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Electric Vehicles in Logistics and Transportation: A Survey on Emerging Environmental, Strategic, and Operational Challenges

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Abstract: Current logistics and transportation (L&T) systems include heterogeneous fleets consisting of common internal combustion engine vehicles as well as other types of vehicles using "green" technologies, e.g., plug-in hybrid electric vehicles and electric vehicles (EVs). However, the incorporation of EVs in L&T activities also raise some additional challenges from the strategic, planning, and operational perspectives. For instance, smart cities are required to provide recharge stations for electric-based vehicles, meaning that investment decisions need to be made about the number, location, and capacity of these stations. Similarly, the limited driving-range capabilities of EVs, which are restricted by the amount of electricity stored in their batteries, impose non-trivial additional constraints when designing efficient distribution routes. Accordingly, this paper identifies and reviews several open research challenges related to the introduction of EVs in L&T activities, including: (a) environmental-related issues; and (b) strategic, planning and operational issues associated with "standard" EVs and with hydrogen-based EVs. The paper also analyzes how the introduction of EVs in L&T systems generates new variants of the well-known Vehicle Routing Problem, one of the most studied optimization problems in the L&T field, and proposes the use of metaheuristics and simheuristics as the most efficient way to deal with these complex optimization problems.

Keywords: electric vehicles; logistics and transportation; green vehicle routing problems

1. Introduction

Logistics and transportation (L&T) activities represent a key sector in worldwide economies, and are a significant contributor to social and economic progress in modern societies. The prevalence of the L&T industry is due to its constant growth and impact in terms of regional Gross Domestic Product (GDP). In particular, road L&T activities using motorized vehicles have significantly increased in response to the rise of globalization and commercial interchanges among countries. With the aim of making them more efficient, L&T systems have been widely studied by the Operations Research/Computer Science (OR/CS) communities for decades. Due to its potential applications to real-life operations, one of the most recurrent topics in the L&T literature is that of modeling and optimizing tour assignments of vehicles. This is known as the Vehicle Routing Problem (VRP) [1]. Numerous variants of this problem have been addressed over the last years. The basic variant is the so-called Capacitated VRP (CVRP), where each customer has a given demand that has to be satisfied without exceeding a maximum vehicle capacity. The VRP with Time Windows extends the CVRP by adding time windows to the depot and the customers. To account for additional real world aspects, the classical VRP has been redefined in various manners that are often called Rich VRPs [2] or Multi-attribute VRPs [3]. Despite the extensive literature in the VRP area, most of the existing contributions have assumed that the fleet to be managed comprises only internal combustion engine vehicles (ICEVs), which is not exactly the current picture.

A large percentage of the oil consumed in regions such as Europe or the USA is used in transport, while road transport accounts for an important percentage of CO_2 emissions of the overall transport activity. Furthermore, the whole transport sector causes about 28% of the total greenhouse gas (GHG) emissions in countries such as the USA. In order to mitigate this situation, one possibility is to incorporate emission costs as an objective to be minimized in routing models, thus trading off environmental and economic goals [4,5]. A different approach is the utilization of less polluting means of transport such as plug-in hybrid electric vehicles and electric vehicles (EVs), whose specific characteristics have to be included in adequate routing models. In effect, as part of the initiative to improve the local air quality, modern cities encourage fleets of vehicles to adopt alternative technologies, such as EVs. Several factors are promoting the use of these technologies, including: (i) companies receive incentives to reduce their carbon footprint; (ii) high variability of oil-based products and long-term cost risk associated with dependence on oil-based energy sources; (iii) availability of government subsidies to reduce acquisition cost; and (iv) advances in alternative energy technologies (such as EVs), which have potential for a more environmentally sustainable solutions at a cost that is starting to be competitive. From both an environmental and energy standpoints, the use of EVs should be a first priority for the reduction of primary energy consumption. Although higher concerns are the advantages of EVs in terms of efficiency and flexibility in the use of energy, the EV technology is currently facing several weak points, which can be summarized as follows: (i) the low energy density of batteries compared to the fuel of ICEVs; (ii) the long recharge times of EVs batteries compared to the relatively fast process of refueling a tank in ICEVs; and (iii) the scarcity of public and/or private charging stations for EV batteries. In earlier years, EVs failed because of excessive battery prices and very short driving ranges. As EVs have become one of the major research areas in the automotive sector, the magnitude of these problems has been notably diminished. Although the replacement of conventional ICEVs with EVs is not profitable under most operation scenarios given the current cost conditions, the availability of increasingly long-lived batteries, the trends for rising fuel costs, and lower EV purchase costs are likely to change the picture [6]. Figure 1 shows the noticeable increase experienced during the last years in the number of EV-related articles published in Scopus-indexed journals, which proves the growing interest that the use of EVs is arising among researchers and practitioners.

Accordingly, this paper identifies and reviews, from an OR/CS perspective, several open research challenges related to the introduction of EVs in L&T activities, including the following dimensions: (a) environmental-related issues; (b) strategic and planning challenges associated with "standard" EVs and with hydrogen-based EVs; and (c) emerging operational issues related to the use of EVs in VRPs. Table 1 summarizes the different research challenges that have been identified in our study and that will be conveniently described and reviewed in different sections of this manuscript. For a better understanding, these research issues have been classified in three dimensions: environmental, strategic and planning, and operational. The paper also analyzes in detail how the introduction of EVs in L&T systems generates new VRP variants, *i.e.*, in the context of the Green VRP, this work points out some of the most promising research lines yet to be fully explored. Finally, the paper also includes a discussion on which optimization approaches can better contribute to deal with these open and difficult research challenges.

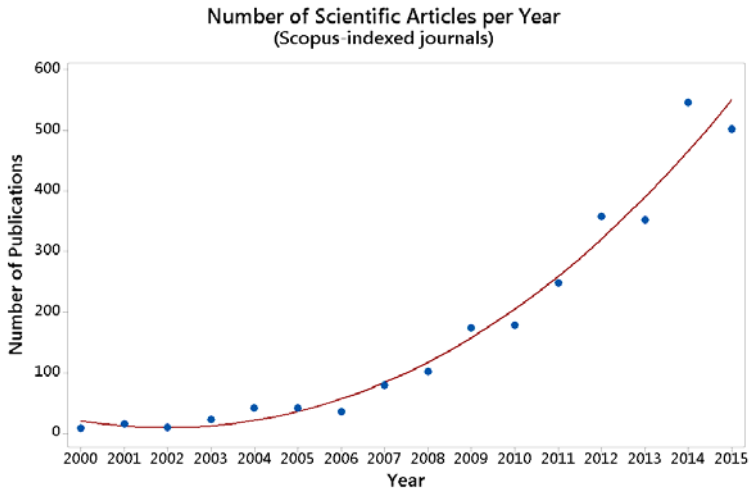

Figure 1. Evolution of electric vehicle (EV) related publications in Scopus-indexed journals.

