Charging Infrastructure for Commercial Electric Vehicles: Challenges and Future Works

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ABSTRACT The journey towards transportation electrification started with small electric vehicles (i.e., electric cars), which have enjoyed an increasing level of global interest in recent years. Electrification of commercial vehicles (e.g., trucks) seems to be a natural progression of this journey, and many commercial vehicle manufacturers have shifted their focus on medium- and heavy-duty vehicle electrification over the last few years. In this paper, we present a comprehensive review and analysis of the existing works presented in the literature on commercial vehicle charging. The paper starts with a brief discussion on the significance of commercial vehicle electrification, especially heavy- and medium-duty vehicles. The paper then reviews two major charging strategies for commercial vehicles, namely the return-to-base model and the on route charging model. Research challenges related to the return-to-base model are then analysed in detail. Next, different methods to charge commercial vehicles on route during their driving cycles are summarized. The paper then analyzes the challenging issues related to charging commercial vehicles at public charging stations. Future works relevant to these challenges are highlighted. Finally, the possibility of accommodating vehicle to grid technology for commercial vehicles is discussed.

INDEX TERMS Commercial electric vehicles, electric trucks, return-to-base model, smart charging system, charging infrastructure.

NOMENCLATURE

BSS	Battery Swapping Stations
CEV	Commercial Electric Vehicles
CS	Charging Station
ET	Electric Truck
EV	Electric Vehicle
GHG	Greenhouse Gases
HDT	Heavy-duty Truck
IPT	Inductive Power Transfer
LDT	Light-duty Truck
MDT	Medium-duty Truck
SoC	State of Charge

I. INTRODUCTION

Human-induced greenhouse gas (GHG) emissions have led to global climate change with increase in the Earth's

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temperature over the past century [1]. In order to combat this climate change threat, the 2016 Paris accord aimed to reduce global GHG emissions so that the average global warming remains within 2°C above pre-industrial temperatures [2]. One of the biggest contributors to GHG emissions is the transportation sector, which generates almost 25% of global CO_2 emissions. Amongst the different modes of transportation, road vehicles are responsible for nearly 75% of CO_2 emissions in the transportation sector [3]. Therefore, the electrification of road transportation has become a critical step towards mitigating direct CO_2 emissions [4]. Accordingly, several governments have set transition plans to electrify their transportation sector by 2050 [4]. By the end of 2020, global electric vehicles (EV) stock reached around 10 million; of which two-thirds were battery electric vehicles. The vast majority of these EVs are light passenger vehicles [5].

Commercial vehicles contributed to almost 40% of global CO_2 emissions of the road transport sector in 2015, and life-cycle GHG of commercial vehicles are estimated to

at least double from 2015 to 2050 under the business-as-usual scenario [7]. Accordingly, the electrification of commercial vehicles represents a promising opportunity to significantly reduce these emissions [8], [9], making the electrification of commercial vehicles an important research area. Most studies on electrifying commercial vehicles have focused on hybridization of these vehicles [10]–[16], due to the small size of batteries and limited mileage of electric vehicles, and lack of public charging infrastructure. For zero-emission commercial electric vehicles (CEVs), including electric trucks (ETs), the initial deployment has focused on light-duty trucks (LDTs), which have been successfully electrified without significant changes in travel behaviors [17]. The deployment of medium-duty trucks (MDT) is still in the early phase, whereas the deployment of heavy-duty trucks (HDT) is in the pilot stage [18]. In recent studies [5], [19], the uptake of commercial electric vehicles, including trucks, were around 250,000 light-duty vehicles, with a stock of nearly 31,000 units of medium- and heavy-duty vehicles. This lack of adoption of commercial electric vehicles has been attributed to the poor policies applied to this sector as compared with light passenger vehicles [18], [20].

However, recent improvements in lithium battery technology [21], [22] have made electric trucks technically and economically viable compared to diesel and alternative fuel trucks [23], [24]. The potential benefits of ETs as compared to diesel trucks over the life cycle of a vehicle have been analyzed in existing studies [22], [23], [25]–[27]. These studies have concluded that even with the high investment costs of ETs, they can perform at least at the same life cycle cost as diesel trucks, especially if the trucks have high annual mileage and battery lifetime. Moreover, regulations and government incentives promoting the use of zero-emission vehicles have increased the deployment of ETs, especially MDTs and HDTs [18], [28], [29].

Several truck manufacturers, such as DAF, Daimler, MAN, Navistar, Nikola, PACCAR, Volkswagen, Volvo, Tesla Inc., and Thor Trucks, have announced significant plans to electrify their MDTs and HDTs, with battery sizes ranging from 300 kWh up to about 990 kWh [19]. The electrification of medium-duty trucks has received the most interest in these announcements due to short-range requirements and the small size of batteries in these trucks. All the announcements have included a model for medium-duty trucks, where some manufacturers have released their commercial trucks for markets, such as Daimler and BYD. Some manufacturers like Navistar, Volkswagen, Thor Trucks, Freightliner, and Tesla Inc. have introduced the production of heavy-duty trucks within their announcements. Contrastingly, many companies have started integrating ETs into their fleets or have announced their ETs procurement. For example, Walmart Inc. announced 45 pre-orders of class 8 Tesla Semi HDTs in 2018 [30]. Similarly in 2019, Amazon announced an order of 100,000 electric delivery trucks from Rivian, whilst Anheuser-Busch announced a plan

to deploy 21 HDTs from BYD in California by the end of 2019 [31], [32].

The potential for electrifying commercial vehicles increases with the availability of suitable charging infrastructure suiting the charging requirements of these vehicles [17], [23]–[25], [33], [34]. Operators of commercial vehicles are unlikely to switch to electric vehicles if the charging process is more difficult, time-consuming, and uncertain [35]. However, due to varied applications of commercial vehicles, as shown in Table 1, there is diversity in their average load, trip length, and daily mileage, which in turn impacts the charging requirements of these vehicles [18], [35], [36]. Additionally, the operational schedules of commercial electric vehicles can impact the charging process of these vehicles at charging infrastructure as compared to passenger vehicles [24].

Therefore, the successful adoption of ETs, especially MDTs and HDTs, in different commercial fleets requires the address of different challenges for charging ETs at possible locations of charging infrastructure. This paper discusses challenges facing the charging of commercial electric vehicles at different charging infrastructure and future works for addressing these challenges. The main contributions of this review paper are:

1) To our knowledge, this paper is the first of its kind that provides a comprehensive overview and analysis of charging challenges for commercial electric vehicles.
2) We highlight and discuss the challenging issues for charging both short- and long-haul commercial electric vehicles. We discuss various recommended approaches and future works to address the charging challenges of commercial vehicles at different locations.
3) We discuss the possibility of leveraging the V2G technology to increase the benefits of commercial fleet operators and provide ancillary services.

The remainder of this paper is organized as follows. Section II introduces commercial electric vehicles. Section III introduces charging infrastructure requirements for commercial electric vehicles. Section IV discusses the charging infrastructure that follows the return-to-base model. The charging of commercial electric vehicles at public charging infrastructure is introduced in Section V. Section VI presents charging for long-haul commercial electric vehicles. Section VII presents potential solutions to address issues in charging commercial electric vehicles. The suitability of commercial electric vehicles for V2G technology is discussed in Section VIII. Finally, Section IX draws the conclusion and summary of this paper.

II. COMMERCIAL ELECTRIC VEHICLES

Commercial vehicles e.g. trucks are broadly classified into three main categories according to their gross vehicle weight (GVW). These categories are light-duty trucks with a GVW of less than 3.5 tonnes (t), medium-duty trucks with a GVW from 3.5t to 15t, and heavy-duty trucks with a GVW greater

TABLE 1. Different applications of commercial vehicles.

