Energy Storage Impact on Light Rail Development

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Abstract– Smart cities imply a range of efficient mobility solutions for people and goods at the same time as minimising the environmental burden. This short paper focuses on Light Rail and particularly Tram systems as having advantages in responding to these needs and is the first stage on a longer project which will provide greater detail in due course. It further considers the alternatives for powering the system as an important component in the development of a clean, attractive and economic urban mass transit resource for the smart city. This leads to energy storage as a potential alternative to continuous energy supply such as overhead cables, and is followed by a comparison of various methods of on-board energy storage including batteries, supercapacitors and hydrogen. Interim conclusions are presented.

Keywords–Energy storage, light rail, tram, battery, super-capacitor, flow battery, lithium-ion, overhead line electrification (OLE)

I. INTRODUCTION

Light rail and trams play an important role for smart cities development. They run on a defined route with partial segregation or can be integrated on-street mixing with traffic. The overall capital cost and civil works is less complex and less expensive than the train and metro counterpart which usually requires heavy infrastructure and tunneling. However, the Overhead Line Electrification (OLE) installing is a difficult task to stop unwanted electric currents from interfering with signaling, telecommunication and lines power supplies. Electrification Engineers, Telecommunications Engineers, Signaling Engineers, Traction Engineers, and Power Supply Engineers work closely together to meet safety and electrification clearance so that nobody is exposed to dangerously high voltages. Installing can be expensive too with high maintenance cost.

In France, there is no question that the French tramways' success is their positive image; low noise, grass, trees, traffic calming, overhead electric line elimination in some places, and urban regeneration; the trams are regarded as part of the city's furniture. Heavy fines are imposed if the OLE is installed in front of a cathedral or over a historic bridge. These issues bring the popularity of battery powered-transportation even if it increases the capital cost to fund a light rail / tram scheme to the city.

One of the key innovations in recent development is the power source. Eliminating the overhead line improves the safety of power line management. Technology advances allow efficient power transfer to trains and low power train systems to run over short distances without using conductive power from the lines. Using battery-based train could be a good alternative in that respect.

II. EUROPEAN STRINGENT AIR POLLUTION CONTROL

In July 2018, the UK Department for Transport called for a public consultation to gather evidence to study the effect of brake, tyre and road surface wear to tackle all sources of air pollution [1]. The earlier clean air strategy focused primarily on tailpipe emissions, currently the Government wants to investigate non-exhaust emissions that all road vehicles can produce. These particles are called Particulate Matter (PM), and it is worrisome that PM emission from brake wear, tyre wear and road wear may be more than from the tailpipe exhaust [2]. Studies estimate that emissions from tyre wear alone make up 5-10% of microplastics deposited in the oceans [3]. The Government is taking harsh actions to get private vehicles off the road and push for modal shift to public transport.

Just 2 months earlier (May 2018), the European Commission took the British Government to court for illegal and dangerous air pollution levels [4]. The legal proceedings are not just targeted at Britain but also Germany, France, Italy, Hungary, and Romania for repeatedly breaching legally binding EU air pollution rules. Brussels are requesting the UK to explain what policies the government would bring to resolve the issue. This incident may be the root cause which triggered the brake, tyre and road surface wear public consultation. The UK Government have already set aside a budget of £3.5bn to tackle roadside emissions with a comprehensive Clean Air Strategy [5] by the end of the year. With every city in Britain needing to meet the healthy air standard of the Directive, solutions must be found in suitable public transport options to support the new air quality plan.

III. PUBLIC TRANSPORT VEHICLE COMPARISON

So how much harmful emission do different public transport modes produce? A matrix comparing urban pollution characteristics has been carried out. The findings provide guidance to the best modal shift for public transportation (Appendix, Urban Pollution Characteristic Matrix).

The Urban Pollution Characteristics Comparison Matrix (UPCCM) is an attempt to rank the pollutants from various forms of urban passenger transport relative to comparable alternatives. The values 0,1,2,3 are non-linear and simply ordinal. To use specific values as percentages or actual metrics (e.g. gm/km or ppm/km) would require consistent data sets and produce large variations across the range of vehicles falling under each class. It is arguable that each sub-category of each vehicle powertrain class should be separated out. It must also be remembered that background pollution from non-transport sources may dominate locally, and particularly around out-of-town power stations.

III. TRAMS FOR INTER-MODALITY AND MODAL SHIFT

The initial finding suggests that the *Electric Tram* is highly rated for modal shift compared to buses to support the government's plan to reduce roadside nitrogen oxides and other harmful species which cause air pollution. The reason to support this rationale is that particulate material (PM) emission from the tyre, brake and road emission of a bus is greater than the emission from steel wheel on steel rail of a typical tram system. In fact, trams produces zero emission from braking and tyre wear. The autonomous pods give a promising rating, but passenger capacity of a typical pod can only accommodate a maximum of 12 passenger per unit versus a capacity of 305 passengers from a typical tram and outweighs the advantage.