Table 1. Open Operations Research/Computer Science (OR/CS) research challenges associated with the use of EVs.

Dimension	Research challenges
Environmental	(1) Including the cost of externalities (noise, air pollution, infrastructure wear, *etc.*) in L&T activities. (2) Analyzing how the increasing use of EVs reduces the environmental impact of L&T activities. Exploring new environmentally-sustainable yet efficient ways of doing freight deliveries in urban areas. In particular, considering energy cost and carbon footprint in Vehicle Routing Problems. Studying the environmental cost of manufacturing EVs as well as producing the energy needed to power them. (3) Measuring the effect of using small EVs (e.g., electric bikes, drones, *etc.*) to perform urban last mile distribution.
Strategic and Planning	(1) Analyzing different EV related technologies and infrastructures (e.g., standard EV *vs.* hydrogen vehicles). (2) Computing the necessary recharging stations, both for standard EVs as well as for hydrogen vehicles, and analyzing their integration in the transport network, *i.e.*, number and type of stations, location, capacity, *etc.* (3) Determining the optimal combination of EVs and internal combustion engine vehicles (fleet size and mix problem). In particular, developing new optimization approaches for the Fleet Size and Mix Vehicle Routing Problem. (4) Exploring potential uses of renewably-generated electricity to power hydrogen vehicles. (5) Quantifying the benefits of horizontal cooperation among stakeholders of EV fleets (e.g., fleet manager, auto manufacturer, electricity supplier, *etc.*).
Operational	(1) Analyzing the impact of EVs recharging times in Vehicle Routing Problems with time-related constraints. (2) Comparing battery swapping *vs.* battery recharging strategies, and proposing the right combination of both. In particular comparing these strategies in Vehicle Routing Problems with EVs. (3) Considering the new issues derived from the driving-range limitations of EVs. In particular, developing new optimization approaches for the Vehicle Routing Problem with multiple driving-range constraints.

The remainder of this paper is structured as follows: Section 2 reviews and analyzes some of the environmental issues related to the use of EVs. Section 3 builds on Section 2 and identifies the main strategic and planning challenges related to the introduction of EVs in "green" L&T activities. Section 4 extends Sections 2 and 3 by focusing on how the introduction of hybrid fleets with both ICEVs and EVs imposes new operational challenges and exploring opportunities on the popular VRP. Section 5 points out some new solving approaches that allow facing these challenges in an efficient way. Section 6 provides an overview of other related emerging issues, such as lifecycle cost analysis and the use of EVs in rural areas and to confront natural disasters. Finally, Section 7 summarizes the main contributions of this paper.

2. Environmental Issues Related to the Use of Electric Vehicles (EVs)

2.1. Environmental Aspects of Transportation

Transportation activities involve the side effects (externalities) of noise pollution, air pollution, and traffic congestion, which current city planning strategies hardly take into account. Given that the transport sector accounted for more than a 25% of world energy consumption, and producing energy increases air contamination, these externalities must be considered to ensure the sustainable growth of transportation worldwide [7]. A complete description of the problem of externalities in transportation would involve the introduction of the following sources of external costs: noise, air pollution, infrastructure wear, visual intrusion, flow congestion, traffic accidents, and so on. Nonetheless, the main environmental studies are performed on the noise and air pollution caused by transportation, due to the fact that they are very well-known externalities. Some reports and studies have tried to assess the economic impact and pricing of these externalities in Europe, but their results have not been conclusive so far. In effect, there is a great divergence in the cost estimation of externalities [8]. According to Korzhenevych *et al.* [9], external costs of transportation activities account for about 8.5% of the GDP in regions such as the European Union. These activities represent one of the largest sources of CO_2 emissions, and there is a strong interest in mitigating their effects.

Nowadays, there is a general agreement on the need to consider these negative externalities when formulating transportation policies and logistic strategies. For instance, the European Union has developed an infrastructure-use taxation system based on the "user and polluter pays" tenet. In extraordinary cases involving infrastructures in mountainous areas, the directives suggested the rise of toll charges. Some of these directives highlight that particular attention should be devoted to mountainous regions, such as the Alps or the Pyrenees, with the consequent apportionment of European Union taxpayers' money to its related projects. The suitable pricing of all the aforementioned externalities is essential for the success of any consideration of adequate payments in transportation policies. As stated before, two main types of traffic-related environmental pollution are considered: air pollution and noise pollution. The previous discussion about the importance of controlling different types of contaminating emissions explains the need for searching new technologies that allow reducing the environmental impact of freight transportation activities. In this sense, the increasing use of EVs in hybrid fleets constitutes a fundamental step in this direction [10]. Some basic figures will help to understand the potential contribution of EVs in promoting sustainability of freight-distribution operations: according to Figliozzi [11], while a diesel van delivering goods in a "standard" city releases about 1.0375 $kgCO_2$/mile, using an EV instead would produce just about 0.01915 $kgCO_2$/mile (notice that this number corresponds to the estimated emissions produced by the source of electrical power necessary to run the EV). In other words, a diesel van (ICEV) covering a mile produces about 54 times the CO_2 emissions released by an EV to do the same distribution activity. Of course, this huge advantage has to be considered along with the associated disadvantages, e.g., limited autonomy of the EVs, reduction of the load to carry per mile, *etc.* Further, there are different alternatives to the use of "pure" or "standard" EVs, among them hydraulic hybrid EVs [12] as well as hydrogen-based EVs [13], which would further reduce CO_2 emissions. From this simple example, it seems clear that the contribution of EVs to environmental sustainability can be significant.

2.2. Environmental Impact of Delivering Goods in Urban Areas

During the last decades, a large percentage of the world's population has moved into cities [14]. Therefore, all L&T issues related to procurement and supply management of cities are critical. City managers try to identify new strategies to increase the quality of life of their citizens while maintaining their economic competitiveness. For that reason, cities around the world are worried about designing sustainable yet efficient ways of doing freight deliveries in urban areas [15]. In Europe and USA, around 80% of the population lives in urban areas already. Since urban areas usually contain large populations, extensive commercial establishments, and an increasing demand of services and commodities, there is a need to increase the frequency of urban deliveries, which requires an intensive use of the existing infrastructure. According to the US Federal Highway Administration, the total vehicle miles of travel increased 21% in the urban areas between 1996 and 2006. In fact, according to Feng and Figliozzi [16], the proportion of freight vehicles crossing urban zones also increased from 4.8% to 5.2%. As discussed before, freight distribution in densly populated cities are related to negative transportation externalities, such as congestion, pollution (both gas emissions and noise), energy inefficiencies, decreasing road safety, infrastructures degradation, lack of roadway capacity and parking space, worse breathing conditions, *etc.* As pointed out by Russo and Comi [17], urban freight vehicles account for about 6%–18% of the total urban travel, for about 19% of the energy use, and for about 21% of the CO_2 pollution.