Vehicle Type	Truck Example	Type of Application	Technical Details	% Percentage [iii]
Class 7/8 Haulage Trucks				
Over the Road Trucks		• Freight Application • Drayage Application	• High Annual VMT[i] • High Average Speed • Highway Driving; Long-Haul Driving	12%
Regional Trucks		• Drayage Application • Day Cabs Application	• Lower Annual VMT • Lower Average Speed • Intercity, or Between cities Driving; Short-Haul Driving	8%
Class 3/8 Vocational Work Trucks				
Intra-city Trucks		• Cargo Application • Freight Application • Delivery Application	• Lower Annual VMT • Lower Average Speed • Intercity, or Highway Driving	20%
Urban Trucks		• Cargo Application • Freight Application • Delivery Application	• Lower Annual VMT • Lower Average Speed • Intercity Driving; Lot of Stop and Start	17%
Site-work Trucks		• Utility Services • Construction Services	• Lots of Idle Time • Lots of PTO[ii] Use	5%

[i] VMT refers to Vehicle Miles Traveled.
[ii] PTO refers to Power Take-Off
[iii] The percentage of the truck population by vocations depends on the California truck population. [6]

than 15t [18]. Each category contains a wide variety of vehicle types, e.g. from long-haul freight to garbage collection trucks, suited to their range of vocational operations. In recent years, the electrification of medium-duty and heavy-duty trucks has been increasingly adopted due to policies supporting zero-emission vehicles uptake and advances in battery technology [5]. Many truck makers have manufactured models of medium-duty electric trucks that have battery bank capacities ranging from 48.5 kWh up to about 350 kWh with an estimated range of up to 400 km [7], [17], [24], [44]. For heavy-duty electric trucks, many models have been announced or produced with battery bank capacities between 120 - 1000 kWh to cover an estimated range of up to 800 km [7], [17], [24], [44]. The specification of some medium-duty and heavy-duty electrical trucks currently available or reported are presented in Table 2.

The applicability of currently available models of CEV to cover the daily travel distance of commercial vehicles depends on the estimated range of CEV and the availability of suitable charging infrastructure [17], [24], [44]. According to

conducted surveys [45], [46], the majority of medium-duty commercial vehicles cover an average daily travel distance of 80–250 km, whilst the average daily travel distance of heavy-duty commercial reaches up to 700 km. Therefore, the reported range of medium-duty CEVs can meet a high percentage of the daily travel distance with a single charging event per day at locations where they park overnight or between shifts [17], [24]. However, some medium- and heavy-duty CEVs have high charging requirements (e.g. long-haul operation, multiple-shift operation etc.) that require high charging rates to be met in a single charging event over the times they are parked. Due to the restricted capacity of some electrical power infrastructure that limits the charging rate of charging infrastructure, multiple charging events are required per day at different locations throughout the routes of commercial vehicles to meet a high percentage of the daily travel distance [17], [44]. Consequently, the number of times CEV may require to be charged per day depends on the daily travel distance of commercial vehicles, the estimated range of CEV, and the charging rate of charging infrastructure.

TABLE 2. Specification of Some commercial electric vehicles (e.g. trucks) reported in literature and projections.

Company	Gross Vehicle Weight (GVW)	Battery Capacity (kWh)	Reported Range (km)	Energy Consumption (kWh/km)	Reference
Medium-Duty Vehicles (GVW: 3.5t to 15t) [18]					
Navistar eStar	5.5t	80	100	0.8	[37]
Smith Newton	6.4–12t	40–120	65–160	0.62-0.75	[7]
BYD	7.3t	145	250	0.58	[38]
Mitsubishi	7.5t	82.8	120	0.69	[39]
EMOSS	7.3–10t	99	145	0.69	[7]
BYD	11t	175	200	0.88	[38]
Daimler	12t	325	370	0.88	[40]
Heavy-Duty Vehicles (GVW: > 15t) [18]					
Renault	16t	200–300	200-300	1.00	[41]
EMoss	18t	120–240	100–250	1.00	[24]
Mercedes-Benz	26t	212	200	1.06	[42]
Renault	26t	200	200	1.00	[41]
Tesla-Semi	36t	600-1000^i	480–800	<1.25	[43]
BYD	36t	350	200	1.75	[38]
Daimler	40t	550	400	1.38	[40]

^{i} Estimated [18].

III. CHARGING INFRASTRUCTURE OF COMMERCIAL ELECTRIC VEHICLES

The availability of charging infrastructure is the most important driver for boosting the adoption of EVs. According to the SAE J1772 standard, the charging infrastructure of EVs can be classified into three levels, based on charging power rate, voltage, current, and location of installation as shown in Table 3 [18], [47]. These levels identify charging duration of EVs, where levels 1 and 2 are known as slow chargers, whilst level 3 is fast charger.

By the end of 2018, the global installation of charging stations dedicated to light-duty vehicles reached approximately 5.2 million. Most of these stations were installed as slow charging private stations whereas public charging stations reached 144,000 fast chargers and 395,000 slow chargers [18], [19]. Further in 2019, many plans were announced to boost the deployment of charging infrastructure. Most of these announcements related to private sector chargers with different capacities. Other announcements cover publicly accessible chargers and fewer commitments for highway charging infrastructure [18].

The suitability of existing charging infrastructure for charging CEVs depends on the power requirements of these vehicles. Level 2 chargers can be used to support overnight charging of light- and medium-duty ETs, whereas level 3 chargers can be used to support fast charging of small and medium-duty ETs. In addition, level 3 chargers can be used for overnight charging of some heavy-duty ETs. Nevertheless, most heavy-duty ETs and medium-duty ETs with long driving distances require dedicated fast-charging

TABLE 3. Charging levels of EV according to SAE J1772 standard [18], [47].

Charging Levels	Level 1	Level 2	Level 3
Phase	AC (1 Phase)	AC (1 / 3 Phase)	DC
Voltage (V)^i	120 V	230-400 V	400 V -Higher
Current (A)	10-16	16, 32 or 63	63-125^{ii}, Up to 400^{iii}
Power (kW)	1.4-1.9	3.7-22	44 -Higher
Installation	Domestic Location	Domestic/ Public Location	Public Location

^{i} The standard of North America.
^{ii} Typical values of DC charging stations [18], [47].
^{iii} Developed DC charging stations [18], [47].

infrastructure with higher power capacities than the existing fast level 3 chargers. Hence, various companies such as Tritium, Phoenix Contact, BMW Group, and Charge Point have announced new plans to deploy high power capacity charging infrastructure of more than 400 kW. Furthermore, Tesla Inc. has announced a plan to add a mega chargers network of 1 MW power capacity that has the ability to provide 640 Km within 30 minutes [18], [24].

