E-Bus Scheduling

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Abstract

The following Review Articles aims at reviewing available literature regarding the introduction of E-Buses in urban public transport networks, with particular focus on the scheduling constraints of both vehicles and crews.

Battery Electric Buses (BEBs) are the type of E-Buses taken into consideration in this review through the lens of the Electric Vehicle Scheduling Problem (E-VSP).

By introducing the planning processes and scheduling objectives that the implementation of e-buses requires, covering then the most impactful constraints that emerge with their adoption (both complete and partial), and concluding with the illustration of the five solution approaches to the scheduling problem deemed more relevant by the authors on the basis of information availability and frequency of use, the article attempts to provide the reader with holistic level information regarding the topic.

1.Introduction

Public transportation plays a vital role in urban mobility, offering a more eco-friendly and efficient mode of transport for millions of individuals globally. In recent times, Battery Electric Buses (BEBs or electric buses in the article) have emerged as a potential solution to tackle the environmental and economic issues linked to conventional fossil-fuel-powered buses, despite the operational challenges arising from their limited driving range. The implementation of electric buses can substantially decrease greenhouse gas emissions, enhance air quality, and reduce operation expenses; these are making them a desirable choice for public transportation systems. Nevertheless, the seamless integration of electric buses into public transportation networks necessitates meticulous planning and optimization of their scheduling, a task that is both intricate and demanding.

According to Eurostat EU-27 data, transport emits about 23% of total GHG emissions in Europe, and road transport is responsible for 72% of GHG emissions from transportation. In this scope, public transportation assumes an important role in decreasing carbon emissions from road transportation. With the development of electric buses in the last decade, it has been seen that BEBs can play a crucial role to decrease carbon emissions from public transportation compared to diesel buses. In addition to this, BEBs are helpful to generate better air quality which improves health outcomes of citizens and reduce noise pollution improving passenger experience. Lastly, they offer advantages to secure country energy demands. (X. Tang et al, 2019)

Since passengers usually have varying socio-economic characteristics and expect a high level of service (i.e., transport systems should be safe, accessible, comfortable, affordable and provide the possibility of reaching destinations quickly (Perumal, R.M. Lusby and J. Larsen, 2019)), the objectives of good scheduling for electric buses include maximizing service reliability, minimizing operating costs, and reducing environmental impact. To achieve these objectives, electric bus scheduling models must consider various constraints, such as vehicle range, charging station availability, and crew availability.

The Electric Vehicle Scheduling Problem (E-VSP) is an optimization problem that involves scheduling electric vehicles, including electric buses, to minimize operating costs while satisfying various constraints.

The objective of the E-VSP is to minimize the total operating cost of the electric vehicle fleet, which includes the cost of energy consumption, vehicle maintenance and crew scheduling.

The scheduling of electric buses involves the allocation of resources, such as vehicles, drivers, and charging stations, to ensure reliable and efficient service. Furthermore, crew scheduling, which is integrated with scheduling of e-buses, involving assigning drivers to specific routes and shifts, is an integral part of electric bus scheduling. The integration of crew scheduling with electric bus scheduling presents additional challenges, such as ensuring that drivers have sufficient rest time and that their schedules comply with labour regulations, creating further constraints for the E-VSP.

This review essay aims to provide a comprehensive overview of electric bus scheduling, focusing on the objectives of electric bus scheduling models, the constraints that must be considered, and the solution approaches that have been proposed to address these challenges. We will begin by discussing the importance of electric buses for public transportation and the challenges associated with their scheduling. Next, we will delve into the objectives of electric bus scheduling models, including service reliability, operating costs, and environmental impact. We will also discuss the various constraints that must be considered, such as vehicle range, charging station availability, and crew availability.

Furthermore, we will explore some of the solution approaches that have been proposed to address the E-VSP, including skip-stop methods, solutions related to battery charging and swapping problems and few other charging methods.