Some of the typical pollutants in urban districts are the following [18]: (i) mono-nitrogen oxides, which are produced by the combustion of fossil fuels and contribute to generate smog and acid rain; (ii) sulfur oxides; (iii) carbon monoxide; (iv) particulate matter; and (v) volatile organic compounds. All the previous gases have negative effects on people's health, as discussed in Bernard *et al.* [19]. As a consequence, there is a strong impulse at international, national, and local levels to mitigate them by switching to zero emissions technologies, the shift to EVs being one of the most promising policies. Also, this shift can be a good solution to relieve other problems related to urban distribution. Thus, for instance, Nüesch *et al.* [20] propose a method to minimize the fuel consumption using hybrid EVs while tracking a given reference trajectory for both emissions and the battery state of charge. Similarly, Collin *et al.* [21] design a generic methodology to incorporate environmental and battery-related constraints into on-line energy management strategies for different types of hybrid EVs, while Chen *et al.* [22] introduce an energy management approach to minimize total energy cost associated with the use of hybrid EVs. Finally, in the context of urban transportation networks, Hwang *et al.* [23] propose a stochastic model to minimize the expected total cost of freight truck activities, where these costs include total delivery time, different types of emissions, and a penalty for late or early arrival.

Urban transport usually involves vehicles operating with low loading levels, thus resulting in a non-efficient use of oil-based energy. Moreover, urban delivery vans have a low average driving speed, and electric engines are more efficient at low speeds. Likewise, the routes covered in urban distribution are quite similar from one day to another, which can facilitate the design of stable policies for battery recharging or battery swapping. It is clear then that a shift from a fossil fuel fleet to an electric-powered fleet is necessary in order to reduce pollutant emissions in cities. A conversion to EVs would imply the conjoint development of transportation and power generation sectors, and would shift GHG emissions from conventional vehicle tailpipes to big electric power plants.

On the one hand, EVs using electricity from the public grid will play a critical role in reducing GHG emissions and in mitigating negative transport externalities. Nevertheless, these reductions in emissions will be only possible within a scenario of low-carbon electricity production, *i.e.*, the replacement of ICEVs by EVs is only reasonable if the electricity generation has a low level of carbon production. Otherwise, one pollutant technology would be swapped by another pollutant technology (maybe less pollutant, but not really sustainable either). Additionally, EVs are ideal to make the distribution of light products with a low emission pollutants impact in city centers. That fact is due to: (i) the lack of gas releases in EVs; and (ii) the usually small size of EVs, which allows them to easily access high congested streets with limited parking space. Many cities allow EVs to use parking spaces for free. Thus, EVs are constrained to a lesser degree by the existence of congestion or lack of parking areas than ICEVs. This implies that the walking distances covered by the drivers of EVs are usually shorter than the ones performed by ICEVs drivers [24]. In fact, it is common to see conventional vehicles double-parked or parked in restricted areas to diminish the walking distance delivery, having to pay in many cases extra costs due to parking fines. Moreover, other advantages of EVs are related to the lower noise level produced by their use in comparison with the noise level of ICEVs [25]. Many papers have been published highlighting the good properties and advantages of EVs [26], but little work has been done so far to evaluate the environmental impact of the EVs production itself and the electricity power generation. In fact, to the best of our knowledge, there is no published carbon footprint comparison between companies which use ICEVs and those using EVs [27].

2.3. Decarbonizing the Last-Mile Delivery Process with the Use of EVs

The study and development of the EV Routing Problem, along with the variation in competitiveness due to the introduction of EVs in hybrid fleets, is a recent study area with many real applications. As noticed by Afroditi *et al.* [28], this study is especially interesting in the "last-mile" delivery process. The distribution process is usually critical in the last mile of the supply chain, where most of the difficult operational decisions to make are present. In effect, it is in this last mile where more details can affect the quality of the delivery service, where more routes are formed, and where the direct contact with the final customer makes a critical mix between L&T and marketing. This situation involves an exhaustive use of L&T resources to achieve the expecting quality of the delivery process. An exhaustive use of resources usually causes more negative externalities (congestion, emissions, and noise, among others). Therefore, the use of EVs in the last-mile activity can help to significantly reduce the level of the aforementioned externalities. This improvement has been clearly shown in many European cities such as Paris, London, or Vienna [29]. Thus, the EVs are revealed as a very useful tool to "decarbonize" the last mile delivery process, although their range limitation could be an important disadvantage in some cases.

The typical design of an EV is conceived in the shape of a small vehicle to take advantage of its capacity and its performance according to the electric power of its battery. Nevertheless, it is also possible to design EVs with the shape of a bike with a small electric engine hybridized with human power propulsion. These bike EVs are usually presented in the way of tricycles to provide them with more capacity. Delivery actions in the last-mile range using electric tricycles are becoming increasingly common, mainly in very congested cities [30]. These vehicles clearly benefit from the option of recharging batteries with the use of human power propulsion. Some companies showing this experience in freight deliveries are, among others: Ecopostale (Brussels, Belgium), B-line (Portland, OR, USA), La Petite Reine (Paris, France), or Txita (San Sebastian, Spain). Some studies performed by these companies range the savings in CO_2 emissions from the 8.5 tons per year (Ecopostale) to the 89.125 tons per year (La Petite Reine) of oil equivalent. Another interesting experience concerning the evaluation of results in last mile delivery optimization is depicted by Browne *et al.* [25], who described a trial of shipped goods from a suburban depot serving customers in London. In their study, the fleet of ICEVs performing deliveries in London was replaced by EVs and tricycles working in a consolidation center in the British capital. The normal use of those EVs is not interfered with by any fossil fuel consumption or greenhouse effect due to the fact that the electricity they use was exclusively generated by renewable sources. By making a direct comparison between the emissions with conventional ICEVs and with EVs, it is possible to conclude that CO_2 emissions fell by 20% if using standard EVs and by 54% if using tricycles. Moreover, GNewt Cargo, the operator of the micro-consolidation center, certified that it is possible to cut the CO_2 emissions by 62%. Similarly, Conway *et al.* [29] describe two case studies in New York (USA) where the use of electric cargo cycles involves a savings of 11–13 tons/year of CO_2 emissions and 2–2.5 lbs/year of particulate matter for the first case, and 8.3 tons/year and 1.6 lbs/year, respectively, for the second case.

As discussed in Bektas and Laporte [5], the inclusion of pollutant emissions in vehicle routing problems has allowed the design of new routing models and the development of new optimization algorithms. Likewise, it has generated an updated classification of pollution pricing models inside the VRP framework [31,32].

