Operational demands as determining factor for electric bus charging infrastructure

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Abstract

Many cities in Europe have ambitious goals when it comes to making their public transport buses emission free. This article outlines the reasoning behind the choices made in the city of Amsterdam with regards to charging infrastructure for electric buses. Emphasising the importance of operational demands, and taking into consideration relevant context factor for this city in particular, the article provides pointers for cities, public transport operators (PTOs) and original equipment manufacturers (OEMs) that are considering to introduce emission free public transport by bus.

1 Introduction

Like many other European cities, the city of Amsterdam has ambitious plans when it comes to introducing electric mobility as a way to improve air quality and reduce climate change emissions. The city of Amsterdam currently has over 1,400 public charging locations facilitating (private) electric vehicles to charge in public space, with the ambition to increase this number to 4,000 by 2018 [1]. For its public transport, the city of Amsterdam has set the goal to have an all-electric bus fleet within the city limits of the Dutch capital by 2025, as agreed upon by the municipality and its current public transport operator GVB organized in a covenant structure [2].

Cities like Warsaw in Poland [3], Paris in France [4], Cagliari on Sicily in Italy [5] and London in the UK [6] are also introducing clean bus lines or even entire fleets, often stimulated from an EU level [7]–[9]. London will introduce some 300 emission free single deck buses in its city centre with the introduction of the Ultra-Low Emissions Zone (ULEZ) in 2020 [10]. It is up to PTOs to meet the operational demands as stated in the tenders making use of emission free technologies.

The city of Amsterdam has chosen to introduce one particular charging technology (In Motion Charging or IMC, also known as hybrid trolley or trolley 2.0) for a first batch of around 30 buses on a total fleet of roughly 200. This technology was chosen after an elaborate feasibility study of available charging technologies, in order to determine the most suitable zero emission technology for this first batch to be introduced in 2018.

This article describes several of the decisions made in the feasibility study, with regards to the infrastructure to charge the electric buses. Based on these decisions, the article will conclude with recommendations regarding the introduction of electric buses at a large scale within urban environments.

2 Operation demands and proven technology as starting points

In a joint ambition in 2015, the municipality of Amsterdam and GVB constructed a covenant to make explicit their goals with regards to sustainable public transport [2]. Part of the agreement is that the introduction of emission free public transport by bus is to be realised whilst taking into account the operational demands: the services provided to the public transport passengers are not to be altered due to the introduction of a new technology. An adherent requirement is that GVB is to make use of proven technologies: the services are not to be provided by prototypes or require extensive testing and experimenting, due to the risk of not being able to meet the operational demands.

In a currently (summer 2016) on-going project preparations are made for the introduction of the first batch of zero emission buses to be introduced in 2018. In the previous phase of the project a detailed feasibility study was performed to determine the preferred technology for this first batch of buses. The choice was made to solely look at fully electric drive trains. Hydrogen fuel cell technology, partly based on previous experiences with this technology in Amsterdam [11], is considered too expensive with the current prices despite providing operational performance similar to conventional diesel fuelled vehicles. This is furthermore underlined by studies such as those of Mahmoud et al. [12], Hua et al. [13] and more recently Lajunen and Lipman [14]. Natural gas was not considered, since a zero emission tailpipe technology is demanded by the covenant.

One of the critical parts of the feasibility study was to establish the most promising and attractive technology for charging the electric buses. Whereas electric drive train technology and electric buses have reached a certain level of maturity, there is still a great deal of technological development for keeping them charged for longer ranges.

This paper will mainly focus on the factors determining the choices made by GVB regarding the charging infrastructure for the buses. First, the operational demands as applicable in Amsterdam are presented. Second, the possibilities of several different charging technologies to meet these demands are discussed given the current technology standards.

