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Goods Distribution with Electric Vehicles: Review and Research Perspectives

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Abstract. Over the past decade, electric vehicles have gained in popularity in several countries, even though their market share is still relatively low. However, most gains have been made in the area of passenger vehicles and most technical and scientific studies have been devoted to this case. In contrast, the potential of electric vehicular technology for goods distribution has received less attention. The issues related to the use of EVs for goods distribution open up a wide range of relevant research problems. The aims of this survey paper are to provide transportation researchers an overview of the technical and marketing background needed to conduct research in this area, to present a survey of the existing research in this field, and to offer perspectives for future research.

Keywords: Electric vehicular technology, batteries, market penetration, profitability, incentives, green transportation, city logistics.

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1. Introduction

Green logistics encompasses the set of practices aimed at controlling environmental externalities in logistics operations (Psaraftis, 2014). The study of this relatively new field has increased in popularity in recent years, as witnessed by the growing number of publications on green transportation (Demir et al., 2014) and city logistics (Gonzalez-Feliu et al., 2014). Research on green transportation has focused on the pollution-routing problem (Bektas and Laporte, 2011) which seeks to design optimal vehicle routes in which routing costs and polluting emissions are jointly minimized. City logistics proposes ways of reducing pollution in urban environments, such as forbidding or restricting the use of heavy vehicles in city centers. The research carried out in these fields focuses on the design of distribution policies that will help diminish the environmental impact of goods distribution. However, relatively few papers have been published on vehicle fleet composition in such a context, although there are some recent interesting exceptions (e.g., Kopfer and Kopfer, 2013; Kopfer et al., 2014; Koç et al., 2014). In particular, little attention has been paid to the use of electric vehicles (EVs) as a means to yield green distribution practices.

The market share of electric cars is insignificant in most countries, with the possible exception of Norway and the Netherlands (Mock and Yang (2014)), and electric vans and trucks are even rarer because of several real or perceived factors related to cost, driving range, speed and reliability. Electric trucks operate on batteries that have a limited lives and are characterized by high costs as well as specific degradation and charging patterns which have to be taken into account in fleet size and mix decisions. In addition, because the number of electric recharging stations is still very small compared with that of conventional fuel stations, the limited range of EVs becomes a critical constraint in purchasing and operational decisions. However, when coupled with interesting incentives, EVs can sometimes become an interesting option for goods distribution. As Taefi et al. (2014, p.3) point out, "many initiatives and involvement in EV experiments are driven by companies awareness and anticipation of regulations for less environmentally-friendly vehicles becoming more restrictive in the future". The deployment of electric freight vehicles should therefore not be automatically associated with profitability, but rather with exploration and preparation in anticipation of expected future developments.

Several project reports provide examples of practices with electric vehicles for goods distribution, most of these in Europe. In North America, large companies using battery electric delivery vehicles include FedEx, General Electric, Coca-Cola, UPS, Frito-Lay, Staples, Enterprise, Hertz and others (Electrification Coalition (2013)). Many U.S. companies operating

battery electric trucks received funding from the American Recovery and Reinvestment Act to cover part of the vehicles purchase costs (US DOE (2013b)). One of project FREVUE's reports (Nesterova et al. (2013)) provides overviews of European companies and projects using these vehicles. The same report also points out to two-phase delivery as being an interesting logistics concept for electric freight vehicles, where goods are first brought to a logistics facility near the denser urban area by conventional trucks before being transferred to the electric vehicles for last mile deliveries. When multiple organisations use the same facility, this is known as an urban consolidation centre (UCC), defined as "a logistics facility situated in relatively close proximity to the geographic area that it serves (...), to which many logistics companies deliver goods destined for the area, from which consolidated deliveries are carried out within that area, in which a range of other value-added logistics and retail services can be provided"(Allen et al. (2007, p.61)). Examples of a UCC using battery electric vehicles can be found in Vermie (2002), Allen et al. (2007), van Duin et al. (2010), TU Delft et al. (2013) and Nesterova et al. (2013).

The issues related to the use of EVs for goods distribution open up a wide range of relevant research problems. The aims of this paper are to provide transportation researchers an overview of the technical background and market penetration information needed to conduct research in this area, to present a survey of the existing research in this field, and to offer perspectives for future research. It is organized as follows. Section 2 describes the vehicle technology, including vehicle types and batteries. Section 3 provides information on the market penetration of EVs as well as their cost competitiveness and adoption incentives. Section 4 provides an overview of the existing research on EVs in transportation science. It covers three topics: fleet size and mix, vehicle routing and optimal paths. Section 5 suggests several promising research perspectives. It is organized around strategic, tactical and operational transportation science issues. The paper closes with some conclusions in Section 6.

2.   Technological background

This section provides a classification of electric vehicle technology under three main headings: electric vehicle types, batteries and battery recharging.

2.1 Electric vehicle types

Electric vehicles are generally divided into Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Fuel Cell Electric Vehicles (FCEVs). An advantage of BEVs and HEVs is their ability to use their electric motor for regenerative breaking (to recuperate kinetic energy) and as a form of frictionless breaking (Larminie and Lowry (2003)). FCEVs can also allow for regenerative breaking if a battery is used to assist the fuel cell (Emadi et al. (2005)).

2.1.1 Battery electric vehicles

A BEV is propelled by one or more electric motors and only uses the power provided by its on-board battery for propulsion (Electrification Coalition (2013)). The large battery is charged from the electricity grid and the powertrain is very simple by design (Tuttle and Kockelman (2012)). Benefits include the absence of tailpipe emissions, high efficiency, as well as much less operating noise; technical disadvantages include a relatively low achievable range and the long time required for charging the batteries because of their low energy density (Pollet et al. (2012)). Their motors can produce great torque at low speeds (MacLean and Lave (2003)) and are generally three times more efficient than internal combustion engines (de Santiago et al.(2012)). BEVs have much less moving parts than internal combustion engine vehicles (ICEVs) and do not require regular oil changes (Feng and Figliozzi (2013)). The regenerative breaking also allows for less break wear, further reducing maintenance costs (Lee et al. (2013)). Typical ranges vary from 100 to 150 kilometers on a single charge for freight BEVs (Nesterova et al. (2013)) and have been reported to diminish over time due to battery ageing (Taefi et al. (2014)). Other factors which temporarily reduce vehicle range include extreme temperatures, high driving speeds, rapid acceleration, carrying heavy loads and driving up important slopes (US DOE (2012b)). Battery size and weight reduce maximum payload for freight BEVs compared to equivalent ICEVs (den Boer et al. (2013)).

2.1.2 Hybrid electric vehicles

Hybrid electric vehicles can be classified according to their powertrain architecture (series, parallel, series-parallel, complex), the level of electric power and function of the electric motor (micro hybrid, mild hybrid, full hybrid) or their capacity to be plugged into an electricity grid to recharge their batteries (Chan (2007)).

