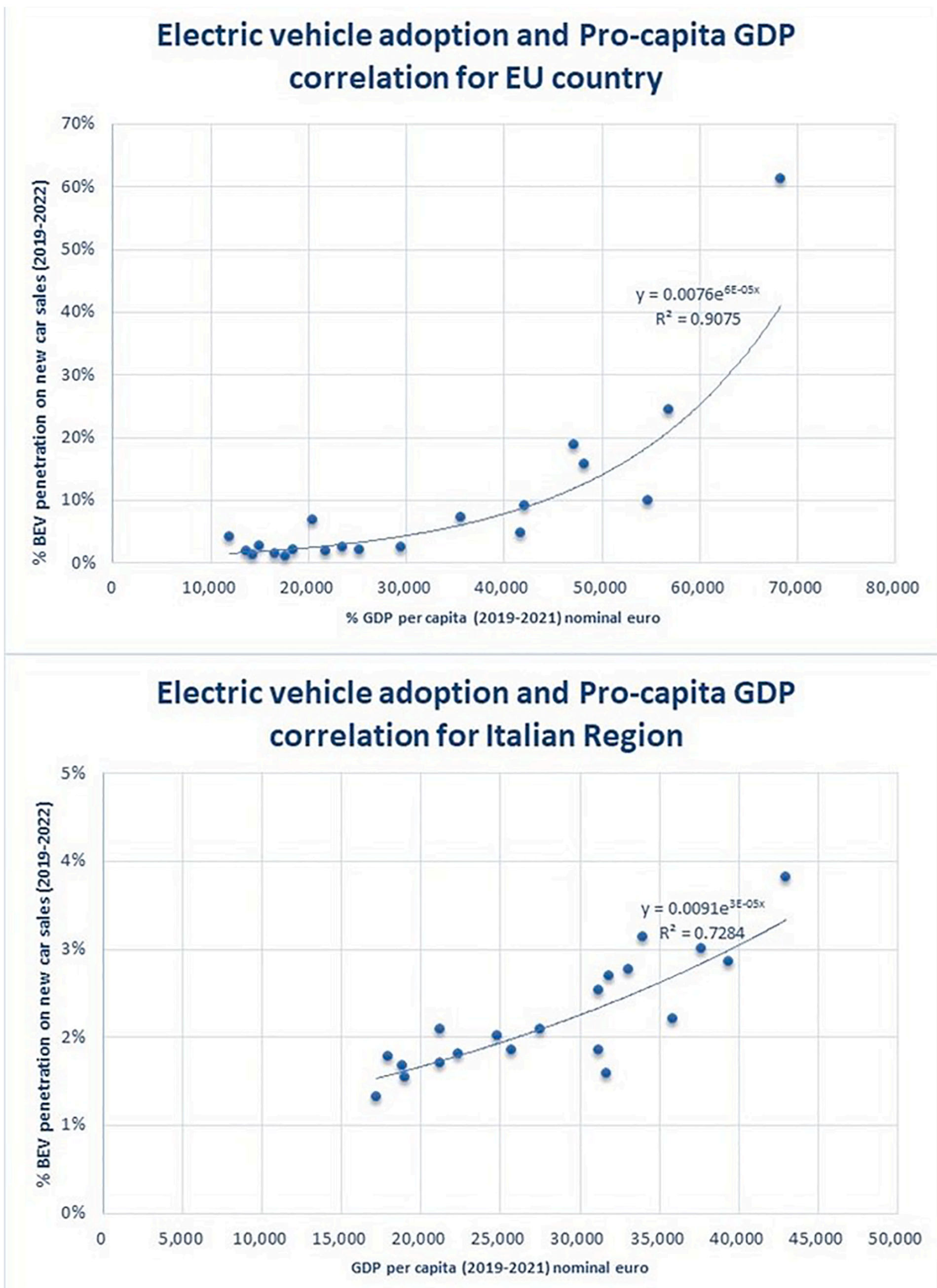

Fig. 11. Electric vehicle adoption and Pro-capita GDP correlation for EU country and Italian Region.

countries (Italy, Belgium, Croatia, Denmark, Estonia, France, Germany, Greece, Hungary, Lithuania, Holland, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Iceland, Norway) and for the 21 Italian regions (Abruzzo, Basilicata, Calabria, Campania, Emilia-Romagna, Friuli-Venezia Giulia, Lazio, Liguria, Lombardy, Marche, Molise, Piedmont, Puglia, Sardinia, Sicily, Tuscany, Trentino Alto Adige, Umbria, Valle d'Aosta and Veneto) based on official data (EUROSTAST and ACI) for the years 2019 and 2022 respectively. The regression results (Fig. 11) show that there is an exponential correlation for these countries/regions between BEV penetration on new car sales and GDP per capita.

These results suggest that policies that limit access to non-electric vehicles can increase social inequalities in terms of accessibility. Similar results are found in other research (e.g. Sierzchula et al., 2014; Tu & Yang, 2019; Ruoso & Ribeiro, 2022) and also in relation to ADAS supported cars.