2.1 Operational demands in Amsterdam

An important prerequisite for the technology choice for charging infrastructure in the city of Amsterdam is given by having to comply with current operational demands. Table 1 shows a summary of these demands as provided by the current GVB bus operation characteristics for both the standard vehicles (12 meters in length) and articulated vehicles (18 meters).

Operational characteristic	*Standard vehicle (12meters)*	*Articulated vehicle (18 meters)*	*Unit*
Average line length	11	11.2	Kilometres
Average distance between stops	450	450	Meters
# of stops per direction	25	25	Stops
Average dwell time at stops	16	20	Seconds
Dwell time per loop (incl. traffic lights, etc.)	19.7	22.3	Minutes
Recovering time at end stops during rush hours (*guaranteed charging time*)	2 (*0*)	2 (*0*)	Minutes
Guaranteed charging time outside rush hours	3	3	Minutes
Average speed	23.5	21.1	Kilometres/ hour
Average moving speed	36.2	32.5	Kilometres/ hour
Frequency during rush hours	5	8	Buses / hour
Maximum shift length of vehicle (excl. night time service)	445	430	Kilometres

Table 1: Operational characteristics Amsterdam bus services [15].

Some noteworthy figures from this table are for instance the limited time per stop of less than halve a minute, the equally limited recovery time at end stops leaving practically no guaranteed charging time for electric vehicles and the maximum service length of the operations of well over 400 kilometres during day time services. When combined with night time services, some vehicles are in operation for a total of more than 600 kilometres per day. In combination with the limited charging opportunities this provides challenging requirements for the on-board energy supply of the vehicles: the battery size.

3 Operational demands as determining factor for charging technology

The characteristics as shown in Table 1, which are considered the operational demands for the electric vehicles, provide a means to review and evaluate the suitability of different available technologies to charge electric buses. After a brief introduction of the currently available charging technologies for electric buses, each of these technologies are reviewed in the light of the stated operational demands. Also, other factors to take into consideration are mentioned.

3.1 Available charging technologies

Different methods exist to provide an electric bus system with the required energy for urban public transport operations. Although not all are considered to have the same technology readiness level, the following technologies are currently considered as readily available (including their respective charging powers and energy carrying capacity).

Slow charging. The slow charging technology considers a scenario where electric buses tend to have large battery packs up (around 300-400 kilowatt-hours (kWh)) and up to a maximum of around 50 kilowatts (kW) for charging. For passenger vehicles (i.e. electric cars), 50kW is considered as a common standard for fast charging, but due to the large battery packs of electric battery buses requires electric buses to charge in around 6 hours. Examples of a slow charging bus system can be found in Paris [4] and Warsaw [3], [16].

Fast/opportunity charging (conductive and inductive). Fast charging or opportunity charging is a system which is operated with smaller batteries than for slow charging: usually a maximum of 150 kWh. Charging power is higher than in the slow charging system, ranging from roughly 50 to 200 kilowatts for inductive charging and up to some 500 kilowatts for conductive charging. Inductive charging is usually performed through a charging device installed in the ground: conductive charging mainly on top of the vehicle through a pantograph mechanic (mounted either on the bus or on a pole). Due to the higher power available for charging, combined with the smaller batteries, the buses have a smaller free range but shorter charging times are required than with slow charging. Examples of fast charging system can be found in Plzen in Czech Republic [17] (combined with overnight slow charging) and in Oberhausen in Germany [18].

Traditional trolley. The trolley buses are attached to an electrical grid consisting of overhead wires (similar to tram overhead wires). The buses are connected to the wires through poles, functioning as the connection between the wires and the electrical engine of the bus. The buses usually are fed with 600 nominal volts and changing current depending on the load as required by the vehicle, to a maximum of roughly 1,000 ampere (resulting in 600 kW). Due to the constant provision of electrical power directly to the propulsion of the vehicle, batteries are not required for driving the buses. Trolley is longest still is use and currently the most widely used electric bus system. Examples can be found across the world (some 300 in total [19]), for instance in Arnhem in The Netherlands [20], Armavir in Russia [21] and Mexico City in Mexico [22].