3. Strategic and Planning Issues Related to the Use of EVs

Due to the different aspects that distinguish EVs from traditional ICEVs, the L&T problems that have been addressed so far for conventional vehicles need to be rethought and reformulated to take into account the new features of EVs. Unlike conventional vehicles, EVs must refuel frequently due to the short length of their batteries in terms of travel distance, *i.e.*, their limited driving range [10]. Thus, users must consider how many miles can be covered before a recharge is needed. There is no doubt that this restricts their use as transport tools. Therefore, the provision of the necessary recharging stations and their integration in the transport network are important issues to address. The main issues to determine are: (i) the number and kind of refueling stations to establish; (ii) the location of these stations; and (iii) their optimal capacity. Moreover, companies need to assess the impact of the introduction of EVs in their fleet, so that they can choose the best size and mix of vehicles to use. Hence, the fleet size and mix is another important issue to analyze. The following subsections are devoted to review and describe the influence of some of these aspects in the L&T arena.

3.1. Different Kinds of Recharging Stations

As EVs are entering the market, there is a rising demand for public refueling stations. Nowadays, when the EV's batteries are depleted there are two possibilities: recharge them or exchange them. Charging stations can be divided into two categories: fast charging and slow charging. A fast refueling station can quickly recharge an EV in less than five minutes [33], but this kind of charging can significantly shorten the life of the batteries. Conversely, a slow refueling station needs a longer time to recharge an EV. At slow recharging stations of Level 1 or 2 (110–240 V), vehicles need to wait from 2 up to 8 h to fully charge their batteries. At recharge stations of Level 3 (480 V), charging a battery fully takes about 20–40 min. Therefore, recharge time has been a critical factor influencing public acceptance of EVs. A major solution could be to remove the existing battery that is nearly depleted and replace the battery with a fully charged one, as proposed by Li [34]. Such a method is called battery swapping. The main benefit associated with the swapping model is the speed. The whole operation could take less than 10 min, which is on par with conventional vehicles and much faster than even some fast recharging stations. Other noted features of battery swap stations include the following: (i) charging depleted batteries can be left for the night when the charging cost is low; (ii) the provision of grid-support service in a centralized charging and discharging manner; (iii) the ability for drivers to resume their journeys in minutes with a full-capacity battery; (iv) the charging of batteries in slow-charging mode to extend their lifetime; and (v) the savings in cost of EVs by providing batteries by operators. As pointed out by Yang *et al.* (2015) [35], a battery swapping model could be considered more appropriate than a battery recharging model since the former not only improves the productivity of vehicles but also lowers the charging cost. Due to the battery driving range limitation and the nature of battery swapping, distribution network optimization with a battery swapping infrastructure could be an important part of establishing any green L&T policy. However, companies can take this possibility, since the best battery swapping infrastructure ownership model is the company-owned business model, which indicates that the L&T companies establish and operate the battery swap stations for the EVs by themselves. This way, determining the ideal battery swap stations location strategy and vehicle routing plan for a distribution network is mainly a question of service level and operational cost for the logistics enterprises.

All in all, the major challenges encountered regarding the kind of EVs recharging stations are summarized next. On the one hand, EV consumers expect a short charging time just like refueling their current vehicles. This requirement makes fast charging stations more preferred, but this kind of charging can shorten the life of the batteries. Moreover, as clearly explained in [36], implementing centralized charging/discharging control under plug-in mode is very difficult, since EV users present a stochastic charging profile. In order to avoid uncontrolled charging, which may produce a significantly increase of the peak load and endanger power system security , some incentive strategies could be proposed. On the other hand, considering the aforementioned challenges, an alternative strategy based on a battery swap station has received increasing attention during recent years [37–39]. However, battery swap stations have the problem of the lack of unified battery standards for various EVs. As will be discussed in the next subsection, the majority of papers in the literature tackle transportation problems using EVs with charging stations. Nevertheless, there is an emerging number of works considering battery swap stations.

3.2. Recharging Station Location

As mentioned before, one of the main issues to be addressed regarding the EVs success is to determine the location of recharging stations. Therefore, it is important to develop methods that allow minimizing the costs of developing an alternative infrastructure. This "station location problem" can be considered a specific case of Facility Location Problem (FLP). The key questions commonly faced by facility planners include: (i) the number of facilities; (ii) the locations of these facilities; and (iii) the types of facilities (in terms of size, product variety and other design aspects). Most location models focus on either minimizing the average cost of travel (the median problem) or minimizing the maximum cost of travel (the center problem). In the particular case of optimally locating recharging stations, several location models have been proposed. These models can be divided in two main groups, node-based and flow-based, depending on their assumptions of refueling demand type [40]. The p-median model is a well-known node-based model that has been used in many articles to locate conventional gasoline or alternative-fuel vehicles refueling stations [41]. However, since the demand for vehicles is generally in the form of traffic flow that passes by the refueling facilities [42], the majority of papers in the literature are based on flow-based models. Specifically, the locations of recharging stations for EVs, which presents some peculiarities due to their limited driving range, is usually tacked using flow-based models. Thus, Hodgson [42] provided a basic theoretical framework for dealing with the problem of locating stations. However, this approach depends on the assumption that, if one station is sited on a node of a path, then all the related traffic flows will be captured. Unfortunately, this assumption cannot be applied to alternative fuel vehicles since these have a limited range and need a multi-stop system to extend their driving distance and carry out long-distance journeys.

In order to achieve the multi-stops needed for long-distance travel, Kuby and Lim [43] proposed a flow refueling location model (FRLM). The objective of the FRLM is to maximize the capture of the traffic flows on each path if a combination of stations sited on the paths can be successfully used to refuel vehicles, so that they can complete their trips. This model needs to be solved in two stages. The first stage is to find feasible combinations of candidate locations of stations to refuel the flows on each path, and the second stage is when these combinations are used as inputs to the model to determine the station locations. Due to the time-consuming process of generating combinations in first stage, Lim and Kuby [44] provided some heuristic algorithms to solve larger scale problems. Capar and Kuby [45] developed a new approach to solve the flow refueling location problem in one stage. Three locating logics were used to check whether a path could be refueled by the sited refueling stations. The first is if there is no station built at the origin then there should be at least one station built within half the vehicle range to the origin node, so that it can be reachable by half a tank of fuel or half a battery charge. The second is if there is a station built at a location, then the next built facility should be within the vehicle range, otherwise the vehicle cannot reach the next station. The third is if the vehicle range is greater than or equal to two times the path length, then a single station at any point can refuel the entire path. However, these logics are available only when the vehicle has regained its full fuel or charge level (for maximum range) after each period of refueling at the stations, e.g., via fuel-tank or battery exchange, which makes the newer approach difficult to apply with regard to multiple types of stations with different refueling or recharging efficiencies. In addition, this approach cannot solve the capacitated location problem, whereby each station has a limited number of demands to handle. Basically, such models do not consider the factors of refueling or recharging efficiency and time, and are limited to the location of a single kind of station for performing the battery exchange (or very fast refueling) to refill the vehicles.