3.1. Train Family Classifications

Tram, tram-train, light rail, ultra-light rail all come under one 'train family' classification. In most cases, it uses electric vehicles running on steel rails, also often referred to as 'steel wheels on steel rail'. There is no legal definition of each one, so for this paper, a working definition has been specified to distinguish their differences as illustrated in Table 1.

Table 1: Characteristics of Train Categories

Train Type	Typical Passenger Capacity	Typical No. of Carriages	Typical* Average Speed	Degree of Segregation	Differences
Train	*5000*	*4-12*	*100+ km/h*	• segregated, ballasted track with movements controlled by signals	New build is expensive in a city, requiring heavy infrastructure or tunneling
Metro	*>3000*	*4 -10*	*50 km/h*	• Segregated track controlled by signals	Often underground in city centres Usually operates at intervals of less than 10 minutes
Light rapid transit (LRT) or Light rail	*1000*	*~8*	*80 km/h*	• Segregated track usually controlled by signals or electronically	Usually uses steel-on-steel (light rail), but can also include Translohr (guided by steel rail but supported on rubber tyres), VAL (supported and guided by rubber tyres), monorails and other proprietary systems
Tram	*300*	*2 or more sets*	*30 km/h*	• *Integrated on-street* mixing with traffic or pedestrian area or • *Segregated on-street* alongside a highway or accessible by pedestrians or • *Segregated off-street* with interaction at junctions	Can operate in the street (defined in UK Transport and Works Act 1992) Requires operation on *line-of-sight (vehicle* can be stopped within the distance the driver can see to be clear ahead)
Tram train	*1000*	*~8*	*30-80 km/h*	• Segregated like a train and • Integrated on-street like a tram	Combines the tram's flexibility and accessibility with a train's greater speed Bridges the distance between main railway stations and a city centre
Ultra light rail	*~50*	*1-4*	*50 km/h*	• Segregated track controlled by signals or electronically or under driver control)e.g. Stourbridge)	Smaller vehicles with lower axle weight than light rail

*stop-to-stop

IV. BASIC CONCEPT OF A BATTERY TRAM

The power level requirement of the tram is much less than the train. A typical power level for a tram with 4 wagons is 0.75MW whereas a train could consume 20MW. Therefore a train requires much higher power and the overhead power line is the only solution for power supply. Trams run on lower power and the power source can be selected from an overhead line or a battery system.

For a fixed route of tram operation, the required energy storage can be estimated accurately. Suitable timetabling of the tram schedule will provide sufficient time for battery charging.

Today the battery is not the only solution for energy storage, there are numerous possible energy storage options for trams. In short, this can be summarized as:

- Super-capacitor
- Flow battery
- Fuel cell

This paper will examine different types of battery energy storage for the possible application for trams.

V. TYPES OF BATTERIES

The conventional lead-acid is no longer much used in mobility application because of the low power density, even the Nickel-metal hydride (NiMH) and Nickel Cadmium

(Ni-Cd) are also not suitable for trams. NiMH and Ni-Cd have a lower energy density than Lithium-ion (Li-ion) battery. The overall life-time is shorter. Also, the Ni-Cd has the high poison material cadmium and it also has an unwanted memory effect. Therefore both of them are rejected for tram application. Today the most suitable version is Li-ion based. The common ones are:

1. NMC

NMC Li-ion is referred to Nickel, Manganese, and Cobalt. This type has a high energy density and is commonly used in cell phone and SUV Electrical vehicle (EV).

2. LFP

This is the Lithium Iron Phosphate (LiFePO4) and is commonly used in EV because of its safety and the relatively high power density. It is also commonly used in cell phone, EV, computer and many mobility applications.

3. LTO

This is the Lithium Titanate Oxide. It has a lower energy density, but its charging rate is very fast. Some reports and products can achieve 4C to 10C. That is to say, the charging time can be 15 min to 6min for a full charge.

There are other Li-ion batteries such as $LiCoO_2$, $LiMn_2O_4$ and $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ well known. Table 2 shows a comparison of them.

Table 2: Emergent Battery Performance Comparison

Lithium-ion Battery type	NMC	LFP	LTO
Energy Density (Wh/kg)	180	140	**100**
Number of Cycles (life time)	1000	2000	10000
Cell voltage (V)	3.8	3.2	2.2
Max C-rate	2	2	8
Cost ($/kWh)	160	180	300

Battery management system [6] is the key protection and monitoring part for all types of battery system. It provides condition monitoring, cell equalization and protection.