2.Electric Bus Planning Process and Scheduling Objectives

The adoption of electric buses needs holistic and complex planning from multiple perspectives, which include charging infrastructure implementation and operational strategies, among others. Tang et al. (2019) expresses that *bus scheduling is one key step in public transit operational planning, and it focuses on how to operate a bus fleet to fulfil the timetable of service trips.*

As stated by Perumal et al. (2019), the planning process for electric bus transportation spans several years and consists of three phases as shown by Figure 1. The strategic planning phase begins approximately three years prior to implementation and involves analyzing infrastructure, planning routes and frequencies, investing in electric bus fleets and charging infrastructure, and determining the placement of charging stations. The tactical planning phase commences one year before the present day and focuses on timetabling, scheduling electric buses and charging infrastructure, as well as crew scheduling and rostering. Lastly, the operational planning phase addresses fleet recovery and is based on the current situation.

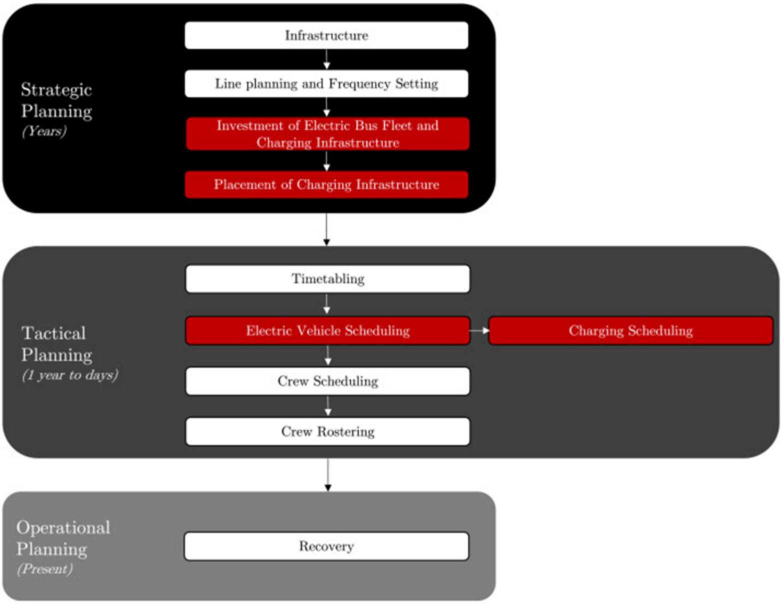

Figure 1: Levels of planning the processing of electric buses.

Through the second phase of the electric bus planning process, the scheduling of electric buses and charging infrastructure is handled and the E-VSP, its objectives, and the objectives of the electric buses scheduling models, are considered as the main drivers for scheduling.

As indicated, the Electric Vehicle Scheduling Problem (E-VSP) focuses on scheduling electric buses in a way that minimizes operating costs while satisfying various constraints. The E-VSP is essential for the successful integration of electric buses into public transportation systems, as it helps ensure reliable and efficient service. Moving beyond, the E-VSP has several objectives like energy optimization, charging infrastructure utilization, emission reduction, passenger satisfaction, cost efficiency, integration with existing systems, scalability, and adaptability.

In the scope of energy optimization, the E-VSP investigates methods to minimize energy consumption in electric bus operations, considering factors such as route length, traffic conditions, and passenger demand. The E-VSP then analyses the optimal placement and utilization of charging stations to ensure seamless operation of electric buses while minimizing downtime and infrastructure costs. According to Olsen et al. (2020) the E-VSP should look for new charging models that reflect the non-linearity of the charging process in a precise way, contrary to what constant and linear charging time models do, increasing the total costs; partial and opportunity charging are incorporated in said models (single/unique depot).

In addition, Chao et al. (2013) expresses that minimizing the capital investment (number of vehicles in the fleet and number of standby batteries in the case of a battery swapping strategy further discussed later in this essay) for the e-bus fleet and the total charging demand in stations, are objectives of the E-VSP.

Furthermore, emission reduction is another issue that the E-VSP considers by looking at the assessment of the environmental benefits provided by electric bus scheduling, focusing on the reduction of greenhouse gas emissions and air pollution in urban areas (Li et al, 2019).