According to the operational schedules of commercial electric vehicles, charging infrastructure can be located at places where vehicles park (depots, yards, aggregators, etc) to enable overnight charging or between shifts, and publicly accessible places to enable charging on route along the daily driving cycle of commercial vehicles.
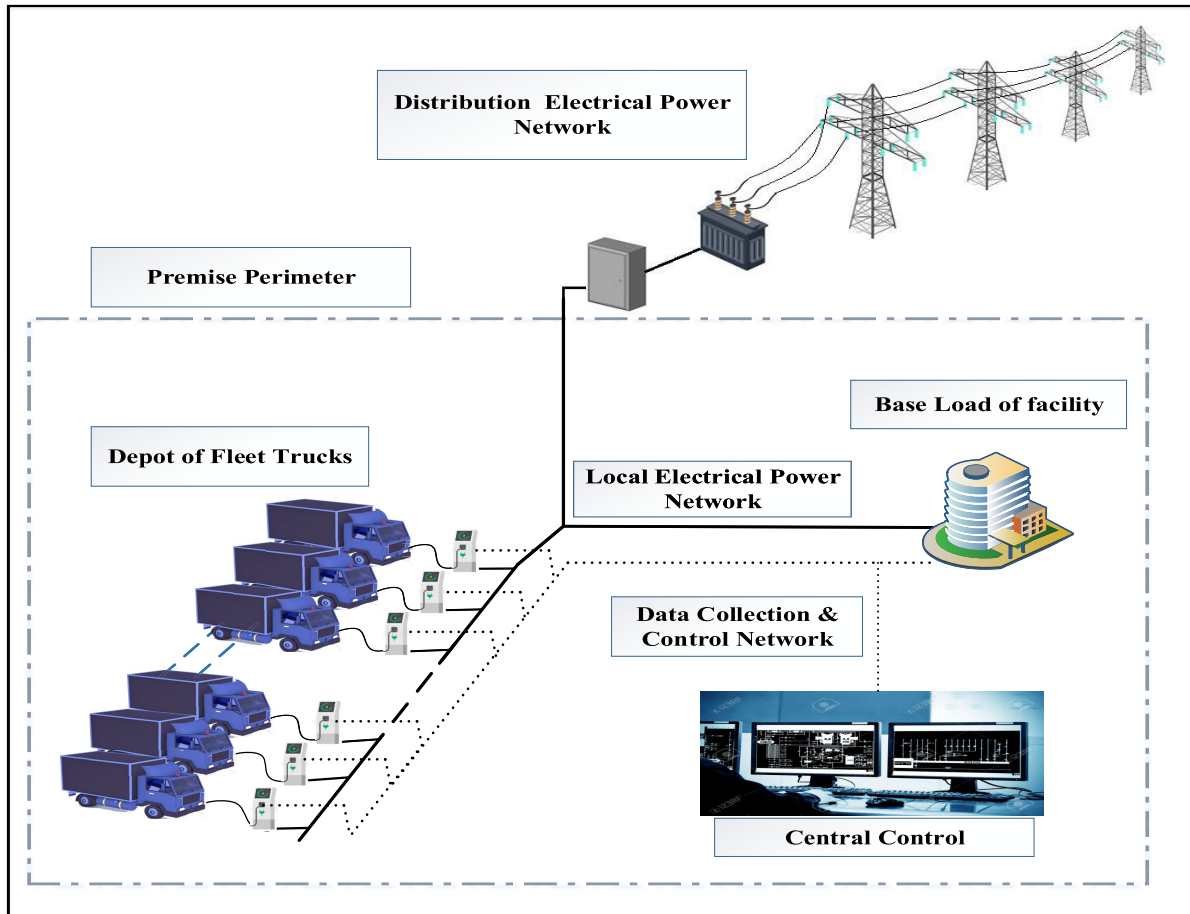
FIGURE 1. Operation model of return-to-base strategy.

IV. RETURN-TO-BASE MODEL CHARGING INFRASTRUCTURE

Due to the spatial and temporal distribution of commercial truck fleet activities and a shortage of suitable public charging stations, most commercial enterprises rely on a "return-to-base" strategy where high-power charging infrastructure is installed at their commercial facilities (depots, yards, industrial micro-grids, etc.) to enable the full charging of ETs outside working hours, such as overnight or between shifts as depicted in Fig. 1 [48]. In the first stage of ETs adoption, the most straightforward strategy is to install a dedicated charging station for each ET that needs to be charged at the commercial facility [49]. However, it is possible for a number of ETs to share the same charging station in order to reduce the capital cost of charging infrastructure as long as this reduction in the number of charging stations does not disturb the operational schedules of ETs [49], [50].

Charging infrastructure is required to recharge ETs fully within their parking time. However, in some commercial applications, full battery capacity is rarely used due to the daily operational schedules of ETs [20], [49]. Furthermore,

TABLE 4. Summary of challenging issues for return-to-base charging.

Main Challenging Issues	References
Upgrading of electric power infrastructure for facilities and distribution grid system	[51]–[54]
Peak demand charge of electricity bills for the commercial facilities	[35], [49], [52], [54]–[56]
Operation conditions of facilities and commercial vehicles	[49], [56]–[60]
Deterioration of battery health of commercial vehicles	[61]

the initial SoC of ETs can change according to any deviation or change in daily operational schedules [20], or braking energy that is recharged into the battery of ETs [49].

Return-to-base charging presents challenging technical and economical issues for commercial fleet and grid system operators, which are summarized in Table 4. These challenges may increase barriers to the adoption of medium- and heavy-duty ETs in different commercial businesses [52], [62]. These challenging issues are discussed below.
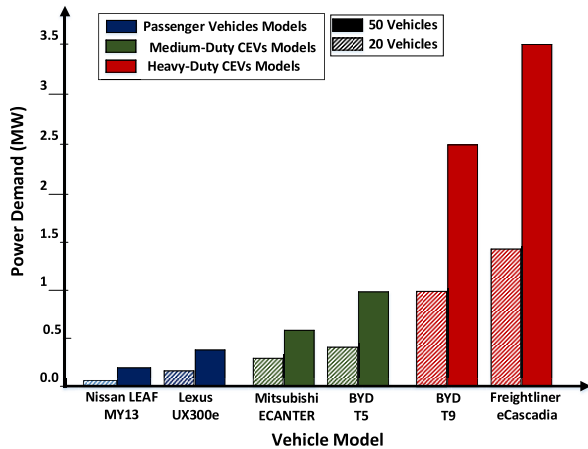
Assumption: The charging rates are selected to ensure the charging of over 7~8 hrs as follows: Nissan Leaf MY13 charging rate is **3.3 kW**, Lexus UX300e charging rate is **6.6 kW**, Mitsubishi ECANTER charging rate is **11 kW**, BYD T5 charging rate is **19.2 kW**, BYD T9 charging rate is **50 kW**, and Freightliner eCascadia charging rate is **70 kW**.

FIGURE 2. Peak power demands for simultaneously charging various EVs and CEVs fleets.

A. UPGRADING OF ELECTRIC POWER INFRASTRUCTURE

As the return-to-base strategy enables only the charging of CEVs at their commercial facilities, these vehicles should have large size batteries to meet required daily driving distances before returning to their charging location. This means the charging infrastructure installed at these locations needs to be of high-power capacity in order to charge these vehicles within the allowed time windows. As a result, there will be a significant increase in peak power demand at charging locations of medium- and heavy-duty CEVs, which in turn has significant impacts on the electrical network assets of these locations [51], [52]. Figure 2 shows peak power demands for simultaneous charging of passenger light vehicles, medium-duty CEVs, and heavy-duty CEVs at commercial location. As can be shown, the simultaneous charging of 20 medium- and heavy-duty CEVs with 11 kW and 50 kW chargers respectively would place loads of 220 kW and 1 MW on the electrical infrastructure as compared to 66 kW that is required to ensure the charging of 20 passenger light trucks. Moreover, with an increasing number of CEVs being charged in commercial locations as shown in case of 50 heavy-duty vehicles, the increase of peak demand can reach 3.5 MW and increase dramatically if faster charging is required. This high power demand may stress the local electrical distribution network (where electricity is delivered to customers) especially during residential peak load hours. In the current market, the light-duty passenger EVs significantly outnumber the electric trucks, and consequently, there may not be enough incentives for the distribution networks to upgrade their facilities to readily meet the demand of electric trucks. In the future, when the electric truck market reaches a certain threshold, the cost-benefit analysis/business case will certainly drive the decisions regarding infrastructure upgrades. [51]–[53].
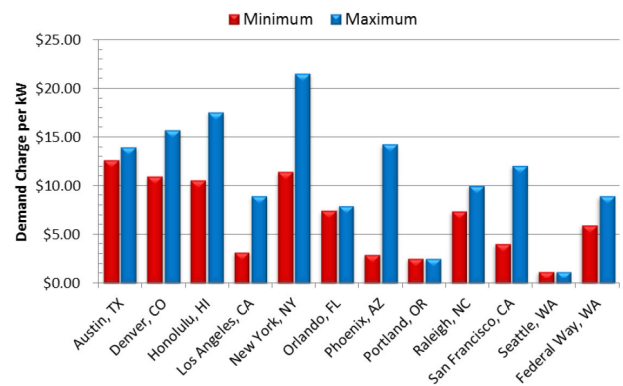

FIGURE 3. Sample peak demand charges from selected metropolitan areas across USA [56].