A Plug-in Hybrid Electric Vehicle (PHEV) is essentially a hybrid electric vehicle with a

larger battery which can be charged from the electricity grid (Tuttle and Kockelman (2012)). It uses an electric motor and an internal combustion engine (ICE), either in series or parallel architecture (Electrification Coalition (2013)). In a series configuration, the ICE is only used to power a generator and the electric motor is the only propulsion component coupled to the final drive shaft, while a parallel configuration allows for both the ICE and the electric motor to be coupled to the final drive shaft and to be used simultaneously or individually (Chan (2007)). While the former offers a simpler design, the latter is more efficient due to fewer energy conversions and to the non-essential sizing of components for maximum power demands (Chan (2007)). A series PHEV is also often referred to as an Extended Range Electric Vehicle (Tuttle and Kockelman (2012)). Parallel PHEVs only allow an electric range in the lines of 30-60 km with lithium-ion batteries (Chan (2007)). PHEVs could be a viable transition technology as it allows short trips to be made in electric mode and alternative fuels to be used for longer itineraries (Abdallah (2013)).

2.1.3 Fuel cell electric vehicles

In an FCEV, a fuel cell generates electricity from hydrogen's chemical energy, from which the output is water, which then either powers the electric motor or charges a battery (Chan (2007)). A battery can be used to store the electric motor's regenerative breaking energy and to assist the fuel cell during sudden load variations that it cannot handle by itself (Emadi et al. (2005)). The hydrogen must be stored on-board either in gaseous or liquid states, or through physical or chemical adsorption (den Boer et al. (2013)). FCEVs can be refueled in a few minutes (Eberle and von Helmolt (2010)) and also offer quiet operation due to the small number of their moving parts (Emadi et al. (2005)), but are less efficient than BEVs since they must convert the hydrogen's energy into electricity before powering the electric motor (den Boer et al. (2013)). Fuel cells have efficiencies of approximately 50% in terms of the proportion of the hydrogen's energy being converted to electricity (US DOE (2013a)) and could also be an option for auxiliary power units in heavy-duty vehicles (Emadi et al. (2005)). The cost of FCEVs is still an important market barrier for this technology (Mock and Yang (2014)), so is the fuel cell's durability which is currently 10,000 operating hours at best (den Boer et al. (2013)).

2.2 Batteries

Batteries are a critical factor in the widespread adoption of electric vehicles since they have a much lower energy density than gasoline (Hannisdahl et al. (2013)). The main options for

batteries in BEVs include lead acid batteries, nickel metal hydride batteries, and lithium-ion batteries (Chan (2007)). Since lithium-ion batteries, compared to other options, have a high energy density (100 Wh/kg), high power density (300W/kg), long battery life and low memory effect (Lukic et al. (2008)), they are the most commonly used alternative for modern passenger and freight BEVs (den Boer et al. (2013)). Energy densities could potentially be tripled by 2030 with the development of technologies such as lithium-sulfur batteries (Duleep et al. (2011)). The battery pack is also the most costly component in plug-in electric vehicles and significantly increases the vehicle costs (Electrification Coalition (2013)). However, significant reductions in battery costs are also expected in the next decades, with a potential reduction by a factor of up to 10 by 2030, compared with 2009 (US DOE (2010)).

2.2.1 Battery lifespan

Batteries are considered to be no longer suitable for electric vehicles when their capacity has been reduced to 80% of the original value (McMorrin et al. (2012)). Their health can be influenced by the way they are charged and discharged. For example, battery deterioration can occur if it is frequently discharged to deep levels (Millner (2010)). This generally implies that only 80% of the marketed battery capacity should actually be used (Valenta (2013)). Deep cycle life refers to the number of times a battery can be discharged to a low state of charge, while shallow cycle life is the number of times it can withstand a small state of charge variation (Duleep et al. (2011)). Lithium-ion batteries in currently used freight BEVs typically provide a 1,000 to 2,000 deep cycle life, which should last around six years; a 4,000 to 5,000 deep cycle life is expected within five years (den Boer et al. (2013)). Many manufacturers have reached 200,000 cycles for shallow cycle life (Duleep et al. (2011)).

Frequently charging the battery too close to maximum capacity can also adversely affect its lifespan (Sweda et al. (2014)), as can keeping it at high states of charge for long periods (Electrification Coalition (2010)). Using high power levels to quickly charge batteries could also have negative impacts, especially if used in the beginning and end of the charging cycle (Zhang (2006)). However, there is still much uncertainty regarding the effects of using high power levels (Hatton et al. (2009)), and recent testings suggest these may not be that significant (Idaho National Laboratory (2014)). Nevertheless, all these factors can speed up the reduction of usable battery capacity, hence shortening vehicle range and battery life (Electrification Coalition (2010)). One way to prolong battery life and reduce their size could be to use them alongside ultracapacitors, which have much higher power densities (Khaligh and Li (2010)).

2.2.2   Battery charging

The most common way of charging batteries is conductive charging, thus implying the need of a cable and a vehicle connector (Yılmaz and Krein (2013). Charging modes are defined by the safety communication protocol between the vehicle and the charging equipment, while charging types refer to the connector used. Overviews of modes and connector standards can be found in Cluzel et al. (2013) and Naberezhnykh et al. (2012b). Charging levels can be divided according to the power rate used, and different classifications are used according to nationally available power levels (Haghbin et al. (2010)). Yılmaz and Krein (2013) refers to three levels based on the SAE Standard J1772: level 1 (1.4 kW to 1.9 kW), level 2 (4kW to 19.2 kW) and level 3 (50 kW to 100 kW), also referred to as fast charging.

Conductive chargers can either be on-board or off-board the vehicle, with unidirectional or bidirectional power flow (Yılmaz and Krein (2013)). Using a higher power level requires larger chargers, thus constraining on-board chargers to lower power levels because of weight, space and cost (Haghbin et al. (2010)). Integrating the charger into the electric drive train is an option to allow on-board high power charging (Haghbin et al. (2010)). While level 1 charging can be supplied with a convenience outlet, levels 2 and 3 require dedicated electric vehicle supply equipment (EVSE) and are the viable options in public charging infrastructures (Yılmaz and Krein (2013)).

Charging times depend on the size of the batteries and the equipment used (US DOE (2012b)). They vary from as little as 30 minutes to several hours, and are not linear during the entire process: "the first phase allows to recharge the battery almost fully and it is linear with respect to time. The second phase is not linear with respect to time and can require some hours to achieve the full charge of the battery and to ensure a uniform recharge of all the cells that compose the battery"(Bruglieri et al. (2014, p.20)).