For deploying battery swapping network infrastructure and battery management, Mak *et al.* [46] developed two distributionally robust optimization models for the battery swap station location problem under ambiguous information on demand distribution. A different flow-based model for economically siting fast-refueling stations, such as battery swapping or hydrogen refilling stations, was proposed by Wang and Lin [47]. The model was formulated based on vehicle refueling logic which can ensure the alternative fuel vehicle has sufficient fuel to move between the nodes, and a feasible path can then be achieved. The model can also be solved in one stage, *i.e.*, it does not need to pre-determine the feasible combination of stations, like the original FRLM does. Moreover, this approach does not need the fuel or charge level after each refueling or recharging to be full, and thus has more flexibility with regard to different situations. Wang and Wang [33] extended the aforementioned model and proposed a bi-objective model to simultaneously consider intercity (path flow demands) and intra-city travel (the nodal demands). The flow-based model was also extended to consider battery recharging efficiency and time to locate sufficient slow-recharging stations for electric scooters traveling in a destination area [48]. However, these previous models still adopt an approach for locating a single kind of refueling stations. In Wang and Lin [47], the authors extended the previous slow-recharging station location model by considering facility budget constraints, multiple kinds of recharging stations, and vehicle routing behavior. These authors also proposed more generalized models to locate multiple kinds of refueling stations for the (maximal) coverage of battery (or non-battery) powered EV journeys on each path. At each site along paths, multiple types of charging stations, including slow-recharging, fast-recharging, and battery exchange stations, would be candidates to locate stations based on consideration of the station locating cost, recharging efficiency and time, and vehicle routing behavior. Furthermore, the available refueling time (also the length of stay) at each site can be divided into three categories, including the sight-seeing or recreational time at attractions, the battery switching time at convenience stores, and the normal refueling time at common sites (similar to the refueling time at gasoline stations). This new proposed model was compared to that produced for siting a single type of recharging station.

You and Hsieh [49] developed another model to address the problem which simultaneously combines the locations and types of recharging stations. In this case, the objective was to find the optimal origin-destination trips and alternative-fuel vehicle kinds of stations such that the number of people who can complete round-trip itineraries is maximized. These authors proposed a hybrid heuristic approach to solve this model.

Regarding hydrogen-based EVs, Melaina [50] performed a preliminary analysis in order to estimate the number of initial hydrogen stations required by emulating the existing gasoline infrastructure. Nicholas *et al.* [51] used geographical information systems (GIS) to map stations to locations. Nicholas and Ogden [52] based the placement of stations on customer convenience, which is taken into consideration by the average travel time to the nearest station. Schwoon [53] combined agent-based trip modeling and GIS to construct various snapshots of the initial hydrogen filling station network along Germany highways, while Stiller *et al.* [54] analyzed hydrogen fueling stations in highly populated regions and corridors in Europe.

3.3. Capacity of Recharging Stations

The size or capacity of recharging stations for EVs affects the transportation planning. Usually, the capacity of these stations is limited and during a specified time, a station cannot serve more than its capacity, especially recharging stations. This means that only a small number of vehicles can be recharged simultaneously. Changing the departure times of vehicles belonging to a logistic company may require different times for recharging. Moreover, travelers who start their trips in different times may also reach a station at different times. In the specified time in which vehicles reach a station, if the station is occupied, the vehicles must wait in queues. The recharge time, capacity of stations, and waiting are important problems that have been mostly neglected in the EVs station location literature. Hosseini and MirHassani [55] is one of the few works in the literature that considers some of these issues. The objective addressed in their work is to establish a strategic plan in order to build recharging stations in such a way that minimize total costs. These total costs include stations-construction cost, waiting time cost, and refueling cost. Olivella-Rosell *et al.* [56] propose an agent-based simulation approach that allows forecasting the EV charging demand in a certain urban area, and they successfully test the efficiency of their model in the city of Barcelona, Spain.

In the specific case of battery swapping stations, when a vehicle arrives, it requests a fully charged battery pallet to replace the nearly depleted batteries it currently holds. The request could either be satisfied by a fully charged battery pallet from the station storage, or by a pallet that is just completing its charging. If the request is indeed satisfied, the vehicle in turn deposits a fully or partially spent pallet. If there are idle battery pallet chargers at the station, the spent battery pallet is placed on one of them and its recharging begins, otherwise it is kept in a queue until a battery pallet charger is available. If, instead, there is no fully charged battery available at the station, then the vehicle could leave and go to a different station. Alternatively, it could wait for a battery to fully charge, which may take some time. The vehicle could even take, if necessary, a replacement battery that is only partially charged and use that partially charged battery to travel to another battery swap station on its route. In this case, the vehicle will have to stop earlier than planned, and this influences the routes planning, which estimated some stops at stations and suddenly the vehicle is forced to perform other not covered stops. Depending on both the number of battery pallet chargers the station holds and number of battery pallets the station keeps on hand, the size and attendant cost of the station will change. The availability of charged battery pallets at any given time depends on the size of the station, the inventory of pallets, and the demand for charged pallets the station is experiencing. The station incurs an indirect cost from the unavailability of charged pallets when an EV arrives for an exchange because the driver will not have to pay for a battery swap, and there may be a loss of goodwill from the unserved customer. Models to evaluate total direct and indirect costs for possible decisions on station sizing and inventory holding would be very important in designing the battery swapping infrastructure.

In the literature related to battery-swap station size, Zheng *et al.* [36] proposed a method for locating and sizing battery swap stations in distribution systems, which are two determinants keys in the take-up of EVs as explained before. The problem is modeled as maximizing the net present value of the battery swap station project, where the battery swap station model, load type, network reinforcement, and reliability are taken into consideration.

In the case of hydrogen-based EVs, since the price of hydrogen exhibits an inverse feedback interaction with the adoption rate of fuel cell vehicles and corresponding demand for hydrogen, this behavior has a compounding cyclical effect [57]. Existing models often fall short with respect to incorporating this effect into capacity decisions. Further, the capacity decision depends on the demand that is unknown *a priori* [58]. Game theory may be required to determine the optimal timing of capacity investment. Thus, for example, Qin *et al.* [59] uses an option-based approach to demonstrate the behavior or optimal capacity decisions considering a variety of factors. Struben and Sterman [60] discusses requirements of sustained adoption of hydrogen EVs, and Gnann and Plötz [61] provide a review of integrated market and infrastructure models.