These factors have negative impacts on the number of ETs that can be charged simultaneously at their commercial facilities. Hence, the electrical power network of a commercial facility will need to be upgraded in order to accommodate increased adoption of ETs within a commercial fleet. At the local electrical distribution network level, additional upgrades may be needed to serve particular charging locations for commercial vehicles in order to address increased power demand [51], [54]. However, the high investment costs of upgrading the electrical network of commercial facilities can be prohibitive in adopting more electric vehicles in commercial fleets. Moreover, the upgrading of a local electrical distribution network adds challenges to the power sector because of its high investment and long time required for upgrading [51], [52], [54].

B. PEAK DEMAND CHARGE AND ELECTRICITY BILL

Electricity used by commercial businesses is usually charged using commercial and industrial electricity rates, which mainly incorporates a per-kWh energy charge plus per-peak-kW demand charge. These demand charges apply to the maximum power (KW) required in any interval (typically 15 minutes) during the month [49], [55]. These rates provide a way by which a utility can recover the projected cost of generation and distribution infrastructure required to meet the peak demand of commercial businesses. These demand charges vary moderately by region and significantly by commercial facilities as shown in Fig. 3 [56]. Moreover, some utilities set higher demand charges for summer power demands than winter power demands [35]. Therefore, the cost of peak demand may exceed 50% of the monthly electric bill for some commercial properties [56].

The unmanaged charging of commercial vehicles at their parking locations, which also purchase electricity for other purposes on the same contract, may considerably increase peak demand charges at these locations [52], [54]. This increase in demand charges depends on whether the peak demand of the parking location's base-load coincides with
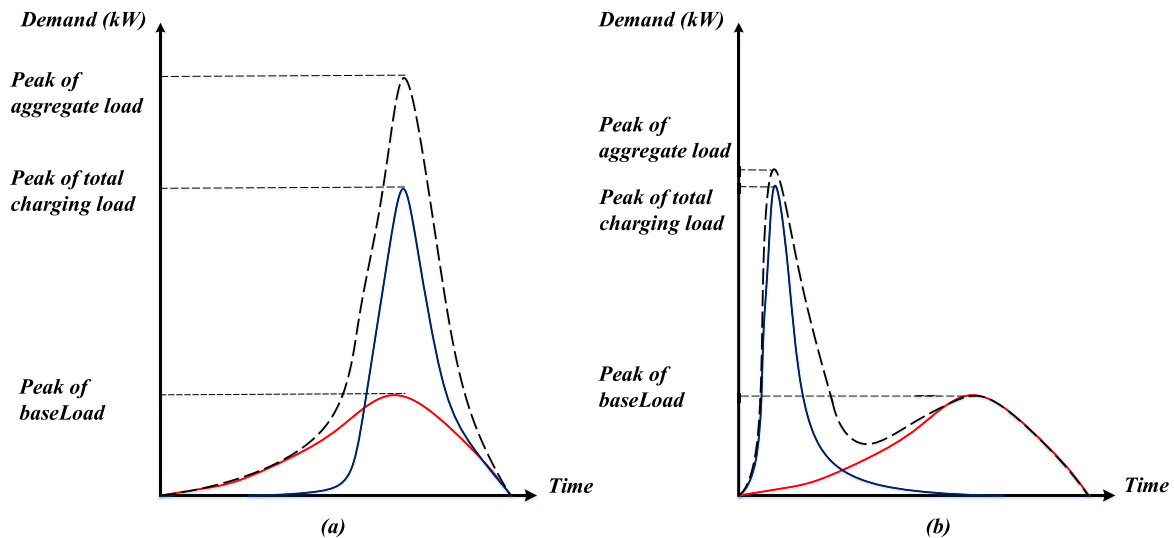
FIGURE 4. The increase in peak demand of the facility: a) Facility's base-load coincides with peak demand of total charging load of CEVs, b) Two peak demands do not coincide [35].

the peak demand of the total charging load of commercial vehicles [35]. If the peak demand of charging load and peak demand of base-load are coincident, as shown in Fig. 4a, the demand charge of the aggregate load is increased by the demand charge of the total charging load. In the case of managing the charging of commercial vehicles outside business hours, peak demands are not coincident, as shown in Fig. 4b. Thus, the demand charge of aggregate load would be less and could even be zero if the peak demand of aggregate load is less than the peak demand of the base-load. The unmanaged peak demand charge scenario in 4a can be very costly and prohibitive for commercial businesses seeking to install charging infrastructure at their facilities [49], [55].

Although the previously mentioned issues are applicable to any electric vehicle fleet getting charged in the commercial area, the charging of commercial electric vehicles is more challenging and prohibitive. This can be shown from Figure 2. According to this figure, simultaneous and unmanaged charging of 20 medium- and heavy-duty CEVs can increase the demand charges to be 3 to 10 times higher than that of passenger vehicles. Another important difference between commercial and passenger electric vehicles is regarding their operational schedules during the dwell period, which is discussed in the following section. These operational schedules may restrict the available charging time for commercial vehicles as compared to passenger vehicles.

C. OPERATION CONDITIONS OF FACILITY AND COMMERCIAL VEHICLES

At some commercial facilities, the charging of ETs meets some operational challenges related to the participation of a facility in incentive-based demand response programs (IBDR), designed to push commercial customers to curtail their demand during peak load periods [49], [57].

This curtailment of demand has its impact on the peak demand of a facility over the charging period [58].

Additionally, the charging of some commercial vehicles involves challenges related to special operational schedules during their parking interval. According to these schedules, ETs need to be moved away from CSs for some operations (e.g., washing and loading of the next day's goods) at some point before the departure from the facility [49], [56]. These operational schedules impact the charging load profile of ETs as well as the availability of ETs for charging process. Therefore, this need to be considered during the charging process of ETs at commercial facilities, which in turn impacts on the capacity of charging infrastructure in these locations [59], [60].

D. DETERIORATION OF BATTERY HEALTH

In the return-to-base charging strategy, commercial vehicles can only be charged at their commercial premise within allowed time windows such as overnight or after shifts. Therefore, the charging of commercial vehicles at their premises must meet their daily transport missions without causing range anxiety. However, the charging and discharging processes of commercial vehicles according to the return-to-base strategy may have negative impacts on the heath of battery banks. Depending on daily operational schedules, commercial vehicle batteries might be discharged frequently to a deep level in order to perform their required transport missions perfectly before returning back to the charging location. Moreover, depending on the charging process, their batteries might be kept at high states of charge for long periods at their premises before they can be used in the future transport missions. The behaviors of charging and discharging processes of commercial vehicles can deteriorate the health of a battery, potentially reducing life cycles and the

maximum capacity of a battery; hence, shortening the daily driving distance that can be performed by ETs [61].

V. CHARGING AT PUBLIC CHARGING INFRASTRUCTURE

Although it is preferred to charge commercial vehicles at places where they park, their charging on route during daily driving cycles may still be needed owing to many reasons. These reasons are summarized below:

1) Due to high power capacity of charging infrastructure located in the parking areas of commercial vehicles, the existing distribution electrical network may not be sufficient for fully charging these vehicles. This requires upgrading of existing electrical networks to accommodate increasing numbers of electric vehicles in different commercial businesses. In some countries, this upgrading of electrical networks needs to be funded by the end-user (fleet operators), which significantly increases the capital cost investment for electrifying business commercial fleets [49]. Therefore, charging of commercial vehicles on route can help to reduce the capital cost investment of charging infrastructure required at a parking area, especially for small commercial businesses [49], [59].

2) In some applications, there are changes and deviations to the operational schedules of commercial vehicles over time, including seasonal deviations, driver behavior, and business needs that cause routes or the number of vehicles to change. These changes impact on daily mileage, which can be higher than electric vehicle range. Therefore, the charging of these vehicles on route is required to accommodate variable operational schedules of vehicles and to relieve range anxiety [50].

3) Some commercial fleet operators may prefer to reduce the investment of the capital cost of commercial vehicles by designating vehicles for multi-shift operations, according to customer orders [54]. This requires either a heavy battery bank to complete these duties, which in turn impacts payload, or return to premises for charging, which may affect duties. Therefore, charging of these vehicles on route is required on the route during dwell periods between successive shifts so as not to disturb payload and duties [59].