In most cases where BEVs are used for goods distribution, they are mainly charged at depots overnight and do not use public charging stations other than during drivers' lunch breaks (Nesterova et al. (2013), Naberezhnykh et al. (2012b), Taefi et al. (2014)). This can be explained by the need to make cost effective use of driver time and by security concerns (Naberezhnykh et al. (2012b)). Also, charging during off-peak hours can allow for reduced electricity rates (Mock and Yang (2014)), and fast charging infrastructures necessary for charging during delivery routes are insignificant in most countries (IEA and EVI (2013)). Fast charging stations could be installed at the depot, but the high cost associated to level 3 EVSE limits interest in fast charging (Hatton et al. (2009)), and the impact of the high power demand from the grid is another issue (Dharmakeerthi et al. (2014)). This could

limit the number of BEVs that could be simultaneously charged with high power levels (Etezadi-Amoli et al. (2010)), potentially requiring investments for transformer upgrades (Electrification Coalition (2010)).

While conductive charging is the most common method for charging electric vehicles, there exist a few other options, such as inductive charging and battery swapping. Another option for powering larger electric vehicles is catenary wires.

Inductive charging involves transferring the power to the battery magnetically via an on-board charger, thus eliminating the need for cables and chords (Yılmaz and Krein (2013)). Stationary inductive charging would be used to charge the battery while the vehicle is stopped, such as on garage floors, in parking lots or at bus stops, while in-road inductive charging could allow for charging the battery or powering the motor even while the vehicle is in motion (den Boer et al. (2013)). Electric buses could be ideal candidates for both types of inductive charging, but the power necessary for several trucks traveling close to each other could limit applications for in-road charging in freight transportation (CALSTART (2013a)).

Battery swapping involves vehicles using automated battery swapping stations which remove the depleted battery and insert a fully charged one (CALSTART (2013b)). Technical barriers include the space and cost associated with the large stock of batteries needed, huge infrastructure costs for the swapping stations, the necessary standardisation of vehicles and batteries, and the risk of battery damage from excessive swapping (Mak et al. (2013), Hatton et al. (2009), CALSTART (2013b), den Boer et al. (2013), Hazeldine et al. (2009)). The stations would also need to recharge many batteries at the same time, which could impact the electric grid (Mak et al. (2013)).

Using catenary wires as a power supply would only be a viable option on highly used free-ways. Under this power option, overhead wires are charged with electricity and a truck uses a pantograph device to slide along the wires and retrieve the power (CALSTART (2013b)). The energy used for electric drive is not stored on-board, therefore allowing additional payload capacity and unlimited electric range when connected to the wires (den Boer et al. (2013)). However, infrastructure costs, business models for access, and visual pollution constitute important barriers for a wider adoption in freight transportation (CALSTART (2013b)).

3. Market penetration

Global manufacturers began producing passenger BEVs and PHEVs in 2010 (Tuttle and Kockelman (2012)), but smaller manufacturers had been producing electric vehicles in several classes much earlier (Sierzchula et al. (2012)), some of which have been used in the logistics sector (Element Energy. (2012)). However, relatively few have produced heavy duty vehicles. Also, in several cases, models on the market are conversions of conventional vehicles where the engine has been replaced by the necessary electric components (US DOE (2012b)).

3.1 Market Shares

Global sales of passenger BEVs and PHEVs were approximately 10,000 in 2009, 45,000 in 2011, 110,000 in 2012, and 210,000 in 2013, with only a few national markets exceeding a 1% market share of all passenger vehicles in 2013 (Mock and Yang (2014)). According to Berman and Gartner (2013) of Navigant, approximately 37,000 BEVs and PHEVs were expected to be sold for fleet purposes in 2013. Some of these vehicles are used in the delivery of lighter goods. For example, battery electric cars have been tested in pizza delivery operations in Hamburg (TU Delft et al. (2013)).

According to Jerram and Gartner (2013) of Navigant, the market for plug-in electric trucks and vans has not taken off as well as that for passenger vehicles. These vehicles have generally only penetrated niche applications while remaining dependent on government incentives. This is partly due to key industry players going out of business, to the conservative nature of fleet operators when it comes to new technologies, to a renewed interest in natural gas, and to the substantial cost premium of EVs. Navigant's reports executive summary also states that the global stock of HEV, PHEV and BEV commercial trucks (class 2 to 8) was around 20,000 at the time of publication, the vast majority of which were HEVs (which do not require plug-in recharging).

Den Boer et al. (2013) state that approximatively 1,000 battery electric distribution trucks were operated around the world as of July 2013. According to Parish and Pitkanen (2012), industry experts have estimated there are fewer than 500 battery electric trucks in use in North America as of 2012, most sales being made in US states with incentives for these vehicles, such as California and New York. Also, approximately 4,500 hybrid trucks were sold in North America as of 2012. The large majority of hybrid and battery electric trucks sold were in medium duty and vocational applications rather than long-haul class 8 applications.

According to Electrification Coalition (2013), the lack of vehicle availability by OEMs in heavier plug-in electric vehicles is another reason for their limited market penetration. Most of these vehicles are offered by small start-up firms. The report states that even if fleet operators tend to focus more on total cost of ownership than purchase costs, they also tend to be risk averse. Therefore, new small manufacturers offering electric trucks have difficulty in penetrating the market.

One of European project FREVUE's reports (Nesterova et al. (2013)) lists similar factors for the limited use of electric freight vehicles in city logistics, notably doubts on technology readiness, high purchase costs, and the limited amount of models on the market. Issues with accessing fast maintenance services from vehicle manufacturers can be another factor of doubt in adopting these vehicles. The report also states that the rapid technology improvements themselves can be a market barrier since a BEV purchased today could quickly lose its residual value and result in missing out on a better generation of vehicles.

However, the Electrification Coalition (2010) has identified several factors making EVs attractive for commercial applications, notably ther lower operational and maintenance costs combined with high utilization rates of fleet vehicles, easy charge scheduling, route predictability, centralized depot recharging, commercial and industrial electricity rates, and corporate image. Even so, a wider adoption of BEVs in distribution applications can only be achieved if these prove to be cost-effective when compared to using conventional ICEVs for the same application.

3.2   Cost competitiveness

Because of the different cost structures between ICEVs and BEVs, the only way to appropriately compare their cost competitiveness is to study their whole life costs (McMorrin et al. (2012)). While commercial BEVs operational costs can be nearly four times lower than diesel trucks, the downside is that their purchase costs are approximatively three times higher (Feng and Figliozzi (2013)). Maintenance costs for BEVs have been reported to be 20% to 30% lower than those of ICEVs (Taefi et al. (2014)) and this advantage should increase with the ICEVs' age (Electrification Coalition (2010)). Combined to lower energy costs, this makes electric vehicles more interesting for long planning horizons.