3.4. Fleet Size and Mix

EVs are likely to be used in delivery fleets with other kinds of vehicles. A well-studied branch of the VRP literature is precisely addressing the problem of heterogeneous fleets in delivery fleets [62]. As noticed in Lebeau *et al.* (2015) [63], merging the VRP research on electric vehicles with the fleet size and mix vehicle routing problem is therefore relevant to come with recommendations for logistics decision makers. One of the first attempts to investigate the specific characteristics of EVs as part of the fleet of a VRP was achieved by Gonçalves *et al.* [64]. They considered a VRP with pickup and delivery using a mixed fleet that consists of EVs and vehicles using internal-combustion engines. The objective is to minimize total costs, which consist of vehicle related fixed and variable costs. They consider time and capacity constraints and assume a time for recharging the EVs, which were calculated from the total distance travelled and the range using one battery charge. Vehicles can recharge anywhere during the routes, involving a time penalty. This way, several scenarios combining kinds of vehicles were evaluated, and finally the results showed that using EVs is a more costly alternative due to the high investment required for acquiring or converting these vehicles. According to Lebeau *et al.* (2015) [63], one of the problems of this model is that the locations of charging spots were not considered, meaning that EVs could virtually refuel anywhere on the delivery round once the battery was empty. Erdoğan and Miller-Hooks [65] improved the previous work by developing the green VRP with the possibility of refueling vehicles at the existing alternative fueling stations along the routes. The contributions of these two works were integrated by Schneider *et al.* [66] in their electric VRP with time windows. Charging locations and charging times are both considered in their model which approaches well the problem of EVs. A similar approach was also developed by Conrad and Figliozzi [67]. Based on a capacitated VRP with time windows constraints, they introduced the limited range and charging times in order to get the recharging vehicle routing problem. Their main difference is regarding charging locations, since these authors consider that charging is possible at some customer locations while the formulation in [66] is more flexible as other possible charging locations are possible in the network.

Bae *et al.* [68] also considered the EV and internal-combustion engines vehicles fleet size and mix problem as a two-player two-stage game. They focused on determination of the level of hybrid or alternative energy delivery fleet for a logistics and transportation company. In order to do that, they constructed a model of self-selection with heterogeneous consumers who value the firm's delivery service along two dimensions: the quality of delivery service and the relative reduction in emissions. These authors concluded that while subsidies may increase the operator's profit they may also result in higher prices for the customers. However, these customers will benefit from a reduction in pollution if more EVs are used. More recently, Van Duin *et al.* [69] dealt with the electrical vehicle fleet size and mix VRP with time windows. The aim is to determine an optimal fleet of EVs and delivery routes to offer a desired service level at minimal cost to a set of customers with delivery time windows. However, as noticed by Lebeau *et al.* (2015) [63], they approached the problem without considering the previous work on battery electric vehicles in VRP. As a result, the model involves similar weaknesses as in [64], *i.e.*, they do not consider the locations of charging points. An EV with a battery swapping system is modeled so that the range of this EV can be doubled. Nonetheless, the swapping system is not reflected in the constraints. It is in fact reflected in the range parameter of the vehicle which is simply doubled, meaning that the battery of the EV can be swapped virtually anywhere on the road. Hiermann *et al.* [70] developed that idea further to propose an electrical vehicle fleet size and mix VRP with time windows that also considers the decisions regarding the fleet composition and the choice of recharging times and locations. This work can be considered as the state of the art of delivery optimization with EVs. If vehicles cannot recharge or swap their batteries on the road, then another different problem can be discussed as in Juan *et al.* [10], who dealt with the VRP with multiple driving ranges, an extension of the classical routing problem where the total distance each vehicle can travel is limited and is not necessarily the same for all vehicles, *i.e.*, the fleet is heterogeneous with respect to maximum route lengths.

Regarding hydrogen-based EVs, additional papers highlight the use of fleet vehicles to take advantage of centralized fueling while hydrogen infrastructure is being developed. Thus, for instance, Mercuri *et al.* [71], Joffe *et al.* [72], O'Garra *et al.* [73], and Brey *et al.* [74] present examples in Italy, United Kingdom, and Spain, respectively. More recently, researchers have begun to include more complete systems into the scope of their models. For example, infrastructure models have been developed for China [75], Europe [76], Germany [77], Great Britain [78], South Korea [79], and the United States [80–82]. For a recent literature review aimed at optimizing hydrogen infrastructure see Agnolucci and McDowall [83].

4. Emerging Vehicle Routing Problem (VRP) Operational Issues Related to the Use of EVs

Novel emerging routing models for EVs have to include the most important practical constraints of logistics service providers that use EVs for last-mile deliveries. First, vehicle capacity restrictions have to be considered for a significant share of delivery operations. Second, many companies, e.g., in the small package shipping sector, face a high percentage of time-definite deliveries, which makes the integration of customer time windows into the routing model a necessity. The second aspect is especially interesting because recharging times for EVs cannot be assumed to be fixed but depend on the current battery charge of the vehicle when arriving at the recharging station. Moreover, recharging operations take a significant amount of time, especially compared to the relatively short customer service times of, e.g., small package shippers, and thus clearly affect the route planning.

Motivated by the current transportation circumstances, Electric Vehicle Management (EVM) has recently emerged as a new challenging problem, which is strongly related to the field of green logistics and has the purpose to expedite the establishment of a customer convenient, cost-effective, EVs infrastructure. Based on the increasing relevance of the problem in the last years, a number of research groups in this field have started working on some particular aspects of this new area. The next subsections analyze some typical strategic, tactical, and operational issues arising in EVM based on the new features of EVs.

4.1. Economic Issues of EVs

This is a strategic objective that tries to determine if the emerging novel EVs technology is sustainable for certain transportation activities. Many papers have been devoted to sustainable operations in the transportation area. However, research on the economic viability of EVs is limited in the production and operations management literature. In addition, the impact of EVs on the associated supply chain is yet to be examined. Research on EVs has been mostly focused on: (i) planning infrastructure deployment [46]; (ii) impact of integrating electric vehicles into the power system [84,85]; and (iii) using incentives to promote EVs [86]. Perspectives and insights on EV adoption are only recently being developed. Thus, in the Avci *et al.* [87] model, the interactions between the infrastructure provider and direct consumers in a principal-agent framework. Kleindorfer *et al.* [88] develop a framework to determine and value optimal fleet renewal strategies for the French postal service, La Poste, under two technology options (EVs and ICEVs), uncertain fuel costs, and uncertain battery prices. Wang and Lin [89] consider a firm's capacity adjustments over time given a portfolio of technology options when the demand and the fuel costs are uncertain. Chocteau *et al.* [90] use a game theory framework to study the value of cooperation between stakeholders such as fleet manager, auto manufacturer, and electricity supplier under multiple coalition settings. They also present conditions under which such cooperation can add value.