Much research has been performed towards the development of contact-less charging infrastructure, especially Inductive Power Transfer (IPT) charging systems, as a convenient and possibly safer way of charging electric vehicles on the road. A typical IPT charging system is usually implemented by an on-board coil installed under the vehicle's chassis, and an off-board powered coil embedded on the roadway [63], [64]. Authors in [65] have estimated that IPT charging infrastructure with a low battery bank in vehicles would be a cheaper alternative for electrifying transportation vehicles in Denmark, as compared to electric vehicles possessing high capacity batteries. Authors in [66] have studied the impact of IPT on the peak demand of a grid system in

TABLE 5. Summary of challenging issues for public charging stations.

Main Challenging Issues	References
Daily operational schedules of commercial vehicles	[50], [54], [71]
Charging cost of commercial vehicles at public charging stations	[49], [54], [71], [72]
Utilization rates of public charging infrastructure	[35], [48], [73]
Stability limits of grid system, especially during peak residential load	[74], [75]

Norway, concluding that electrifying all major roads with IPT charging infrastructure would increase the peak demand by 7%, with most of the load coming from heavy-duty vehicles. However, many challenges have this far restrained the application of the IPT charging infrastructure, especially for heavy vehicles, including limited energy transfer distance, electrical safety issues, reliability, efficiency, and high infrastructure investment costs [64]. Further, as commercial vehicles are assumed to select routes to minimize their travel time cost, the choice of route of CEVs would be limited by IPT charging infrastructure [63].

Another method to power electric vehicles on the road is the installation of battery swapping charging (BSS) infrastructure, where electric vehicles can replace their almost depleted battery bank with a fully charged battery bank [29], [67]. This exchange process of the battery may only take few minutes at a BSS [68], [69], making this method of charging an efficient candidate for batteries with the highest energy density (potentially with the longest driving range) [68]. Additionally, BSSs can provide many benefits to the grid system in terms of required upgrading in electrical infrastructure and ancillary services in different intervals [70]. However, the high investment cost of BSSs and the high cost of the battery swapping activity may restrain the deployment of these stations [68]. Moreover, there is need to be a standardization of battery types and sizes to suit the different models of vehicles that need to be charged at swapping stations [49].

Conductive charging stations, on the other hand, can be gradually sized and scaled up according to the power requirements of CEVs. Thus, charging stations do not require as high investment costs in infrastructure as other alternatives [24]. Therefore, high-power charging stations are beginning to emerge across different countries in public locations to facilitate the charging of CEVs during their driving cycle as depicted in Fig. 5. Most of these stations, as in the case of Tesla's charging stations, are intended to facilitate the sale of the vehicle, as opposed to serving as commercial charging stations. To increase the adoption of CEVs and provide an opportunity for investors to make revenue on their investments, public charging infrastructure will need to be accessible to all-electric vehicle models [35].

Several governments and electric utilities have announced targets to deploy high-power publicly accessible and on-highway charging infrastructure. In the United States,
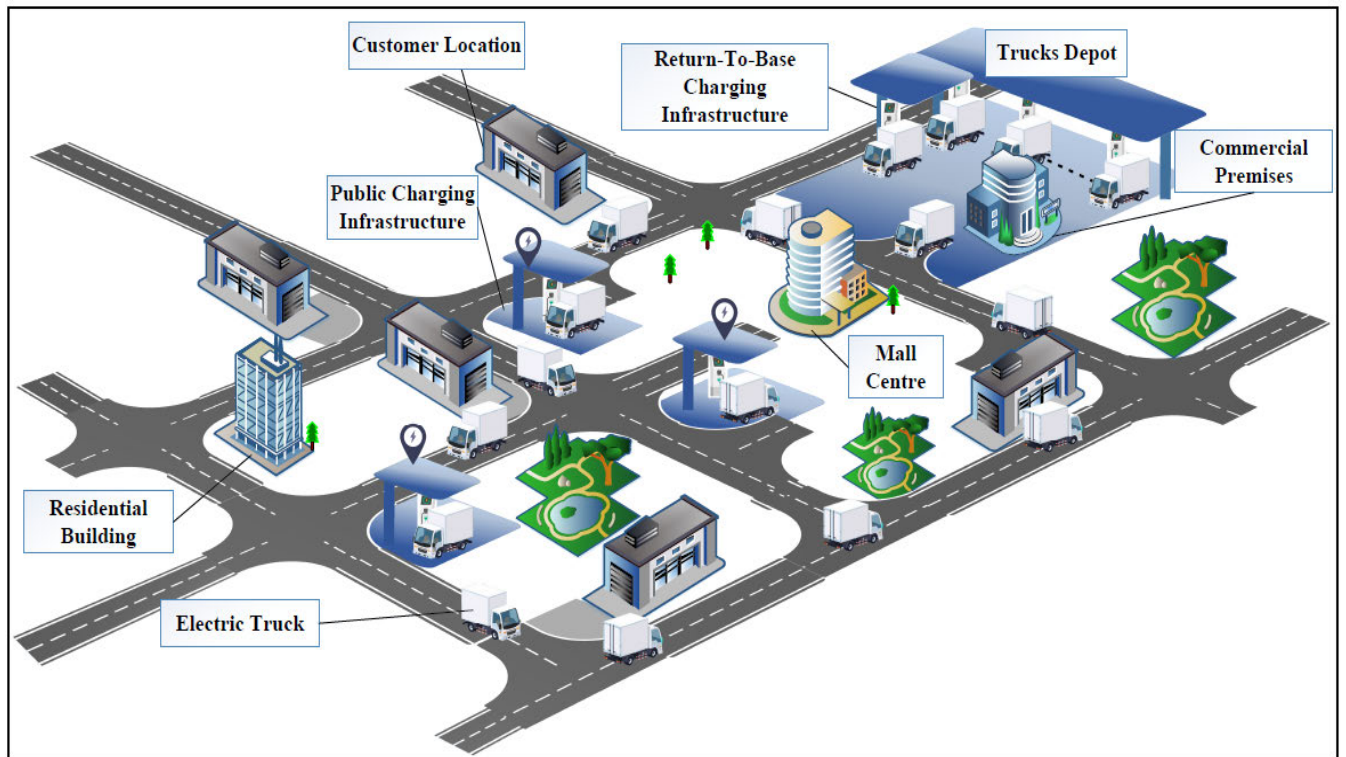
FIGURE 5. Operation model of public charging infrastructure.

large utilities, such as DTE Energy, Duke Energy, and Consumers Energy Company, are deploying pilot projects for public charging infrastructures [19]. In Europe, the European Union has supported the deployment of public and highway charging stations across the trans-European transport network through the "Connecting Europe Facility" initiative, which is a key EU supporting instrument (EC2019e). Moreover, Iberdrola have started to deploy 400 public charging stations in Spain [76]. In China, state-owned utilities, such as State Grid Corporation of China and China Southern Power Grid, have plans to deploy more than 100,000 charging stations by 2020 [19].

In addition, a diversified set of private sector stakeholders have announced plans to deploy public and highway charging infrastructure. Large charging station operators, such as Tritium, Phoenix Contact, Charge-Point, and EV-Box, have announced a goal to deploy public charging infrastructure in the United States, Europe, and the Netherlands. Amongst vehicle Original Equipment Manufacturer (OEMs), Tesla Inc., Electrify America (a subsidiary of Volkswagen), and Porsche have all announced public chargers across the United States [19]; whilst SAIC have set targets to deploy 20,000 public charging points in China [77]. Moreover, many joint ventures between vehicle OEMs, such as Ionity that is a joint venture of BMW Group, Daimler AG, Ford Motor Company, and Volkswagen Group with Audi and Porsche as funded by the European Commission, have announced plans to deploy highway charging stations [19].