One way to decrease the cost premium and allow for additional payload capacity is to be able to right-size the battery (Electrification Coalition (2013)). However, the smaller battery would require more frequent deep discharges, which could accelerate battery deterioration ((Pitkanen and Amburg (2012)). Another option for reducing upfront costs while also ad-

dressing concerns about battery life is to lease the battery for a monthly fee based on energy consumed or distance traveled (McMorrin et al. (2012)). However, uncertainties regarding battery residual value limit many fleets' interest in battery leasing (Pitkanen and Amburg (2012)), most likely because these will be integrated into the leasing fee. While numerous studies have analyzed whole life costs for battery electric cars (e.g., Tuttle and Kockelman (2012), Prud'homme and Koning (2012), Thiel et al. (2010), Delucchi and Lipman (2001), Offer et al. (2010)), the business case of commercial BEVs has been less treated.

Davis and Figliozzi (2013) have compared whole life costs of battery electric delivery trucks with that of a conventional ICEVs serving less-than-truckload delivery routes. They considered two types of BEVs and one type of ICEV. They simulated 243 different route instances, varied by using different values for five parameters: the number of customers, the service area, the depot-service area distance, the customer service time, and the customer demand weight. Different battery replacement and cost scenarios were also studied. The planning horizon was set to 10 years and the vehicles' residual value at 20% of their purchase price. The results show that although the BEVs' TCO was highest in 210 out the 243 instances, a combination of factors can allow them to be a viable alternative: high utilization rates, low speeds and congestion, frequent customer stops during which a ICEV would idle, other factors amplifying the BEVs' superior efficiency, financial incentives or technological breakthroughs to reduce purchase costs, and a planning horizon above ten years

Feng and Figliozzi (2013) developed a fleet replacement optimization model for fleets with one BEV type and one ICEV type. The objective is to minimize the discounted sum of all costs over a planning horizon of 30 years. Several scenarios with varying annual utilization rates and ICEV fuel efficiency were analysed. Findings indicated that the BEV becomes competitive when used over 16,000 miles per year, especially in environments where the ICEV has low fuel efficiency. The breakeven analysis indicated a planning horizon of at least 12 years is necessary to recuperate high capital costs, and that in environments where the ICEV fuel efficiency is high, a price reduction ranging from 9% to 27% for the BEV, depending on utilization, would be necessary to achieve cost-effectiveness. The break even values for the BEVs to be competitive were found to be within realistic value ranges for congested urban areas. The sensitivity analysis identified the planning horizon, the purchase price and the utilization level as critical factors for the BEV's competitiveness. Including a battery replacement in different scenarios was found to significantly decrease the electric vehicles' competitiveness.

The appropriateness of BEVs for goods distribution ultimately depends on the context of their intended use, but the high purchase costs resulting from the batteries has been shown

to be a major cost effectiveness barrier. As a result, at this stage incentives are likely to be needed to increase the commercial use of BEVs (Taefi et al. (2014)).

3.3   Incentives

Several national governments have already set up measures aimed at increasing the commercial use of BEVs. Local policies can also be very useful for promoting BEVs for goods distribution. A few interesting examples of such incentives are provided below.

3.3.1   Financial incentives

Financial incentives reduce the upfront costs of EVs and their charging equipment (IEA and EVI (2013)). One form is purchase subsidies granted upon buying the vehicle (Mock and Yang (2014)). Examples of this are the California Hybrid Truck and Bus Voucher Incentive Project and the New York Truck Voucher Incentive Program which provide up to $50,000 and $60,000 respectively towards battery electric truck purchases (Parish and Pitkanen (2012), New York State Energy Research and Development Authority (2014)). In Europe, the city of Amsterdam covers up to €40,000 for the purchase of such trucks (den Boer et al. (2013)). Another example is the UK Plug-in Van Grant, which covers 20% of the cost of battery electric vans up to £8,000 (McMorrin et al. (2012)). Companies can also receive such subsidies for participating in demonstration or performance evaluation projects (US DOE (2013b)). In Germany, up to 50% of the investment can be covered by participating in such projects (Taefi et al. (2014)). Furthermore, some countries such as Norway, the Netherlands, the UK and France offer subsidies for the installation of the charging equipment (AustriaTech (2014)). Finally, tax exemptions are another financial incentive used for lowering ownership costs of EVs. These include exemptions from VAT, vehicle registration taxes, fuel consumption taxes, and company car taxes (AustriaTech (2014)). Overviews of EV tax exemptions can be found in IEA and EVI (2013), ACEA (2014), US DOE (2012a), and Mock and Yang (2014).

3.3.2   Prioritized access incentives

Local incentives for prioritized access often yield significant daily cost and time savings (Cluzel et al. (2013)). One mechanism is to grant BEVs access to high occupancy lanes or bus lanes, such as in Utrecht, Lisbon, and Trondheim (Nesterova et al. (2013)). London and Oslo have also experimented with such access incentives and have identified issues such as conflicts

with buses and insufficient coverage of the road network by the bus lanes (AustriaTech (2014)). BEVs can also be exempted from certain road tolls, as is the case in Norway (Hannisdahl et al. (2013)). Another concept used is Low Emission Zones (LEZs) in city centres to reduce emissions and promote the use of cleaner vehicles. Many LEZs in which electric vehicles are permitted can be found in Dutch cities. These apply to commercial vehicles over 3.5 tonnes GVW (AustriaTech (2014)). In Rome, diesel freight vehicles pay an annual fee of €570 to have access to the city centre, while electric freight vehicles pay €300 (AustriaTech (2014)). Another example is the London Congestion Charge; the daily rate for accessing central London is £10, but electric freight vehicles are fully exempted from this charge (McMorrin et al. (2012)). Another form of priority access which can be offered to BEVs because of their noiseless operation is extended delivery time windows (Nesterova et al. (2013)). For example, in s-Hertogenbosch, only silent trucks can enter the city centre between 12am and 7am , and similar testings have taken place in Barcelona and Dublin where the extended time window was 10pm to 7am (AustriaTech (2014)). EVs can also be exempted from restrictions regarding the maximum weight of vehicles allowed in city centres, as is the case in Amsterdam (TU Delft et al. (2013)). Finally, preferential parking is another way to encourage the use of commercial BEVs, either in allocating free spaces or designated loading and unloading docks (AustriaTech (2014)). For example, in Bremen, an environmental loading point close to the city centre provides a dedicated loading area exclusively for Euro 5 diesel vehicles and electric vehicles up to 7500 kg GVW (MDS Transmodal Limited (2012)).