When it comes to passenger satisfaction, the E-VSP aims to evaluate the impact of electric bus scheduling on passenger satisfaction, considering factors such as wait times, travel times, and service reliability. Tang et al. (2019) explains that the E-VSP should be able to minimize en-route breakdown, reduce delay cost to both passengers and operators, and enhance robustness against stochastic traffic conditions which, due to high variability, can be an issue for schedules based on fixed trip times, while at the same time optimizing vehicle schedules and electric fleet sizes. Li et al. (2019) also highlights the importance of passenger experience (waiting penalty – dependent on case-by-case operational strategy) and indicates that the external cost caused by emissions (if the fleet involves mixed type of vehicles) should also be considered.

Another issue for operational efficiency is cost. For a cost-efficient operation, the E-VSP examines the economic feasibility of implementing electric bus scheduling in public transportation systems, considering factors such as operational costs, electricity prices, maintenance costs, and initial investment. Rogge et al. (2018) indicates that minimising the total cost of ownership (TCO) should be targeted by the E-VSP as the main criterion in investment decisions between different alternatives. Required fleet size and type of e-buses, in-service costs unrelated to energy consumption like crew driving hours, bus specific costs related to energy consumption and investment in charging infrastructure, should all be considered.

3.E-Bus Scheduling Constraints

This section summarizes the constraints that are to be considered in the Electric-Vehicle Scheduling Problem (E-VSP), with the addition of conventional Vehicle Scheduling Problem (VSP) constraints that also apply to Battery Electric Buses (BEBs). When considering e-bus constraints, it can be argued that all constraints are derived from two limitations that BEB's present compared to diesel fuelled and more conventional vehicles: range and charging time.

Range, related to battery capacity, and charging time, are in fact the two central constraints to consider when considering an e-bus fleet.

From these two constraints, all other constraints regarding planning and operations stem out, in a direct or indirect manner.

While some models these constraints come from differ in the way that they consider multiple or single bus depots, or mixed or uniform fleets, the constraints are here presented together independently of these aspects.

Each constraint has been generalized to the level that it allows for multiple references to be assigned to it, based on the different articles reviewed by this essay that it was found in; without voiding it of its significance through this generalization process.

General VSP constraints, applicable to the E-VSP are first presented, while E-VSP specific constraints are presented further in this section.

The timetables for trips are planned in advance and vehicles should run strictly on the basis set by them (Chao et al., 2013); since each depot has a given maximum capacity (Tang et al., 2019; Chao et al., 2013), the number of vehicles at a station cannot exceed the station capacity (Chao et al., 2013); each trip is assigned and performed exactly once (C. Tang et al., 2023; Josephine et al., 2015), and run by exactly one vehicle (Chao et al., 2013); every trip is connected by only one preceding and subsequent trip (C. Tang et al., 2023), and each vehicle block contains a feasible sequence of trips (Josephine et al., 2015); all available buses during a given period are assigned to a run type (Perumal et al., 2022).

Time-based constraints regarding the E-VSP include no time overlap between events (e.g. charging and service trips) assigned to one vehicle (Rogge et al., 2018; Olsen et al., 2020); charging done only within a pre-defined time window (Rogge et al., 2018); travel time feasibility (Wang et al., 2022); and route time feasibility (Perumal et al., 2022).

Battery capacity and e-bus driving range constraints are battery capacity limitations (Olsen et al., 2020; Josephine et al., 2015); State of Charge (SOC) check to determine whether or not a bus has sufficient remaining energy to complete a trip and the successive deadhead trip (Olsen et al., 2020; Chao et al., 2013; Rogge et al., 2018; C. Tang et al., 2023; Wang et al., 2022) taking into account a safe driving ratio variable (Li et al., 2019); unit distance energy consumption of a trip in relation with running speed and stop density (C. Tang et al., 2023); driving range and maximum distance without recharging (Wang et al., 2022; Perumal et al., 2021; Josephine et al., 2015) on all service arcs (Li et al., 2019); battery renewal constraints (Perumal et al., 2021); minimum SOC energy level threshold when traveling from one stop to another (Perumal et al., 2022); minimum vehicle battery capacity level (Josephine et al., 2015).