However, the charging of CEVs on route at public charging infrastructure presents some challenging issues, which are summarized in Table 5. These issues may impact charging infrastructure operators and fleet operators both technically and economically. These challenging issues are discussed below.

A. DAILY OPERATIONAL SCHEDULES

Commercial vehicles provide timely and regular service to their customers and operate on daily operational schedules that reflect daily business hours. Some commercial vehicles have strict operational schedules so that they are not able to interrupt their trips to charge their batteries [71]. Moreover, some fleet operators prefer to charge their vehicles on the road at locations where vehicles are typically parked during lunch breaks, between two shifts, in order to avoid any disruption to their operational schedules. Therefore, the deployment of public charging infrastructure must be aligned with duties and routes required by transport missions of commercial vehicles and located at areas around their destination and parking place during the day [54], [71].

Nevertheless, due to the diversity of required transport missions, with different destinations and routes for commercial vehicles, there is a likely lack of public charging infrastructure at some destinations and parking locations if they cannot achieve an acceptable daily utilization rates. Moreover, this could create restrictions on maximum power available at charging infrastructure if the charging of these vehicles
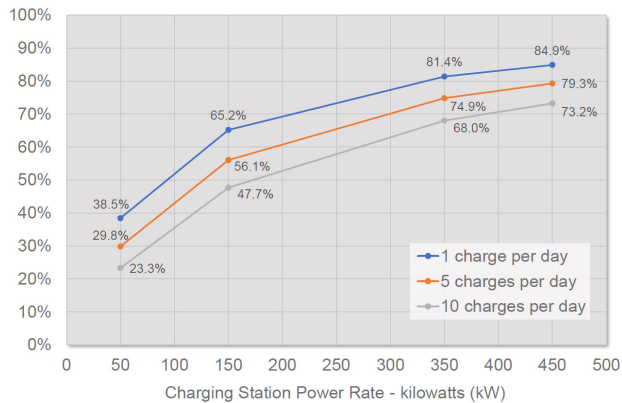
FIGURE 6. Impact of high utilization rate per day on spreading demand charge over many charging events. [73].

takes place during peak-hour periods [54]. These restrictions would likely disrupt the operational schedules of commercial vehicles due to long charging time, unplanned wait time, and long-distance between transport routes and charging infrastructure location [50], [54]. Therefore, the charging process of CEVs at public charging stations should be coordinated with driving cycles according to the operational schedules of these vehicles.

B. UTILIZATION RATES OF CHARGING INFRASTRUCTURE
The utilization rate of charging stations reflects the percentage of time that a charging station is actually dispensing electricity. As the revenues of charging infrastructure depends on the kWh of electricity sold per unit time, a charging station with a low utilization rate has a substantial risk of not being able to recover their outlay through revenue. Therefore, a charging station needs to maintain a sufficiently high utilization rate by increasing the number of charging events at the charging station and reducing the time in which a vehicle is plugged idly into the cable of a charging station.

In addition, a high utilization rate of public charging infrastructure can realize economies of scale and reduce operating costs of charging infrastructure such as demand charge [48]. As shown in Fig. 6, which is excerpted from a study on fast charging in the Midwest [73], the high utilization rate of charging station per day spreads the demand charge over many charging events; thus, mitigating the impact of demand charge on the total electricity bill. This encourages collaboration amongst varied stakeholders, such as utilities, automakers, and infrastructure providers to increase the deployment of public charging infrastructure.

To take advantage of existing investments on transformers and utility service upgrades, charging infrastructure should be organized to include more charging stations. This arrangement will help to achieve more returns to scale on capital costs of charging infrastructure. However, increases in the number of chargers in any given infrastructure requires more charging events to maintain a high level of utilization. Therefore,

newly added charging stations need to have at least the same utilization rate as existing stations [35].

Achieving a high utilization rate of charging infrastructure requires an optimum localization of public charging infrastructure in a way that considers the spatial and temporal diversity of operational schedules of commercial vehicles to cover a large area of charging demand [35].

C. CHARGING COST OF COMMERCIAL VEHICLES
Electrical utilities apply Time-Of-Use (TOU) tariffs, where electricity price is more expensive when the electric demand on the grid is higher. This is an effective way to shift the charging load of light-duty EVs to off-peak load hours of the grid system. However, commercial vehicles do not have the same flexibility to shift charging according to TOU tariffs [54]. As commercial vehicles generally operate on specific operational schedules during business hours, TOU tariffs can make it very costly when charging these vehicles on route, during lunch breaks, between two shifts, or after an early shift [54], [71], [72].

In recent years, many researchers have studied real-time tariffs, which consider the higher levels of distributed energy resources into the grid, as a way to mitigate the impact of grid peak load. Real-time tariff information can provide an opportunity to reduce the charging cost of commercial vehicles during their driving cycles [54]. However, these tariffs may also increase the charging costs of some commercial vehicles due to their strict operational schedules. Thus, a smart charging system is required to coordinate the charging process of commercial vehicles on route in a way that helps reduce the charging cost of these vehicles while ensuring their operational schedules [49], [54], [71], [72].

D. STABILITY LIMITS OF THE GRID SYSTEM
Due to the high-power capacity of the public charging infrastructure of commercial vehicles, especially heavy-duty vehicles, the capacity of electrical networks at locations of infrastructure has to be sufficient to supply the required charging power. Further, the impact of a charging infrastructure on the performance of electrical networks needs to be within stability limits, especially during the peak period of residential loads [74], [75].

VI. LONG-HAUL COMMERCIAL ELECTRIC VEHICLES
The long daily ranges of long-haul commercial vehicles require large battery banks to be charged at warehouses. However, the weight of the large battery banks would affect the payload ratings of long-haul vehicles [33]. Table 6 shows the battery weight ratio of the total GVW for some currently available long-haul CEVs. As can be shown, increasing the battery capacity to improve vehicle range will increase the ratio of battery weight to GVW, which in turn reduces the maximum payload capacity. The reduction of the maximum payload of long-haul CEVs compared to diesel commercial vehicles has been analyzed as illustrated in Figure 7 [22]. This figure shows the weight breakdown

TABLE 6. Battery weight ratio of total GVW of some long-haul CEVs.

CEV Model	GVW (t)	Estimated Range (km)	Battery Capacity (kWh)	Battery weight (kg)^i	Battery weight to GVW (%)
BYD T9	36t	200	350	2800	7.8%
Tesla-Semi	36t	480	600	4800	13.4%
Tesla-Semi	36t	800	1000	8000	22%

^{i} Battery weight is calculated based on energy density of 0.125 kWh/kg [22].
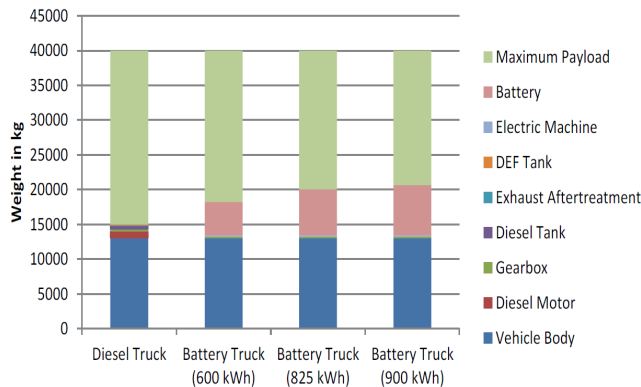

FIGURE 7. Weight breakdown of main components for diesel vehicles and CEV with different battery capacities [22].

of main components for the diesel vehicles and CEVs with different battery capacities. As can be shown, the maximum payload of the CEV is restricted at most to 23% as compared to the diesel vehicles.

Therefore, the electrification of long-haul commercial vehicles necessities an optimal combination of battery bank dimension and high-power capacity of public charging stations along a route [22]. Nevertheless, the charging of long-haul vehicles on route meets many challenges, due to the rigorous operational schedules of these vehicles [59]. There are many regulations that can limit the number of hours long haul vehicles may be operated per day before a compulsory rest period. For example, The Federal Motor Carrier Safety Administration, an agency of the United States Department of Transportation, limits hours of service to 10.5 hours per day, after which eight hours of rest is required [78]. Similarly, according to the EU legislative regulation, hours of driving are limited to 4.5 hours followed by a rest period of at least 45 min [22].