4. Electric vehicles in transportation science

From an operational research point of view EVs and ICEVs share several features, namely a restricted autonomy and a limited capacity. However, the autonomy of EVs is typically more limited, the availability of recharging stations for EVs is rather restricted and their recharging time is considerably longer, compared to that of ICEVs. Moreover, EC possess a number of characteristics that differentiate them from ICEVs: they can sometimes recharge at customer locations, possibly while service is being carried out, they can generate energy by decelerating and battery efficiency depends on recharging policies. Finally, relations and incentives may have an impact on the adoption of EVs. In what follows we will review the main transportation science literature on EVs regarding fleet size and mix, vehicle routing, and optimal paths.

4.1   Fleet size and mix

The fleet size and mix literature related to EVs is relatively recent and limited. It does not yet cover all EV specific features just mentioned. We are aware of four recent contributions in this area.

Van Duin et al.(2013) sought to determine the ideal fleet of BEVs for cargo distribution to a set of customers in Amsterdam's inner-city from a potential depot serving as a small transhipment facility for deliveries in city centre. The problem is formulated as the Electric Vehicle Fleet Size and Mix Vehicle Routing Problem with Time Windows. The aim is to determine an optimal fleet of BEVs and delivery routes to offer a desired service level at minimal costs to a set of customers with delivery time windows. Customer time windows, service times, number of served customers and their demands are considered, as well as the limited autonomy, reduced payloads, high purchase costs and low operational costs of the BEVs. The model ensures that the vehicles always have enough energy to return to the depot and to perform their tours without recharging, and that tours do not last longer than a specified duration. The authors used a sequential insertion heuristic to solve a real instance with two types of electric trucks: the Cargohopper Type 2.1 and the Cargohopper Type 2.2. The number of customers varies according to the day of the week, ranging from 155 to 219. The fleet configuration with the lowest average cost per delivery and service level over 99% was chosen among ten predetermined potential configurations and the best one was recommended for implementation. They also determined scenarios in which the total cost of operating these vehicles is lower than that of the current method of delivery, excluding the consolidation centre's operating costs. Their findings show the ability of modern BEVS to perform urban distribution as well as to reduce air and noise pollution in city centres. However, subsidies and a high utilization would be required for financial profitability.

Gonçalves et al. (2011) have studied the VRP with Pickup and Delivery with a heterogeneous fleet of BEVs and ICEVs vehicles. The problem was formulated as a mixed integer linear program in which the objective is to minimize total fixed and variable costs. Tour duration and vehicle capacity constraints are considered in the model. Charging times are fixed and depend on vehicle range. The vehicles can recharge anywhere during the routes, and the only effect this has on the routes is a time penalty. The number of times the vehicle must stop to charge is determined by dividing the total distance to be traveled by the vehicle range. The model was applied to a Portuguese battery distributor which both delivers batteries and recuperates them from its customers. Customers are also visited for other reasons, such as technical assistance and collection of claims. Three scenarios were

evaluated: one using a fleet of two types of ICEVs, one using a fleet of two types of ICEVs and one type of uncapacitated BEVs, visiting customers without pickups or deliveries, and one using exclusively one type of BEVs. The results showed that using EVs is a more costly alternative due to the high investment required for acquiring or converting these vehicles.

Bae et al. (2011) cast the EV and ICEV fleet size and mix problem as a two-player two-stage game between a regulatory agency and an operator. The regulatory agency imposes environmental standards and can offer tax and price incentives to encourage the acquisition of EVs. It may also specify maximum emission constrains. The fleet operator works in a completive environment and seeks to offer good quality service while minimizing its costs. The authors developed and solved an equilibrium model for this game. They 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. In addition, energy price shocks and the resulting intensification in price competition will put late EV adopters at a disadvantage, but as the benefits of EVs become clearer, their adoption should increase, leading to more price competition and benefits to the customers. While imposing stricter environmental regulations should increase the adoption of EVs, providing subsidies may induce better results. Finally, a wider initial quality difference in products and services between firms is likely to result in a greater response from latecomers, resulting again in higher competition.

As discussed previously, Feng and Figliozzi (2013) have also studied the BEV and ICEV fleet size and mix problem; readers may refer to Section 3.2 for more information on their findings.

4.2   Vehicle routing

In recent years there has a growing interest in the integration of environmental aspects in the study of the Vehicle Routing Problem (VRP) and its variants. For recent surveys, see Demir et al. (2014) and Lin et al. (2014). In what follows we survey some recent contribution to this area in the context of EVs.

One interesting problem is the Green VRP (GVRP) introduced by Erdoğan and Miller-Hooks (2012). In this problem, vehicle routes and refueling (or recharging) of alternative-fuel powered vehicles (AFVs) at alternative fuel stations (AFSs) are determined simultaneously. The authors formulated the problem as a mixed integer linear program whose objective is the minimization of the distance traveled considering a limited driving autonomy and the given locations of of AFSs, as well as constraints on the number of tours and their dura-

tion. However, vehicles are assumed to be uncapacitated. Refueling time is assumed to be constant, an assumption which may not be ideal for using the model for BEVs unless a fast charging infrastructure is available. Customer service time is also assumed to be constant. The authors used a modified Clarke and Wright savings heuristic and a density-based clustering algorithm to construct a set of feasible tours, followed by a postoptimization phase. Numerical experiments were performed using typical parameters for biodiesel-powered vehicles. Forty small problem instances with 20 customers were designed to evaluate the impacts of customer configuration and the number of AFSs on the heuristics performance compared to exact solutions obtained via CPLEX. Twelve larger problem instances with up to 500 customers inspired from a medical textile supply company in Virginia were also tested. The results indicate that as the number of AFSs increases, costs decrease for the same number of served customers, more customers can be served, and the total distance traveled decreases.

A few other papers have also studied the GVRP, either by directly focusing on BEVs or by considering alternative fuel vehicles in general.

Taha et al. (2014) have also proposed a mixed integer linear programming formulation for the GVRP, different from that of Erdoğan and Miller-Hooks (2012) by allowing return paths visiting more than one AFS. They solved the small sized instances proposed by Erdoğan and Miller-Hooks (2012) to optimality.

Omidvar and Tavakkoli-Moghaddam (2012) have added delivery time windows, customer demands and vehicle capacity constraints to the GVRP, while also integrating the effect of congestion. The working day is discretized into intervals with different congestion levels, speeds and travel times. The AFVs can refuel at AFSs along their routes and can stay at customer locations during congestion periods. The objective is the minimization of the sum of vehicle, travel and emissions cost. Small instances were solved to optimality, while larger instances were solved by a simulated annealing (SA) and by a genetic algorithm (GA). The SA yielded better results than the GA at the expense of larger computational times.