4.2. Fleet size and Mix Issues of EVs

A critical issue arising when EVs are incorporated into the set of vehicles to be managed gives place to the so-called VRPs with heterogeneous fleet. Contributions related to fleet size and mix considering EVs are recent and very limited. A Mixed Fleet or Heterogeneous VRP considers problems where different types of vehicles are available. It was first introduced in Golden *et al.* [91]. Subsequently, Baldacci *et al.* [92] identifies five major subclasses differing in the number of vehicles available (limited and unlimited), whether a fixed cost per vehicle is considered or not and if the routing cost depends on the vehicle type. The original formulation in [91] considers an unlimited number of vehicles with fixed acquisition costs and vehicle type independent routing costs, which can be classified as a Fleet Size and Mix VRP with Fixed costs (FSMF).

As described in [70], Liu and Shen [93] proposes the fleet size and mix VRP with time windows reformulating the FSMF to take into account time windows. The routing cost corresponds to the so-called *en route* time , which is the time between departing from and returning to the depot menus de cumulative service time at the customers in the respective route. This approach was tested using a new benchmark set based on the well-known Solomon instances for the VRP with time windows.

4.3. Charging Networks Issues of EVs

One major barrier to the success of EVs is the limited number of refueling stations. Due to the restricted range of batteries, the establishment of an infrastructure to facilitate recharging is a pressing concern. Two critical factors determine the need for infrastructure services such as battery swapping and recharging: daily driving distance and battery range. Due to the large capital costs involved in infrastructure investment, economic factors are very important in determining the number and location of stations. Therefore, studies must work to provide a theoretical basis for station deployment, such as with a facility location model, to economically and efficiently serve EV trips [33]. Location problems in general are spatial resource allocation problems dealing with one or more service facilities serving a spatially distributed set of demands. The objective is to locate facilities to optimize a spatially dependent objective such as the minimization of average traveling time or distance between demands and facilities. The most studied practical problem in this context concerns hydrogen station location. General criteria are proposed for identifying effective locations for early hydrogen stations: (i) close to areas with high traffic volume; (ii) in places to provide fuel during long distance trips; (iii) at high profile locations to increase public awareness; and (iv) in places that are accessible to individuals who are buying their first fuel-cell vehicle. These criteria are also needed to be taken into account in EVM in order to ensure consumer confidence in the reliability of the refueling network [33].

4.4. Routing Issues of EVs

Routing of EVs is a critical aspect of EVM, it consists of designing routes for maximizing the autonomy of vehicles. Efficient EV routing plays a major role for encouraging EV use. The energy shortest path problem and the energy routing problem and some relationships between these emerge as new challenges to face in the EVM. Restricted driving distance between battery charges is a fundamental impediment to increase consumer adoption of EVs. In the small-package shipping industry, several big companies, such as DHL, UPS and DPD have already started using EVs for last-mile deliveries, particularly in urban areas. Moreover, governments in all parts of the world promote the electrification trend and plan to provide the required infrastructure. As mentioned earlier, a successful transition from conventional vehicles to EVs requires the development of novel efficient route-planning techniques that take into account the specific features of EVs. Currently, the maximum driving range of most EVs is estimated to be about 100–150 miles [16], but it can be decreased significantly by cold temperatures and so-called range anxiety [94,95]. Thus, the available range is potentially not sufficient to perform the typical delivery tour of a logistics service provider in one run or to reach customers located far from the depot. Because reducing the number of deliveries performed by one vehicle is clearly not a profitable option, visits to recharging stations along the routes are required. These recharging visits have to be explicitly considered in the route planning to avoid inefficient vehicle routes with long detours, especially if the number of available recharging stations is scarce. In a recent work, Hung *et al.* [96] propose a queuing modeling framework to develop efficient routing strategies for EVs requesting charging at available stations. These authors show that the proposed routing strategies contribute to improving the throughput of the queuing system and also to reducing stopover times. In addition, Liu *et al.* [97] analyze a heterogeneous fleet version of the VRP in which the goal is to find a routing solution minimizing the carbon footprint. Similarly, Fang *et al.* [98] try to minimize the carbon footprint generated by bird watching tourist activities throughout optimal routing design supported by geographic information systems.

Table 2 summarizes some of the main decision variables, constraints, and objective functions related to the new VRP variants that emerge when considering heterogeneous fleets of ICEVs and EVs.

Table 2. Details of some new VRP variants related to EVs.

Variant	Decision Variables	Constraints	Objectives
Fleet size and mix	(1) Determine the number and type of EVs to be purchased. (2) Determine the ideal composition of the heterogeneous fleet.	(1) Environmental standards and price incentive to acquisition of EVs. (2) Fixed and variable charging times. (3) Limited budget to renew the fleet of vehicles.	(1) Minimize the acquisition and operating costs of new EVs. (2) Maximize the satisfaction of customer needs. (3) Minimize the environmental impact.
Charging networks	(1) Determine number and geographical position of recharging stations. (2) Determine capacity of recharging stations. (3) Determine technology of recharging stations (low or fast recharge). (4) Decide between swapping or recharging of batteries.	(1) Limited budget to install new recharging stations. (2) Needs of EVs to recharge or exchange batteries.	(1) Minimize the investment and operating costs of charging networks. (2) Maximize the level of service to customers.
Routing	(1) Determine the number of visits to recharging stations. (2) Determine the timing of visits to recharging stations. (3) Allocate available recharging resources to vehicles in recharging stations. (4) Select the option of recharging or swapping batteries.	(1) Geographical position of recharging stations. (2) Capacity of recharging stations. (3) Fixed or variable recharging/swapping times.	(1) Minimize routing cost considering recharging operations. (2) Minimize routing times considering recharging operations. (3) Minimize recharging and swapping costs.

5. Solving Approaches for VRPs with EVs

As discussed in the previous sections, the introduction of EVs in freight fleets imposes a number of strategic and operational challenges that must be efficiently addressed with the use of novel methods and approaches. This is particularly true for VRP models, which can be classified into three levels according to their degree of realism (Figure 2). The classical-basic VRP models are mainly theoretical models that allow the development of mathematical approaches, either if they use exact or approximate solving methods. These models are used to test solving methods in controlled environments, which allows assessing their performance before being used in practical applications. The classical-advanced VRP models are characterized by a higher level of realism, *i.e.*, large-scale problems, multi-objective functions, integrated routing and logistics. Examples of the latter are: VRPs combined with packing [99], allocation, inventory management [100], *etc.* More advanced and complex VRP variants are included in this category. Usually, these problems have been solved by metaheuristic approaches, such as Genetic Algorithms, Iterated Local Search, Ant Colony Optimization, Simulated Annealing, *etc.* Most of the existing work in the VRP literature so far deals with these two classical types of models. Recently, however, and due to both the maturity of existing exact and metaheuristic methods as well as to new business needs, new Rich VRP models are being considered. The solving methods for these models combine different exact and metaheuristic approaches (matheuristics) [101] or even simulation with metaheuristics (simheuristics) [102]. Simheuristics allow considering uncertainty both in the objective function and the constraints of a VRP model, thus making these models a more accurate representation of real-life routing distribution systems. These hybrid methods not only can deal with uncertainty and real-time decision making [103], but they can also consider aspects such as richer objective functions (including environmental costs), dynamism [104], diversity of vehicle driving ranges, multi-periodicity in the distribution activity, integration with other supply chain components, *etc.*