Consequently, the charging activities of long-haul vehicles must be during rest periods, as depicted in Fig. 8. This will require long-haul vehicles to stop at locations with multiple high-power charging stations to meet their operational schedules. However, simultaneous operation of multiple chargers enforces significant challenges to the power grid in terms of costly reinforcement to an existing network [78]. Moreover, these multiple charging stations impact the stability of a grid system, especially during peak hours [71]. These restrictions impact the number of vehicles that can be charged at a specific location and thus the utilization rate of charging infrastructure [22].

Overcoming the above-mentioned limitations associated with charging long-haul vehicles will require proper sizing and localization of charging infrastructure along highway routes. There should be cooperative work between electric utilities, fleet owners, and truck stops to locate the best sites for the charging infrastructure in a way that considers the stability of the power systems and operational schedules of long-haul vehicles [22], [71], [78].

VII. POTENTIAL SOLUTIONS TO ADDRESS DIFFICULTIES
To mitigate the aforementioned issues in charging heavy electric vehicles, public charging stations dedicated for commercial electric vehicles need to be optimally located. Moreover, optimal charging strategies need to be designed for coordinating the charging process of commercial electric vehicles at different locations.

A. OPTIMAL LOCATION OF CHARGING INFRASTRUCTURE
The locations of public charging infrastructure should be optimized in a way that considers the diversity of transport missions of commercial vehicles, the stability limits of the grid system, and the high utilization rate of charging infrastructure [74], [75].

In the literature, many studies have discussed the optimal placement of public charging infrastructure, as summarized in Table 7. As can be observed, few studies have investigated the optimal location of charging stations for commercial vehicles. A number of these studies have focused on the location-routing problem that incorporated the determination of the optimal locations of charging stations in EV routing problems of commercial businesses to ensure the continuity of service along routes [79]–[82]. In these studies, the locations of charging stations were optimized with the objective of minimizing total investment and operating costs, considering various constraints such as loading capacity, battery capacity, and customer time windows. The candidate charging station locations were selected at customer vertices, depot, intra-route facilities, and other vertices available with the same customer coordinates. However, in the location-routing problem, EV routing and charging station location are considered simultaneously. Therefore, the locating and routing decisions are made by the same fleet operator who may prefer to install charging stations away from the depot to increase the driving ranges of their electric vehicles.

Other studies have investigated the localization problem of charging stations that are accessible for different
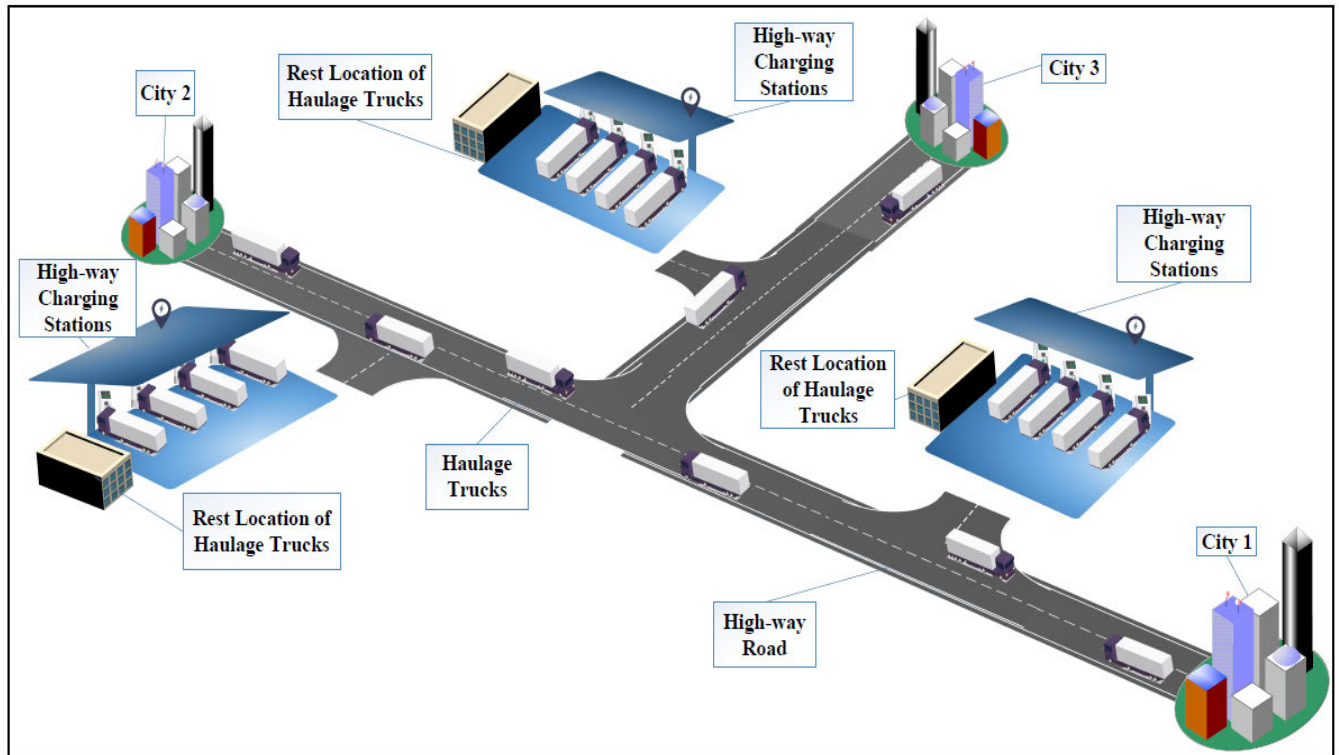
FIGURE 8. Operation model of haulage trucks.

TABLE 7. Summary of conducted studies for optimal localization of charging infrastructure.

References	Key Outcomes
[83]–[87]	A flow refuelling location model that determines the optimal locations of charging stations along the network nodes and dispersed along arcs of paths between origin-destination pair with the objective of maximizing the traffic flow considering limited range EVs and charging station capacity.
[88], [89]	A general corridor model for optimally locating charging stations that support long trips across the highway network between origin-destination pair with the objective of minimizing the total cost and maximizing long-distance highway trips that can be completed considering limitations of the number of stations and EV range.
[75], [90]–[92]	An optimization model to locate optimally charging stations at candidate locations at special existing facilities, like parking lots and gas stations with the objective of maximizing coverage area and minimizing the total number of the missed trips per day and the total cost of the charging stations considering the charging consumers' behavior, and the distribution power network.
[79], [80], [82]	Incorporation of the decisions of charging station's location at customer vertices, depot, and other vertices available with the same customer coordinates in routing problem of EVs with the objective of minimizing the total cost, inclusive, the construction cost of charging stations, cost of electricity recharged at charging locations, and wages of working time.
[71]	A multi-objective optimization model to locate combinations of charging stations for different commercial EVs at candidate sites with the objective of minimizing the quantity of failed trips and total cost of infrastructure considering trip duration, distance, and dwell time.
[93]	A constrained optimization model to locate and dispatch portable charging stations in EV network during busy traffic hours with the objective of relieving the load on fast-charging stations, minimizing waiting times at charging stations, and reducing the impact of total EV demand on peak residential load.

commercial vehicles, such as [71], [109]. In these studies, multi-day travel data collected from different commercial electric vehicles was pre-processed, and stop points were clustered to define candidate sites for charging stations. These clusters were ensured to be within threshold diameters so that to the distance between the charging station and points

of interest did not exceed a preferred maximum value. The locations of charging stations were optimized at candidate locations to minimize trip failures and the total cost of infrastructure, considering trip duration, distance, and dwell time.

In addition, the North American Council for Freight Efficiency (NACFE) has suggested a chronological roadmap

TABLE 8. Summary of conducted studies for smart charging strategies.