Schneider et al. (2014) also extended the GVRP by integrating time windows, customer demands and capacity constraints to the problem, while focusing exclusively on BEVs, in contrast to the previous studies focusing on all AFVs. As a result, recharging times were dependent on the vehicles battery charge upon arrival at a recharging station, i.e., they were not fixed. However, batteries must be fully recharged whenever charging occurs. The authors considered a hierarchical objective function whose first term is the fleet size minimization and whose second term is the minimization of the total traveled distance. They have developed a hybrid metaheuristic combining variable neighborhood search (VNS) with tabu search (TS). Their heuristic could solve the small size instances to optimality with up to 15 customers

and yielded an average gap of 0.35% on larger instances involving up to 100 customers and 21 recharging stations.

Montoya et al. (2014) also studied the GVRP, while focusing on general fleets of zero-emission vehicles like Erdoğan and Miller-Hooks (2012)), rather than exclusively on BEVs like Schneider et al. (2014). Their objective is to minimize total distance traveled to serve a set of customers considering vehicle range limitations, maximum route duration and available AFS infrastructure. Service times and refueling times are assumed to be constant, and no time windows are considered, as in Erdoğan and Miller-Hooks (2012). The authors solved the problem by means of a modified multi-space sampling heuristic which includes three randomized Traveling Salesman Problem (TSP) heuristics within a route-first cluster-second approach, as well as an autonomy reparation procedure to ensure route feasibility. They compared their results to those obtained by Erdoğan and Miller-Hooks (2012) and Schneider et al. (2014) and found their approach to be competitive while being relatively simple.

Another variant of the VRP with BEVs studied by Conrad and Figliozzi (2011)) is called the Recharging VRP (RVRP). However, in comparison to the previous VRP variants where recharging was allowed en route at dedicated stations, here recharging occurs at the customer locations. A service time penalty is incurred when a vehicle recharges, and this can be done while servicing customers. Vehicle capacity constraints and customer time windows are considered. Customers have identical service times but unique demands. The objective function is hierarchical, the first term being to minimize the number of routes and the second being to minimize the total costs associated with distance traveled, service time, and recharging time penalties. The authors used a heuristic based on iterative construction and an improvement algorithm for the capacitated VRP with time windows, described in Figliozzi (2010). They conducted experiments on instances containing 40 customers. The results show an increase in distance traveled and in the number of vehicles for lower vehicle ranges and longer charging times, and hard time windows significantly increase fleet size and distance traveled while also complicating recharging feasibility.

Another interesting variant to the VRP with EVs is to integrate PHEVs in the problem, as was done by Abdallah (2013). The aim of this problem is to minimize the cost of using a fleet of PHEVs to serve a set of customers, by minimizing the time these vehicles run on gasoline while respecting customer time windows. In this case, minimizing total distance does not guarantee minimal costs since the lower operational costs of the electric drive mode has the potential of offering more savings even if longer routes are traveled, but in the electric mode. The model imposes constraints on the number of vehicles available and on their loading capacities. It assigns them to customers while respecting time windows, service

times and demands. At each node, there is the possibility to either charge the vehicles battery to achieve a greater electric range, or to continue to the next open time window using the ICE if the battery dies. An interesting feature of this problem is that one can choose how much to charge the battery according to a charge function, rather than force a full charge to maximum capacity as in the previous studies. This makes the model more usable if fast charging is not available, since trade-offs can be made between the time spent charging and the required energy for feasible routes. The author first solves the problem by using Lagrangian relaxation to find solution lower bounds, and then apply tabu search.

Barco et al. (2012) study a public transportation VRP variant with BEVs while also coordinating the charging schedule of the vehicles to minimize costs and battery degradation. Customer node demands therefore specify passengers to be picked up and dropped off at another node, rather than goods to be delivered. An energy consumption model is applied to the VRP graph so that all edges between two nodes represent minimum consumption paths. The objective function is to minimize the energy consumption of all routes while answering all transport demands. Once this is done, the charging schedule problem minimizes the charging and battery degradation costs in order to be able to perform the set of routes in the VRP solution. Charging costs vary according to energy prices in different charging stations and at different times of the day. Battery degradation costs result from factors like the charging power level, the average state of charge and the depth of discharge. A differential evolution algorithm is applied to solve the charging schedule problem, while the optimization tool XPRESS was used to solve the VRP.

4.3   Optimal paths

Several studies focused on the case of a single electric vehicle traveling from an origin to a destination by trying to determine an optimal path with respect to energy consumption, cost or time. Others consider a predetermined path and attempt to find an optimal recharging policy for minimizing total recharging costs. In what follows we present a few of these studies.

Artmeier et al. (2010) consider the problem of energy-optimal routing of BEVs, which is similar to the classical shortest path problem. However, the problem is different for BEVs since these vehicles can recuperate energy while decelerating by using their electric motor for regenerative breaking. The authors therefore allow certain edges of the graph to have negative costs in terms of energy consumption, for example when the vehicle travels downhill. Limitations due to the battery capacity mean that not all origin-destination paths

are feasible. Therefore, the problem is a constrained shortest path problem, in which the battery charge is bounded by its capacity. The aim of the problem is to determine an origin-destination path, given an initial battery charge, so that the constraints on the battery charge are respected and the remaining charge upon arriving at the destination is highest. The authors proposed algorithms with a worst-case cubic complexity for this problem. Numerical experiments were performed on a road network near Munich containing 776,419 nodes and 1,713,900 edges. Eisner et al. (2011) and Sachenbacher et al. (2011) have later developed more efficient algorithms for the same problem.

Fontana (2013) also studied the problem of determining optimal paths for BEVs and incorporated some stochastic features. However, here the focus is not only on energy consumption but also on travel time. The objective is to determine an origin destination path of least duration as well as the vehicle speed, while respecting an energy consumption limit and considering uncertainties regarding time and energy consumption resulting from traffic, weather, accidents, other drivers' behavior, etc. The author has developed an energy consumption model to determine the expected consumption on each edge. Energy recuperation on certain edges is considered. Several solution methods were proposed including Lagrangian relaxation, techniques from robust optimization, A* search, and dynamic programming. Real-world data were used to construct instances based on typical trips in Massachusetts and Michigan, on which numerical experiments were conducted. Instances were varied for same trips by setting different energy consumption requirements. Estimates for lower bounds obtained by Lagrangian relaxation suggest that the proposed algorithms could find near-optimal solutions within a few seconds. Trade-offs between several paths duration and energy consumption were also identified using a Pareto frontier, indicating that changing routes can often significantly reduce energy consumption while only slightly increasing travel time.

Sweda and Klabjan (2012) considered the problem of determining a minimum-cost path for electric vehicles and integrated the idea of allowing the battery to be recharged along the path. The aim is to determine a minimum cost origin destination path, such that the battery charge always remains above a minimum threshold and below its capacity. In this case, the authors do not use zero as the lower bound on the battery charge constraint because of potential battery degradation resulting from very low depths of discharge. The problem is formulated as a dynamic program. The terms used in the optimality equations refer to the cost of recharging, the cost of traveling between two nodes, and the value function upon reaching the next node. A backward recursion algorithm is applied to find an optimal path. However, certain conditions must be satisfied in order for the state-space to be discrete and

the backward recursion algorithm to be applicable. Therefore, the authors also propose an approximate dynamic programming algorithm for more general instances.