Charging process constraints include recharging can only happen at charging stations (Olsen et al., 2020); buses leave the depot after full charging (Rogge et al., 2018; (Tang et al., 2019); flow constraints of charging infrastructure network (Rogge et al., 2018); at any point the capacity of each refuelling station must be satisfied (Li et al., 2019); buses should not be charged between two trips (C. Tang et al., 2023); re-charging time and needs (Perumal et al., 2021; Wang et al., 2022; Josephine et al., 2015; Perumal et al., 2022); minimum recharging duration (Perumal et al., 2021); the energy provided from the charging station does not exceed the maximum battery capacity (Perumal et al., 2022); a vehicle can only be charged at defined stop points (Josephine et al., 2015); minimum proportion of chargers of each type with respect to the number of electric buses in the fleet (Perumal et al., 2022).

Crew scheduling and crew requirements constraints involve early, day and late work modes with time shift (Wang et al., 2022); work intensity constraints (Wang et al., 2022); (local) labour regulations (Wang et al., 2022; Perumal et al., 2021); daily driving trips (Wang et al., 2022); driver wages (Wang et al., 2022); maximum duration of a duty without break (Perumal et al., 2021); minimum break duration (breaks often allowed only at certain bus stops) (S.S.G. Perumal et al., 2021); maximum number of driver vehicle changes (Perumal et al., 2021); continuous attendance of vehicles, during idle time (Perumal et al., 2021); every trip is covered by exactly one block and one duty respectively (Perumal et al., 2021); duties are selected to cover deadheads (Perumal et al., 2021).

Furthermore, monetary constraints, externality constraints and other types of constraints should be taken into account: operation costs (Wang et al., 2022); Time of Use (TOU) power price policy and electricity prices (Wang et al., 2022); carbon emission constraints (Wang et al., 2022); total (vehicles plus chargers) procurement cost not exceeding allocated budget (Perumal et al., 2021; Perumal et al., 2022); a bus cannot be operated after a certain age and has to be salvaged (Perumal et al., 2022), and the End of Life (EOL) of an e-bus battery is conventionally defined as a remaining capacity of 80% to prevent operational complications (Rogge et al., 2018); and, the total power consumption during each time period cannot exceed the contracted capacity (Perumal et al., 2022).

4.Solution Approaches

The complexities of the VSP applied to BEBs require tailored approaches that should be applied on a case-by-case basis considering local characteristics of different kinds. In this section, different solution approaches to solve the e-bus VSP will be covered. The list is not meant to be comprehensively exhaustive, but it aims to give an overview of the different strategies that can be adopted to overcome the limitations that e-buses present when compared to more conventionally fuelled vehicles; keeping in mind that no solution can be utilized to solve all criticalities and constraints at once, but instead as an approach in combination with others, hence the name "Solution Approaches"

The following are the solution approaches covered in this section. They range from charging process solutions to ones regarding daily service operations changes:

- Skip-stop;
- Battery swapping;
- Adoption of different charging time models;
- Static and dynamic rescheduling;
- Opportunity/Pantograph charging.

4.1 Skip-stop

The skip-stop is a strategic method applied in the electric bus scheduling process for public transportation systems. This model aims to optimize the efficiency of electric bus operations by skipping stops along a route for route optimization purposes, thereby reducing travel time, energy consumption, and operational costs. The skip-stop method is particularly beneficial for electric buses, as it helps to conserve battery life and extend the range of the vehicles.

In the skip-stop method, bus stops are categorized into different groups, with buses only stopping at designated stops within each group. This approach allows for a more streamlined service, as buses can bypass certain stops, reducing dwell time and accelerating the overall journey. The skipped stops are still serviced by alternate buses, ensuring that passengers have access to transportation, albeit with slightly longer waiting times at certain stops. Tang et al. (2023) assesses the case study conducted in Dandong, China which tests the skip-stop approach. *The experimental results show that compared to using a full-stop strategy, the use of a skip-stop strategy can reduce the total system cost by 15.09% and improve the average energy utilization rate by 9.02%* comparing to full-stop methods by which electric buses need to stop at every stop along a route. The test consisted of 27 stops on a length of 13 km. In the case, the skip-stop method was utilized when the charging level of electric buses reached the minimum required battery state of charge (SOC) which is defined to avoid battery damage and lifespan reduction. In this case, 30% of battery capacity.