Also for **economic sustainability**, ongoing technologic innovations present risks and opportunities (Table 3). The opportunities concern the reduction of transport costs due to reduced energy costs (e.g. renewable energy costs and mechanical efficiency of electric motors) and driving costs (autonomous driving) for passengers and freights (e.g. Gruel & Stanford, 2016). The practice of sharing promises to provide an opportunity to save and/or make money (Fang et al., 2016; Heo, 2016) and in general to facilitate sustainable economic growth (Bonciu & Balgar, 2016). Clements and Kockelman (2017) through a quantitative approach, examine the socioeconomic effects of the introduction of AVs in the United States considering many economic sectors (e.g. the automotive industry, electronics and software technology, trucking and freight movement, personal transport, auto repair, medical services, legal assistance, construction and infrastructure, land development, digital media, oil and gas). In their research, they provide an estimation of economy-wide effects that could lead to an increase of 8% of US gross domestic product (GDP). Due to the diffusion of new technologies is expected an increase revenues from different sector such as data services, digital media, electronics and software (Alonso Raposo et al., 2018). New services linked to vehicle automation and connectivity will increase revenues from data services and increased demand is expected in sensors, controllers, actuators, self-driving software, maps, etc. that will be required for automated driving. Manufacturing and service industries, both big and small and medium-sized enterprises (including start-ups), will also profit from new business opportunities that concern automation and robotics, services for citizens' mobility, and new transport services, (European Economic and Social Committee, 2017).

Revenues from road transport commercial operations could increase as fuel consumption and travel time decreases with truck platooning, number of truck drivers needed decreases (even if wages could increase with a more technical role, e.g. monitoring the CAV) and if driver time restrictions no longer apply (Alonso Raposo et al., 2018, European Economic & Social Committee, 2017).

Furthermore, it is expected increases in capacity for existing infrastructures (with smart roads and CAVs) (e.g. Diakaki et al., 2015), demand for new roads construction could instead decrease saving expansive new motorways construction projects. Other possible economic risks related to the decarbonisation of transport concern the possibility of increases in production costs due to semi-monopolistic control of minerals such as rare earth and related geopolitical conflicts.

These effects are the ones currently perceived by experts in this first stages of the seventh revolution and at the time is not known how is going to be the final balance on sustainability between opportunities and risks

In addition, there will be impacts that at this early stage are very difficult, if not impossible to anticipate as already happened for other revolutions in history. This may include the shape of cities, the same structure of inter-personal relationships and the society as well as the production/ distribution cycles. These are the kind of effects that follow from the law of "unintended consequences" pertaining to revolutions. Only time will tell.

5. Conclusions

In this paper, we presented the technological innovations that are affecting virtually all aspects of transportation systems under a holistic perspective. Transport revolutions, produced by a combination of technological innovations and related organizational ones, affect the structure of society in significant and often unpredictable ways in a relatively short period of time. Under this perspective, the trajectories of innovation in separate areas, such as new energy vectors to decarbonize transport, autonomous driving, and innovative mobility services converge and interact. Their interactions and evolutions will define the land-scape of future mobility systems for people and freight and probably will change the structure of our society, as it has been the case in a few corresponding historical circumstances. In this paper, after analyzing the past and the 6 revolutions that occurred in remote and recent history, we analysed what are the current developments of the above innovations and some of the potential effects, either desirable or not, they could have on environmental, social, and economic sustainability of the transportation system.

Focusing on the possible impacts of the seventh revolution on urban areas, history shows that changes in transport produced changes in urban design and (e.g. Mumford, 1961; Lynch, 1964) therefore changes in sustainability (Cugurullo et al., 2021). For examples, the spread of AVs could lead to a reduction in car ownership and therefore the number of cars in the city could potentially decrease. Consequentially, many urban spaces currently meant for automobiles could become obsolete, thus becoming prone to being repurposed as bike paths, gardens and public places which would increase urban sustainability. However, the development of very comfortable cars driven by an artificial intelligence that promises onboard productive and recreational activities, it could increase the demand for cars, and therefore the amount of urban spaces and energy that is needed to sustain them. So, it is therefore important that decision-makers in the near future know the risks and opportunities of the seventh revolution and can make rational decisions in order to exploit the opportunities and keep the risks under control.

The challenge for transport policy -makers will be to imagine possible futures and making decisions in a context of deep uncertainty (e.g. Marchau et al., 2019). Deep uncertainty is referred to one in which there are a virtually infinite number of possible future scenarios without the possibility to give a-priori probability to them.The uncertainty sources at this point are related to (i)demand, (e.g. socioeconomic variables related to travel demand, users' trip and travel behavior); ii) supply (e.g. supply performances, technological disruptive innovations) and iii) context (e.g. societal values and preferences, global and local regulations) (Cartenì et al., 2022). The new decision making challenge will require new approaches to the task allowing open and dynamic settings as well as the structuring as dynamic processes (e.g. Cartenì et al., 2022). In addition to knowing the opportunities and risks of the seventh revolution, public participation is essential to imagine and create a sustainable future of urban transport and mobility, given the intrinsically political nature of the process. To this end, Acheampong et al. (2023) proposed a multi-criteria visioning and appraisal framework and methodology to help the decision makers to envision the role of new mobility in the future.

To this end, scientific research can help shape the future of mobility The perception of the current time as a revolutionary phase should change the approach of researchers and practitioners in the wide field of transportation system analysis with respect to the last evolutionary decades. Future research, in addition to sector specific evolutions, should focus on the actual holistic deployment of the seventh revolution trying to continuously update its combined effects and anticipate as much as possible its trajectory in order to reduce undesirable ones while boasting desirable ones

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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