Sweda et al. (2014) studied the problem of determining optimal charging policies along a predetermined path which are cost effective and improve battery longevity. The objective is to minimize the total cost of recharging along the path according to the initial battery level at the origin node, while constraining the battery charge to always remain above zero and below maximum capacity. A stopping cost is used when the driver stops to charge the battery at a node, considering factors such as the time taken to do so, fees charged by the station owner, reducing battery life by one cycle, and a penalty if frequent stops are made. Overcharging costs are incurred when charging the battery beyond a threshold over which degradation occurs, and these costs increase when using higher voltages. The authors derive optimal charging policies for general paths where charging is only allowed at prespecified nodes, and for two specific path types:paths with continuous charging capability where charging can be done anywhere along the path, and paths with equidistant charging locations at prespecified nodes. An optimal policy is determined through a forward recursion algorithm for the general paths, while the optimal number of stops for the continuous and equidistant charging paths are obtained by solving a closed-form expression before determining the corresponding optimal policy. The authors have also developed two heuristic methods to find fast, simple and effective policies. They have tested the performance of their methods using data of the US Interstate 90, and data generated from a simulated urban route with several origin-destination trips and different values for the driving range, overcharging threshold, and overcharging cost rates. The optimal policies show that overcharging is more costly than recharging more frequently when considering degradation costs.

Arslan et al. (2014) have integrated PHEVs into the minimum cost path between two points. They consider battery swapping stations instead of battery charging stations. In this context, the option of refuelling the vehicle with gasoline is also available. Since a shortest path is not necessarily the minimum cost path in this context because the operational costs are lower for electric driving, a depreciation cost is used to penalize long distances. Additionally, a cost is incurred for each stop . Battery degradation costs are associated with deep battery discharges. The objective is to minimize the total travel cost associated with electricity and gasoline, the battery degradation cost, the depreciation cost and the stopping cost. The authors propose three solution techniques: a mixed integer quadratic constrained program, a dynamic programming based heuristic, and a shortest path heuristic. Numerical experiments were conducted using problem instances that represent various network structures and user behaviors. CPLEX solves the problem to optimality, but running times can

become quite high as the node number increases. The heuristic methods can solve much larger problem instances and find near-optimal solutions within reasonable running times.

Kobayashi et al. (2011) also seek to determine an optimal origin-destination path for BEVs while allowing the vehicles to stop at charging stations if necessary. Slow and fast recharging stations are considered, but regenerative breaking is not taken into account in their approach. The methodology first identifies potential stations when the vehicle cannot complete the path from its origin with its remaining charge. Dijkstra's algorithm is then used to find a least travel cost route using the identified stations. Depending on the driver's priority, traveling costs either focus on distance traveled or on traveling and charging time. The charging level of the stations, in addition to their location, is considered. However, no battery degradation component is considered as a result of excessive fast charging, and the vehicles must be fully charged when stopping at a station. Numerical experiments were conducted on a Japanese map with 2,500 hypothetical charging stations (2,200 slow stations and 300 fast stations), while prioritizing travel time rather than distance. Results showed that the method is effective but also requires more computational time than conventional route search methods due to the calculations needed for finding potential stations.

Alesiani and Maslekar (2014) are also interested in determining optimal paths for BEVs by allowing them to stop at charging stations along the way if necessary. A feature of this problem is that individual paths are determined jointly for a fleet of BEVs, each vehicle having its own origin-destination pair. Furthermore, the authors incorporate the idea of allocating charging stations to the vehicles so as to avoid having many vehicles at the same one simultaneously. The goal is to minimize total costs related to energy consumption and charging times resulting from concurrency at the stations, while respecting constraints with regards to battery capacity, the number of charging stops allowed per route, and the number of vehicles that can be charged at the stations. Energy recuperation is also considered. The problem is solved with a modified evolutionary genetic algorithm. Numerical experiments show that this approach allows a better distribution of the vehicles among the stations.

Siddiqi et al. (2011b) and Siddiqi et al. (2011a) exclusively consider fast charging stations along the path and use a multi-constrained optimal path (MCOP) algorithm to determine an optimal origin-destination route. The objective is to minimize total distance traveled while respecting constraints regarding travel times, traffic delays, charging times and charging costs. Charging times also include waiting times that can occur at the stations. The MCOP formulation is first transformed into an unconstrained optimization problem by using a penalty function method, which is then solved with an algorithm based on simulated evolution in (Siddiqi et al. (2011b)) and particle swarm optimization in (Siddiqi et al. (2011a)).

The algorithms were implemented in Java, and numerical experiments based on a Saudi Arabian city with 108 nodes and 432 edges show the superiority of their method compared to other popular MCOP algorithms. Siddiqi et al. (2012) further studied the problem by using a simulated evolution based algorithm but on a multi-objective shortest path formulation of the problem. Another distinction is that the stations are placed at road intersections (i.e., nodes) rather than along road segments (i.e., edges) as in their MCOP approach. The goal is to minimize three objective functions regarding charging time, path length and travel time respectively, while never running out of energy. Numerical experiments were carried out on the San Francisco Bay Area and on Colorado road networks.

5.   Research perspectives

Compared to ICEVs, EVs generally pollute less and produce less noise and are thus perceived as a more sustainable means of goods transportation. As noted in Section 3.3, the societal advantages of using EVs translates into a number of incentive schemes designed to increase the competitiveness of EVs.

From a cost perspective, EVs require lower maintenance costs and incur lower operating costs, but have high purchasing costs. As mentioned by Feng and Figliozzi (2013), the purchase cost of commercial electric vehicles can be three times higher than that of ICEVs, while the operational costs of commercial electric vehicles can be nearly four times lower. This, however, depends on the price of electricity in the market of operation. At present, the adoption of EVs for goods transportation is somewhat dependent on incentives, thus indicating that this greener form of transportation is not yet economically viable. Therefore, the cost competitiveness of EVs highly depends on future technological developments related to these vehicles, coupled with governmental investment in adequate infrastructure and incentives. Nonetheless, a number of important features can already be identified as necessary when studying freight distribution with electric vehicles.

Based on the review presented in the previous sections, we will present a number of important interrelated modelling issues that are relevant to the emerging research area of goods distribution with EVs. In Sections 5.1–5.3, we discuss research perspectives at the strategic, tactical and operational levels.