Charging Location	References	Key Outcomes
Charging of EVs at Locations where they park	[94]–[96]	Centralized charging scheduling strategies to optimize EV charging process in household and park of workplace considering charging cost as well as major constraints of the power grid.
	[97], [98]	A smart charging management framework of multiple levels for coordinating the charging process of PEVs across different aggregators and working place parking lots respectively, considering total electricity purchasing costs and system peak load.
	[20], [58], [99]	A novel control approach was developed to control the charging rate of charging points with the objective of minimizing electric demand charges of maximum building load and power loss of the charging process while satisfying the charging requirements.
	[100]	A fuzzy logic inference-based algorithm to coordinate the appropriate charging or discharging for each connected EV in the parking lot in a way that satisfies the charging needs of EV uses, and avoids the overloading of the power system.
	[101], [102]	Decentralized charging scheduling strategies to optimize the charging process of EVs with the objective of minimizing the charging cost.
	[103]	A new time of use (ToU) tariff model to shift the charging load of large-scale EVs integrated into the existing grid system with the objective of minimizing the accelerated aging of transformers.
Charging of EVs at Public locations	[104]	A smart charging strategy for charging PEVs at public charging stations that have multiple charging options and different pricing options with the objectives of minimizing charging time, travel time, and charging cost.
	[105]	A distributed algorithm is used to control the queues of EVs between neighboring charging stations along the highway with the objective of minimizing the waiting time at charging stations.
	[106]	Incorporation of the EVs fleet charging process on the route into the EV routing problems by enabling the partial recharging strategy at stations considering customer time windows and vehicle capacity constraints.
	[107]	Vehicle routing model that considers the partial charging of EV fleet on-route with the objective to minimize charging time, and waiting time at charging station.
	[108]	A new coordinated dynamic pricing model to drift the EV toward the charging stations that are underutilized with the objective of reducing the impacts of charging load of EV on the peak of residential and during peak loads hours.

for deploying charging infrastructure for commercial vehicles [48]. The proposed process includes key considerations of operational schedules of vehicles and grid infrastructure. A similar process needs to be developed to facilitate the adoption of commercial vehicles and to mitigate the challenges of localizing public charging infrastructure [78].

B. SMART CHARGING STRATEGIES

Smart charging strategies intend to coordinate the charging process of electric vehicles at different locations in a way that achieves a wide range of control objectives. Due to the different challenging issues of charging commercial electric vehicles, smart charging strategies should be designed to manage the charging process at public charging stations, as well as at locations where these vehicles are parked.

1) SMART CHARGING STRATEGIES FOR RETURN-TO-BASE CHARGING INFRASTRUCTURE

The charging process for electrical truck fleets at commercial premises needs to be optimized to mitigate the impact of charging load on electrical distribution networks, as well as to reduce costs for upgrading electrical networks and demand charges [52], [62].

In the literature, as shown in Table 8, much literature has been proposed to coordinate the charging process of EVs at places where they park. Most of these studies have focused on coordinating the charging of EVs with the objective to minimize charging costs. However, as stated previously, peak

demand charge has also a significant impact on the electricity bills of commercial facilities. Therefore, some studies, such as [20], [58], [99], have proposed charging strategies that distribute the charging load of electric vehicles over the available parking time as a significant way to mitigate the impact of peak charging load on the electricity bill of a parking area.

In [20], the charging of FedEx Express Navistar eStar all-electric delivery vehicles with an 80 (kWh) battery pack at its commercial premise has been analyzed. According to this analysis, the managed charging of a fleet size of 100 electric vehicles can ensure demand charge savings of approximately $11,500 per month in contrast to unmanaged charging. The managed charging of a fleet size of 200 vehicles can reduce demand charge to about $23,000 monthly.

In addition, smart charging strategies should consider the different scenarios of operational schedules of ETs during parking time to minimize the peak demand of a facility. Further, different operation conditions of commercial premises, such as demand response programs, and their impacts on the charging of ETs considering their strict operational schedules should be included in the design of smart charging strategies.

2) SMART CHARGING STRATEGIES FOR PUBLIC CHARGING INFRASTRUCTURE

In order to address the aforementioned issues, the charging process of commercial electric vehicles at public charging stations needs to be scheduled. These vehicles can be charged

fully or partially at different charging stations along their route of driving cycle, according to the limitations of the vehicle's operational schedules and TOU tariff of electricity.

According to the operational schedules of commercial vehicles, there is a limitation on the maximum time in which each customer along the route of a driving cycle should be served. This limitation impacts the maximum time available for the charging process of commercial vehicles at each charging station. In addition, the maximum time of charging is affected by the following parameters:

1) Waiting time in the queue due to potential congestion at charging stations. Longer waiting time reduces the maximum charging time allowed at a charging station.
2) Location of charging station from a truck's daily route. ETs will need to detour to reach stations located a distance from the main route, which reduces the time allowed for charging processes.
3) Charging power rate of charging stations has its impact on charging time. Stations with high-power rates require less time to charge ETs as compared to stations with low charging power.

In addition, the charging process of commercial ETs at public charging stations needs to be coordinated to allow for longer charging times at stations with low electricity prices, provided that the maximum time allowed for each customer is considered. Nevertheless, as high-power charging stations usually have higher charging prices, there should be a trade-off between the reduction of charging time and the increase of charging cost according to the operational schedule of vehicles.

Depending on the location of the charging station along the route of the driving cycle, an electric truck may run out of charge before reaching a charging station. Therefore, feasible charging stations that can be used to charge commercial vehicles need to be placed at locations that are accessible by the existing SoC of an electric truck.

VIII. V2G TECHNOLOGY FOR COMMERCIAL ELECTRIC VEHICLES

Due to high battery capacity, commercial electric vehicles can present a new area of growth and investment by adopting V2G technology. In V2G technology, a commercial vehicle can provide ancillary services to the electricity grid such as voltage and frequency regulations based on specific contracts [110]–[113]. The operational schedules of some fleets of commercial vehicles, which have fixed routes and specific daily missions of service and transport (such as service/utility vehicles and delivery vehicles), can help to ensure the availability of commercial vehicles for ancillary services during the driving cycle and the contractual V2G capacity of the fleet. In addition, the centralized coordination of a large number of commercial vehicles at places where they park for a long time, such as depots and public parking, can help to ensure the application of V2G technology; provided that this technology will not disturb fleet operation by decreasing range or delaying availability [78], [114].

The application of V2G technology for commercial electric vehicles can result in economic and environmental benefits. The authors in [114] conclude that in areas where grid voltage fluctuates heavily and prices of the ancillary services are high, a significant reduction in total ownership costs of electric vehicles can be obtained through lifetime V2G services revenue. Moreover, the average net revenue from lifetime V2G technology can offset investment costs required for upgrading grid-accessibility equipment [110], [114]. Beside the economic benefits of V2G for fleet operators, the application of the V2G technology for commercial vehicles can significantly mitigate GHG emission effects. The life cycle GHG emission savings resulting from V2G technology can in turn offset other emissions related to electricity generation and transmission phases required to charge electric vehicles. This can provide further savings for fleet operators once emissions taxes are applied [78], [114].

IX. CONCLUSION

This paper discusses and summarizes the challenges of charging commercial electric vehicles (CEVs) at their premises and public locations. For commercial vehicles that follow deterministic operational schedules, the return-to-base charging strategy fits well. However, this strategy could result in technical and economic issues for fleet operators and utilities. In this paper, these issues have been discussed and analyzed. Existing literature and possible future works related to the return-to-base charging strategy have been discussed in detail. The paper then highlights the main challenges of charging commercial electric vehicles at public locations. Relevant solutions and future works are also summarized. The large battery capacity of commercial vehicles can be leveraged to increase the revenue of fleet operators by accommodating V2G technology provided that the operational schedules of ETs are maintained. Consequently, this paper deliberates about V2G technology and relevant solutions for commercial fleet operators. We believe this timely review paper can assist researchers to identify and address future challenges in areas of commercial vehicle electrification.

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