One of the key advantages of the skip-stop method is its potential to reduce energy consumption in electric buses. By skipping stops, buses can maintain a more consistent speed, which in turn reduces the energy required for acceleration and deceleration. This is particularly important for electric buses, as their battery capacity is a critical factor in determining their operational efficiency and range. According to the experiment results gathered in Dandong, China, Tang et al. (2023) shows that trip energy consumption cost was reduced by 4.97% compared to full-stop strategy.

Additionally, the skip-stop method can contribute to improved passenger satisfaction by reducing travel times for those on-board the bus. Passengers traveling longer distances can benefit from a faster journey, as the bus makes fewer stops along the route. However, it is essential to strike a balance between the benefits of the skip-stop method and the potential inconvenience to passengers who may experience longer waiting times at the kipped stops. Tang et al. (2023) expresses that passenger waiting time cost in stations which have not been served by electric buses, decreased by 10.07%, and passenger in-vehicle time cost dropped by 13.86% comparing to the full-stop method. On the other hand, passengers who have to wait at stops skipped by the first arrival buses feel more frustrated due to the extra waiting time.

As indicated by Tang et al. (2023), the skip-stop strategy has 2 specific constraints for operations along with other classified constraints in previous sections of the essay. These are: no two consecutive stops are both skipped in the same trip and the skip-stop strategy is not used by two consecutive trips.

In summary, the skip-stop method is a valuable tool for e-bus scheduling in public transportation systems. By selectively skipping stops, this approach can optimize energy consumption, reduce travel times, and improve overall operational efficiency. However, careful planning and consideration of passenger needs are crucial to ensure that the benefits of the skip-stop method are maximized while minimizing any potential drawbacks negatively impacting passenger travel experience.

4.2 Battery swapping

Battery swapping as a solution approach tries to directly tackle the charging time constraint that e-buses present when compared to more conventional diesel-powered buses. It is based on the exchange of batteries with a low State of Charge (SOC) for fully charged stand-by ones kept in a battery charging station.

The approach and case study presented by Chao et al. (2013) is based in Shanghai, China and considers fast battery chargers and an automated rapid battery exchanging system that can complete a battery exchange operation in 12 minutes, from the time the bus enters the station to the time it can return to service. Though a more conservative time of 15 total minutes is considered (Chao et al., 2013), this yields a nearly 72% charging time reduction compared to the 53,53-minute average charging time presented by Olsen et al. (2020) considering five bus types and four different charging time models.

Furthermore, in the Chao et al. (2013) model and case study, buses undergo a battery exchange in two separate instances: when the remaining energy in the battery is not sufficient to power the remaining service trips the bus is assigned to, and to preventively charge ahead of peak hour service trips.

While these clear charging time saving results seem to indicate that battery swapping would be the ideal solution for the E-VSP, some drawbacks are also evident.

Chao et at. (2013) present their vehicle scheduling model with battery exchanging with the objective of minimizing the capital investment, both in terms of number of vehicles and standby batteries, and the charging demand in stations for this type of strategy. This highlights the high capital investment required for this approach, primarily derived from the added number of batteries needed to be purchased to be kept on standby during daily operations. In the model developed by Chao et al. (2013), specific constraints are utilized in addition to the more conventional E-VSP ones. These are: vehicles change batteries either when the remaining energy is not enough to fuel the remaining trips, or to charge ahead of peak hours (Chao et al., 2013); battery exchange operation time constraints (15mins in the specific case examined in the article) (Chao et al., 2013; C. Tang et al., 2023); and, stand-by battery charging time constraints (Chao et al., 2013).
The model does not offer a single optimal solution but a set of Pareto optimal points instead. This is due to the conflict between the minimization of fleet requirements while at the same time

minimizing the charging demand in stations; a decrease in vehicle fleet investment will in fact result in an increase of the total charging demand, while a decrease in the total charging demand will result in a required investment increase. Therefore, a solution with different levels of these two variables will be chosen according to different criteria depending on the case specific characteristics and the inevitable bias of different kinds of decision makers.