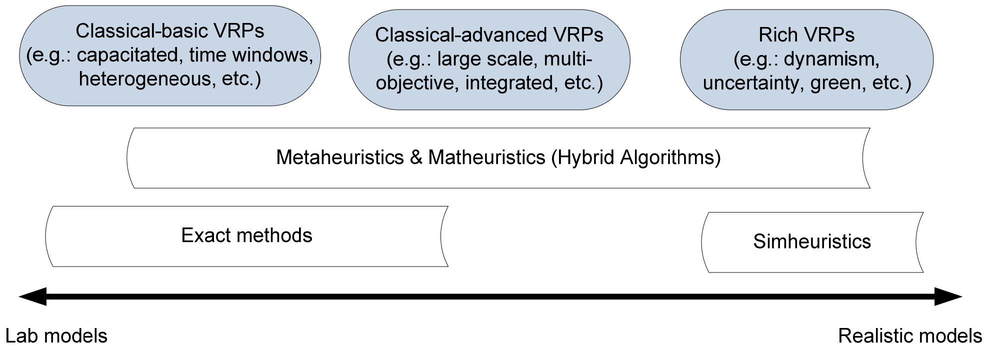

Figure 2. Classification of Vehicle Routing Problem (VRP) models according to their degree of realism.

6. Other Related and Emergent Issues

As some experts point out, life cycle cost analysis is a necessary step in order to properly assess the long-term benefits associated with substituting ICEVs by EVs. Thus, Aguirre *et al.* [105] perform a study to compare the lifecycle environmental costs (energy inputs and CO_2 emissions) of an ICEV, a hybrid vehicle, and an EV. According to their results, the hybrid vehicle is the most effective in terms of CO_2 emissions and also the one offering the lowest net present cost. However, the EV was the most efficient in terms of total environmental impact during its lifetime. Gao and Winfield [106] investigate the lifetime GHG emissions and energy use for different types of fuel-efficient vehicles, showing that all of them improve, in both dimensions, the values associated with ICEVs. They also conclude that all these advanced vehicles require more energy for production than ICEVs, mainly due to the additional power electronics and battery packs. Nevertheless, the energy savings in the fuel cycle for these advanced vehicles compensates the marginal energy required during the vehicle cycle (production stage). Li *et al.* [107] compare the vehicle cycle energy and gas emission impacts of both ICEVs and EVs in China. According to their analysis, when considering the entire life cycle EVs are the best choice in terms of energy consumption and gas emissions. However, these authors also remark the importance of solving some operational and technological challenges, e.g., charging facilities location and capacity, before massively adopting EVs as the standard solution. Finally, Noori *et al.* [108] analyze the life cycle cost and life cycle environmental emissions of ICEVs, hybrid electric vehicles, and three different types of EVs. According to their results, ICEVs are the most cost effective vehicle type in terms of life cycle cost. However, they also conclude that shifting towards EVs reduces the environmental damage costs when considering the vehicle lifetime. At the same time, they also notice that the use of EVs has a high impact on the water footprint due to upstream electricity generation and to the water consumption necessary for battery production.

Regarding the use of EVs in rural areas, Aultman-Hall *et al.* [109] discuss suitability and charging requirements in these environments. They conclude that, although hybrid vehicles will still have substantial utility in these areas, EVs are quickly becoming an attractive alternative for rural mobility demand, especially in those areas with an acceptable power supply and vehicle charging infrastructure. Newman *et al.* [110] support the idea that EVs can be extraordinarily useful in sub-urban and rural areas, especially as a complement to deficient public transport infrastructures. Nevertheless, they also notice that, quite often, habitants of rural areas have difficulties buying EVs due to their relatively low purchasing power. Wappelhorst *et al.* [111] recognize two of the main obstacles impeding the expansion of EVs: their cost and their driving range limitations. In order to partially overcome these problems, they propose the use of intermodal concepts and car-sharing practices. After some empirical studies, the authors conclude that car-sharing of EVs could have the same positive adoption level in rural areas as in the urban ones.

Interruption of power supply causes serious problems in civic life, especially during the evacuation of stricken areas. It impacts medical institutions, interrupts the supply chain, and causes serious damage to the economy. Therefore, in disaster cases it is essential to minimize the period of power failure. Focused in the vehicle industry, Kinomura *et al.* [112] describe the development of Toyota's electricity supply system, through which vehicles supply power directly to electrical devices, and may supply power at either a home site or at an evacuation center in the event of a natural disaster. Yamamura and Miwa [113] consider the design of an effective control method for store-carry-forward energy distribution after a disaster in which EVs and plug-in hybrid vehicles are mobile units having power generation and power storage capabilities. Finally, Yamagata *et al.* [114] propose and extend the concept of a community-based disaster resilient electricity sharing system. In this system, electricity generated from widely introduced photovoltaic panels is stored in the not-in-use cars.

7. Conclusions

This paper has reviewed some of the existing literature related to the introduction of electric vehicles in road transportation, paying special attention to environmental issues; the emerging strategic and operational challenges; the use of hydrogen electric vehicles as an alternative to other types of electric vehicles; and the new variants of the popular vehicle routing problem that arise as a consequence of introducing electric vehicles in the distribution fleets. From this analysis, it becomes evident that the use of sustainable energy sources in road logistics and transportation is more necessary than ever, and constitutes a critical factor for the evolution of an economically and environmentally stable world. The incorporation of electric vehicles in the road distribution activities, especially in urban areas, shows a promising trend yet to be explored in its full potential. However, the expanded use of electric vehicles raises a number of concerns and challenges that complicate planning efforts. From an operational research point of view, the following strategic and operational challenges can be highlighted: (a) the development of infrastructure networks for battery recharging/swapping, including the number, location, type, and capacity of the associated stations; (b) the size and mix composition of hybrid fleets with both traditional vehicles, hybrid electric vehicles, and pure electric vehicles; (c) the severe feasibility constraints imposed using heterogeneous fleets of vehicles with different driving ranges; (d) the additional time-window constraints related to short driving ranges; and (e) the economic impact of the introduction of electric vehicles over the entire supply chain. The development of new optimization and hybrid optimization-simulation methods to efficiently cope with these challenges, including dynamic scenarios and scenarios with uncertainty, is a necessary step to promote the desirable shift towards more sustainable energy sources in the logistics and transportation arena.

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