In motion charging/hybrid trolley. Hybrid trolley, trolley 2.0 or In Motion Charging (IMC), is a system which consists of battery buses with usually no more than 50 kWh batteries that can run autonomously. The batteries are charged through overhead wires on selected sections of a route, which the vehicles connect to with poles (similar to the traditional trolley buses). Currently charging power is maximised at less than 100 kW for charging whilst standing still due to heat restrictions of socket connecting the poles of the bus to the overhead wires. Charging power whilst driving is similar to traditional trolley (the heat restriction doesn't apply due to the cooling effect of moving the socket along the overhead wires). IMC is a relatively new technology: examples of application of the technology can be found in Castellon in Spain [23] and in Vienna in Austria [24] (the later currently only charging whilst standing still).

Above four bus/charging configurations were considered by GVB as the most suitable candidates for the electrification and charging of buses in the city of Amsterdam. For more details and further reading on these technologies: please see sources like [25], [26] and [27].

3.2 Meeting the operational demands of Amsterdam

Using the operational demands as a starting point for the business case calculations and ultimately the choice of technology has so far proven to work well for Amsterdam and presumably also for operators in cities such as London with high operational demands. This is underlined by cases studies in Riga in Latvia [28], Porto in Portugal [29] and Münster in Germany [25]. This holds from a municipal point of view, as well as for PTOs and OEMs.

The overall importance to take into account the operation requirements when making costs calculations of electric buses is furthermore emphasised by Lajunen [26], based on extensive costs calculations. The study recommends that "it is highly important to take into account the operating environment and understand the technical performance of the new technologies in different conditions" when selecting an alternative drivetrain for city buses.

Assuming a worst-case energy consumption including auxiliary functions such as heating of 2 kilowatt-hours per kilometre for standard (12 meter buses) buses and 3 kilowatt-hours for articulated (18 meter) buses, the different charging technologies can be evaluated in terms of meeting the demands of the Amsterdam bus services. The energy consumption figures where derived using detailed calculations assuming the UITP's Standardised On-Route Test cycle number 2 (city area usage) energy demands [30] as well as calculations for specific routes within the Amsterdam network. For more detail on the overall energy consumption of electric buses see for instance [26] and [25].

The following observations are made when valuing the different charging technologies in terms of meeting the average Amsterdam operational demands.

Slow charging: Battery vehicles provide flexibility in terms of routing (which can change due to road works or changing routes due to changed travel demands) and the absence of the need to charge during operations. However, current battery vehicles cannot meet the required range of an average bus route in Amsterdam per shift of well over 400 kilometres. For example: driving 400 kilometres with a standard vehicle requires some 800 kWh of battery capacity (at 2 kWh/km). In case a vehicle is to drive the additional night shift, adding up to over 600 kilometres in total, some 1,200 kWh. Even if buses with this energy storage would exist, they would require a charging time of at least 6 to 10 hours, leaving too little time to provide the demanded services. Furthermore the batteries would add a great deal of weight to the vehicle, thereby reducing energy efficiency.

Opportunity charging: Although significantly shorter charging times are required for these vehicles with current technologies, it remains difficult to implement this technology in a city like Amsterdam due to limited available time per stop on-route. With guaranteed charging times depicted in seconds rather than minutes, and less than 3 minutes of guaranteed charging time *outside* rush hours, the opportunities are too short for significant charging with currently available systems. In addition, the Amsterdam concession is confronted with changing end stops due to changing traveller demands. This puts a heavy burden on hardware investments and costs of connecting to the electricity grid.

Trolley: This technique meets practically all the demands as set by the Amsterdam circumstances, due to its constant availability of energy and absence of required charging time. However trolley buses are inflexible in terms of re-routing, which is required due to for instance construction works and overall changing routes. The required infrastructure is a significant investment which also requires maintenance, both negatively influencing the business case. Furthermore, overhead wires can provoke negative reactions when constructed in residential areas.