4.3 Adoption of different charging time models

With most E-VSP solution methods often over-simplifying electric battery powered vehicle charging procedures, Olsen et al. (2020) proposes charging time models that better reflect the non-linear nature of the charging process in a more precise way, compared to more conventionally utilized constant and/or linear charging time models. The presented models have the benefit of being able to be applied to different types of charging strategies such as: overnight charging, opportunity (commonly pantograph) charging, and battery swap.

Olsen et al. (2020) focuses their model on lithium-ion batteries, currently the most used type of battery, which present constant current/constant voltage (CC/CV) charging procedure characterized by two phases: the first being a linear battery charging phase, and the second one being a battery charging phase presenting a non-linear profile.

The simplification issue with most of current E-VSP solution models indeed lies in this second non-linear phase. More specifically, constant charging time models provide an overestimation of the time windows required to charge a BEB, therefore leading to unutilized waiting times at charging station for buses that could already be operating service routes. The main reason behind this overestimation is caused by the fact that constant charging times do not take battery SOC into consideration at the start of the charging process, which assumes the need for charging the entire battery capacity.

The direct effect of this overestimation is the higher demand for the vehicle fleet to cover for longer charging times than needed, increasing the total costs, through the bus procurement cost, without need.

Olsen et al. (2020) derives from this that the potential for partial battery charging remains unutilized. While constant charging time models mainly impact BEB operators by increasing their costs, while not necessarily impacting user experience and operations, this is not the case for linear charging time models.

According to Olsen et al. (2020), linear charging time models underestimate the time required to charge a BEB, leading to violations of vehicle range restrictions. Bus breakdowns during operation can therefore happen with more frequency due to the real SOC of a BEB being often lower than the planned one, having serious impacts on public transport users experiencing the effects of said breakdowns.

Instead of the constant and linear charging time models, Olsen et al. (2020) proposes two models that more precisely follow the second phase of the lithium-ion battery charging procedure. The first one being the logarithmic model and the second one being the exponential one.

The latter is more precise than the former, but both these models can yield better results in the actual charging time estimation, therefore overcoming the estimation flaws of the constant and linear charging time models, offering a possible solution to prevent the issues presented above.

4.4 Static and dynamic scheduling

Most E-VSP models and solutions consider trip times to be fixed and traffic conditions to be deterministic; two assumptions that simplify the vehicle scheduling problem but do not represent the real stochasticity of road traffic conditions.

Road traffic conditions in fact present a high degree of variability that can heavily impact trip times depending on different parameters, such as time of day and weather conditions. Considering the lower range that BEBs have and the effect that traffic conditions have on bus energy consumption, en-route breakdowns and increased costs derived from delays, are two direct impacts that these imprecise assumptions can have.

Tang et al. (2019) presents a robust scheduling model that takes the stochasticity of road traffic conditions into account, while also optimizing vehicle schedules and electric vehicle fleet sizes in a single-depot case. To do so, they introduce two separate VSP problems: the Static Vehicle Scheduling Problem (S-VSP) and the Dynamic Vehicle Scheduling Problem (D-VSP).

The S-VSP introduces a buffer-distance in the model, that hedges against the impacts of stochastic traffic conditions on energy consumptions, mainly caused by speed changes, ensuring that e-buses don’t run out of charge en-route. The higher the value of said buffer-distance, the higher the scheduled cost, but this increase can be compensated through the cost savings derived from the increased robustness provided by this value compared to a lower one. The opposite is also true, where a lower buffer-distance value allows for a reduction in scheduled cost but at the expense of a higher breakdown rate.

The D-VSP on the other hand adopts a computationally more complex approach that yields better results in highly variable road traffic conditions, making it relatively insensitive to them.

By dividing a day's bus operation into a set amount of time periods, Tang et al. (2019) developed a model based on dynamic programming that considers Automatic Vehicle Location (AVL) traffic data and updated forecasts of future traffic conditions based on historic data. At the end of each time period, each bus's schedule is re-evaluated considering the remaining range based on the battery SOC, and the dynamic program is able to determine if a re-schedule is necessary or else if a bus can continue with the pre-determined schedule made at the start of operations; the option to deploy additional vehicles and commence a charging procedure for others is also evaluated at each time period change. The model developed by Tang et al. (2019) is also able to determine the impacts that each decision made at the end of each time-period, will have on future periods in terms of deployed/available fleet and battery SOC; all to minimize the sum of operational costs in the considered period and the cost expectations of future ones.