5.1 Strategic perspectives

The strategic perspectives of BEVs ownership in goods transportation mostly relate to fleet composition issues, i.e., the best choice of fleet size and mix when considering a potential mix of ICEVs and EVs. The ownership of BEVs should encompass purchase cost, operational and maintenance costs.

A substantial part of the purchase cost of BEVs is related to the battery cost. The battery size and weight influence the payload of BEVs, and thus impacts the effective capacity of vehicles. The size of the battery also influences the driving range of BEV. Therefore, choosing the correct battery type is paramount in fleet acquisition questions. We note that significant reductions in battery costs and weights are also expected in the future. Thus, it is worth examining the impact that such developments may have on fleet composition. Furthermore, battery aging will gradually reduce the maximum range over time. Other factors influencing the battery lifetimes are discussed in the following sections.

The use of BEVs and ICEVs essentially implies dealing with the potential distance ranges that these vehicles can traverse without recharging or refuelling, respectively. The issue of refuelling ICEVs has been rightfully ignored by the transportation science community since there exists an abundance of fuel stations for conventional vehicles, the refuelling times are negligible and refuelling stations offer similar services. However, these conditions do not hold for BEVs. Indeed, the recharging infrastructure is scarce and refuelling times can be heavily affected by the type of service offered by the particular recharging station. Two main categories of charging stations exist: slow (level 2) and fast (level 3), the latter being much more costly. Furthermore, fast charging dictates high power demand levels from the electricity grid. Thus, the charging infrastructure depends on the local electricity grid capabilities.

Naturally, charging capacities are subject to technological developments and should be considered. However, the decision of purchasing BEVs should explicitly account for the existing infrastructure since this influences the strategic capacity of BEVs in terms of potential range. Furthermore, a fleet operator may also consider investing in recharging infrastructures, at depots, customer locations or even along long-haul paths.

A measure for the battery life is the number of times a battery can be discharged to a low state of charge. Lithium-ion batteries currently used for freight BEVs typically provide a 1,000 to 2,000 deep cycle life, which roughly translates into six years of operation (den Boer et al. (2013)). This should be carefully considered in fleet investment decisions. Finally, the fleet size and mix issues should not be limited to battery electric vehicles, but should also

include HEVs and FCEVs.

5.2 Tactical perspectives

Once purchased, BEVs necessitate taking a number of tactical decisions mainly pertaining to charging policies, which in return influence the battery lifespan. While there exist several ways of recharging batteries, the most common is conductive charging. Therefore, considering the current state of the conductive charging technology, one important decision relates to where the EVs can recharge. This can be a combinations of charging at the depot, at a customer location or at a charging station.

In reality, when BEVs are used for goods distribution, it is common not to use the public infrastructure and to fully charge them overnight at the depot (Nesterova et al. (2013), Naberezhnykh et al. (2012b), Taefi et al. (2014)). While charging at customers' location is an option, it requires a joint agreement with customers, with respect to charging times and rates.

Recharging along a path, be it at a public station or at a customer location, would make sense if fast charging could be performed at these stations. The slow recharging infrastructure would require several hours to fully recharge a typical BEV, and therefore would be less relevant considering a daily shift in short-haul transportation. Additionally, fast charging infrastructures remain relatively scarce in most countries except Japan (IEA and EVI (2013)). Therefore, for most countries it seems logical that vehicles should mostly recharge at the depot. Furthermore, fast charging reduces battery lifespan. It particularly affects battery health when used at the beginning or at the end of the charging cycle (Zhang (2006)). The cost of recharging should also be accounted for when addressing the issue of charging policies, since electricity is often cheaper during the night and off-peak hours.

Finally, a potential tactical decision relates to leasing batteries. Battery leasing is currently available for a few electric vans but not for electric trucks. The existence of such an option for trucks might help their market penetration.

5.3 Operational perspectives

Considering the tactical recharging policy, operational decisions should be made in an attempt to optimize the battery life while not compromising the operational cost of serving customers. Charging batteries too close to their maximum capacity or keeping them at high states of charge for long periods can adversely affect their lifespan (Sweda et al. (2014)

and Electrification Coalition (2010)). Furthermore, battery deterioration can also occur if it is frequently discharged to deep levels (Millner (2010)). Therefore, deciding when and how much to recharge is a critical operational issue since this directly impacts the potential distances traversed by the BEVs.

Some models work with fixed charging times, or assume that the battery is charged to its full capacity whenever it is charged. More realistic models could explicitly target battery charge times and schedules as a means to optimize battery life. Furthermore, the BEV's payload should also be accounted for especially in light of its relationship with the battery size.

The literature on optimal paths addresses battery properties in a more explicit fashion, e.g., it considers the negative impacts of charging with higher power levels and too close to maximum capacity, as well as discharging to low levels. Another example is to explicitly account for regenerative braking along the paths. This leads us to the conclusion that the elaborate battery health models should be gradually transferred to the vehicle routing context.

The competitiveness of BEVs is amplified when considering congestion, which is particularly realistic in the case of urban distribution. Finally, a number of random factors may temporarily reduce the BEV's range, e.g., extreme temperature, high driving speeds, rapid acceleration and driving up important slopes (US DOE (2012b)). These can be captured by designing stochastic models in order to quantify their impact on the achievable range.

6.   Conclusions

The integration of EVs in goods transportation depends on a number of factors related to cost, technology, infrastructure, electricity sources and financial incentives. Since future trends in these areas are highly uncertain, the problems needed to be solved by the transportation science community are also likely to evolve over time, thus creating important research challenges. However, we believe that modelling these features and developing adequate solution procedures to the resulting models is vital as it allows the study of the current problems and of future scenarios, within a rigorous framework.

Considering the current state of technology, BEVs are more appropriate for city distribution than long-haul applications because of the battery limitations. Typical daily distances traveled by urban delivery trucks are often lower than the range of commercial BEVs (Feng and Figliozzi (2013)), which has been shown to be suitable for real routing patterns of lo-

gistic service providers, even if the vehicles' reduced payload remained a concern expressed by drivers (Ehrler and Hebes (2012)). Therefore, BEVs are more suitable for last-mile deliveries in urban areas involving frequent stop-and-go movements, limited route lengths as well as low travel speeds (Nesterova et al. (2013), TU Delft et al. (2013)). Their reduced pollution and noise is also more relevant in urban areas and thus more likely to be rewarded by incentives. These factors should certainly be of concern to researchers working in the area of city logistics.

Finally, we highlight the fact that BEVs do not only compete against ICEVs, but also with other cleaner alternatives such as compressed natural gas, in which the superiority of BEVs can be even harder to establish (Valenta (2013)). Furthermore, significant improvements in ICE vehicle efficiencies can be expected in upcoming years (Mosquet et al. (2011)). This fact should not be ignored in the fleet size and mix research.

Acknowledgments

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