In Motion Charging: For demanding operations like those of Amsterdam IMC seems to be a fitting technology. The difficulty of limited charging time due to very limited dwell times (both on-route and at end-stops) is overcome by charging whilst driving. The costs of the infrastructure are considerable smaller than for a traditionally trolley system (due to fewer kilometres of overhead wires), whilst an IMC system is more flexible in terms of changing routes due to the free range of the vehicles. This is however strongly dependent on the available free range (i.e. the battery capacity) of the vehicles and the available sections of overhead wires to charge the still relatively small battery-pack compared to battery buses.

3.3 Points of consideration

With regards to the capabilities of the available technologies of meeting the operational demands of Amsterdam, there are means to overcome the mentioned barriers. When it comes to not meeting the free range demand (in the case of battery buses) or a technology requiring more than the available charging time (i.e. for opportunity charging), a pragmatic solution could be to introduce *additional buses*. Naturally this leads to additional costs which should be considered in the total investment and costs of ownership. Apart from vehicle costs this will add costs in wages for additional drivers and possible additional kilometres for interchanging the vehicles once their energy source is depleted or when vehicles require additional charging time.

In general, all the findings with regards to operations and technology translate into costs. When constructing a business case of any sort for the introduction of electrical buses, it is important to consider the system as a whole: the vehicles, the required charging infrastructure and the operations that are to be performed. Each of these elements self-evidently influence the business case of the bus system, and should therefor carefully be considered when introducing emission free public transportation by bus.

It is furthermore important to point out that the conclusions as presented here are based on average figures of the complete set of bus routes for the city of Amsterdam. For the feasibility study of the Amsterdam situation, an extensive total costs of ownership calculation was made: at the level of individual lines and at a network level. Although differences per route exist, the findings as presented here hold for the Amsterdam situation in general. These differences do emphasize the importance of comparing operational demands with technology performance at a detailed level. Particularly infrastructure costs can differ significantly due to the (urban) surroundings, e.g. crossings with overhead wires or being able to place the required electricity infrastructure in place. Sharing charging infrastructure for instance significantly lowers the required investments for the system: sharing with other modes of (public) transport or in a shared (balancing) system with (large) electricity users.

Another solution/technology is *battery swapping*. This also requires additional kilometres to the battery station, creating non-service kilometres and drivers operating empty vehicles. Moreover to the authors' knowledge no successful large scale examples of battery swapping of electric buses exist [31], and was not considered a proven technology.

Furthermore there are system alternatives such as changing the bus-operation scheme or review public transport as a whole (i.e. the role of buses in the public transport as a whole), which were not considered.

3.4 Conclusion

After an extensive review of the possibilities for currently available charging technologies for electric buses to meet the operational demands of the city of Amsterdam, as well as taking into account the before mentioned considerations, GVB has chosen IMC as the most suitable candidate to implement for its first batch of electric buses. The operational demands proved to be determinative in the decision for the charging technology.

The coming period technical details will be further elaborated and buses and infrastructure provisioned, to allow an introduction of the vehicles by 2018.

4 Recommendations for cities, PTOs and OEMs

This paper has provided a review of charging technologies to enable large scale operation of electric buses in a municipal context. Although the Amsterdam context has played a major role in the chosen charging technology, there are some more general observations made regarding the choice for charging technology leading to several recommendations.

Operational demands prove to be a determining factor in the choice for the charging technology of electric buses. Elements such as route and service length, available charging time on-route and at end stops are determinative for the requirements of the charging technology.

In addition, it is recommended to consider the entire bus system when introducing emission free public transport by bus: the vehicles, the charging infrastructure and the operations. Each of these elements strongly influences the business case of the available technologies. Using tools such as Total Costs of Ownership (TCO) calculations can play an important role in comparing different technologies and ultimately in choosing a technology.

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