While, as mentioned before, the D-VSP is computationally heavier than the S-VSP, it can yield the smallest realized total cost while being rather insensitive to traffic stochasticity compared to the S-VSP. Compared to the traditional VSP, Tang et al. (2019) introduces the buffer distance parameter to hedge against the stochasticity of energy consumption due to stochastic traffic conditions, as a specific constraint of the static scheduling model.

4.5 Opportunity/Pantograph charging

As indicated by Perumal et al. (2022), the use of electric buses requires special charging facilities which have to be accommodated into the current infrastructure. In this section, we will mention pantograph charging which is one of the charging methods for electric buses into public transportation.

Pantograph charging is an innovative and efficient method of charging electric buses, which has gained significant traction in recent years due to its ability to minimize downtime and facilitate seamless integration into existing public transportation systems. This charging method utilizes a specialized overhead charging infrastructure, which connects to the electric bus via a retractable pantograph mounted on the roof of the vehicle. The pantograph, a conductive device, establishes an electrical connection between the bus and the charging station, allowing for the rapid transfer of energy to the vehicle's battery. Perumal et el. (2022) expresses that a pantograph charger can be installed at intermediate bus stops and has a charging power of 300 kilowatt in where the optimal size of the electric bus fleet is determined as well as their battery capacity, which is measured in terms of kilowatt-hour (kWh).

One of the key advantages of pantograph charging is its ability to provide high-power, fast charging capabilities however pantograph chargers have a high installation cost (Perumal et el., 2022). This enables electric buses to recharge their batteries in a matter of minutes during scheduled stops or layovers, reducing the need for extended charging periods and allowing for continuous operation throughout the day. As a result, pantograph charging can significantly improve the operational efficiency of electric bus fleets, making them a more viable and sustainable alternative to traditional fossil fuel-powered buses.

The charging infrastructure can be easily integrated into existing bus stops or depots, minimizing the need for additional land or construction. Moreover, the modular nature of pantograph charging systems allows for easy expansion as the number of electric buses in a fleet grows, ensuring that the charging infrastructure can keep pace with the increasing demand for clean and efficient public transportation.

In addition to its fast-charging capabilities, pantograph charging offers a high degree of flexibility and scalability, but at the same time requires a specific constraint for the scheduling process. This constraint is defined by Perumal et al. (2022) with the requirement of energy balancing at each bus stop along a specific line.

5. Conclusions

The incidence of electrified bus fleets in urban centres is projected to grow. Nonetheless, given the inherent limitations and challenges posed by electric bus technologies, it is essential to make further refinements to the present bus transportation planning concerns. Therefore, the planning process and scheduling of electric buses are recognised to be vital and fast-growing concern for cities.

In this essay, the objectives of the E-VSP, electric bus scheduling constraints and solution approaches for both electric buses scheduling strategies and charging problems, have been presented after reviewing 11 related publications.

Since the investment amount and production capacity of electric bus manufacturers, in the following short and mid-term time periods, the public transportation fleets will be mixed fleets with both electric and diesel buses.

According to findings, as suggested by Rogge et al. (2018) mixed fleets provide benefits, especially for peak hour flexibility because of some constraints for electric buses like range, battery capacity and electricity prices. In the long-term, if further technological revolution will be realised for battery technologies, fleets with only electric buses will be able to provide more benefits to society.

It has also been also noticed that the scheduling strategies, methods, decisions, and ways of introduction of electric buses into public transportation depend on fleet size, city charging infrastructure systems, and demand on the route. Case-by-case evaluation and decisions are therefore vital for electric buses scheduling since each case presents different requirements, specifications, and constraints, keeping in mind that integrating two or more planning problems into a case, add further computational complexity but further improvement in efficiency of electric bus transportation systems.

As numerous technological constraints exist in relation to the scheduling of electric vehicles, the advancement of recovery techniques that facilitate the real-world implementation of electric vehicles is considered a prospective field of study.
This Review Article attempted to review articles that were available on the wide topic of e-bus scheduling and could be further integrated with articles concerning said technological advancements in the field.

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