VI. SUPER-CAPACITOR

Super-capacitor [7] has high power density and its power level can be more than 10 times as compared with LFP. Its lifetime is also long. One million cycles of operation are commonly available. It is an electronic component without chemical reaction for energy storage, therefore it is safe and static energy storage is used. However, its energy density is low and around 3Wh/kg. Because of the low energy density, it is usually used together with battery energy storage so that a hybrid energy storage is used.

One of the drawbacks is the self-leakage of the super-capacitor. A fully charged super-capacitor loses its energy gradually through internal energy dissipation and its rate is much higher than the battery. A suitable energy management system is needed.

The hybrid cell that is a combination of Li-ion battery and super-capacitor is an electrical design method to place both energy storage units to complement their weakness. The Li-Super-capacitor has recently emerged from a few manufacturers to make a chemical cell with both features. An energy density of 30Wh/kg is available in the market.

VII. FLOW BATTERY

It is called Redox Flow battery. Red refers to reduction and Ox refers to oxidation. It is a chemical process. It stores energy in liquid electrolyte solutions which flow through a battery of electrochemical cells during charge and discharge. The common types are:

- Iron-Chromium (ICB) Flow Battery
- Vanadium Redox (VRB) Flow Battery
- Zinc-Bromine (ZNBR) Flow battery

The merit of the ReDox flow battery is that its energy storage is in the electrolyte so that the energy is stored in a liquid form and can be added or removed from the trams. Two cylinders of Anolyte and Catholyte can be found in the Redox flow battery. The 'charging' can be done in minutes by refill or exchange of the electrolyte. Therefore it could be a good candidate for trams energy storage.

Today, reaction cells consist of ion-exchange members that is a technology for further development into a long lifetime and low cost. The Vanadium type is a common version. The efficiency of 85% to 95% is available. Although its efficiency is lower than Li-ion which usually has 99% and Super-capacitor which is 99.9%. Because of its flexibility of energy storage in form of the liquid, therefore it has a high potential for trams energy storage.

VIII. FUEL CELL

Hydrogen fuel cell or Proton Exchange member (PEM) fuel cell [8] is not suitable for trams because of the storage in form of hydrogen is not acceptable by the public even though it is proved to be safe and in use by buses in London and other cities. Hydrogen is a highly flammable gas and in its compressed or liquidized form [9] is still a concern for electric mobility.

Aluminum oxide fuel cell (AlOFC) is the suitable form of the fuel cell for energy storage in trams. Aluminum is a safe solid fuel without the danger of explosion. The AlOFC has a high energy density. Presently it can achieve 300Wh/kg and it has a further potential of 600Wh/kg or higher. Its cost is similar to LFP. The fuel is Aluminum and therefore the fuel is simple for storage and transportation.

VIIII. CHARGING STATION

The charging facilities or charging stations for different energy storage options are quite different. The cost implication are also different. The charging method can be classified into

- Conductive charging
- Wireless charging
- Battery swapping

1. Conductive charging

For most of the battery, the charging time is roughly inversely proportional to the C-rate. The standard or lower cost battery is around 1 hour for a full charge. The timetable of the tram schedule should be allocated with charging.

If the charging time needs to be shortened to 15 min or less, the battery cost is much higher. The super-capacitor has a very high C-rate of around more than 15. Therefore it takes less than 4 minutes. However, the cost of charging facility increases because it needs to handle higher power.

2. Wireless charging

This method eliminates the wire harness issues and makes the charging easy to handle. There is a stationary wireless charger so that the charging is done when the tram stops. Therefore wireless charger can be installed in the station. The charging power density of 50kW/m2 is now available. Therefore considerable charging time is needed. i.e. the current design does not provide sufficient power if the charging is only allowed when the trams stop in the station.

Another one is move-and-charge that allows the tram to charge when it is running. However, this technology is not yet mature. The power level and the cost are not favourable.

3. Battery swapping

This method has been fully discussed over many years and the trams need to be specially made to cater for battery swapping. Battery-swapping technology is mature, but more work is needed to ensure the power connection of the battery system to the trams is secure and less aging. Battery swapping also introduces a lot of operational issues and hence many electric mobilities did not use this method.

4. Refill Fuel

This method is to refuel the fuel cell or the Redox Flow battery because both types need to add or replace the fuel. PEM need hydrogen refill. AloFC needs to refill the aluminum. The Redox fuel cell also needs to refill the electrolyte. The refill is relatively straightforward. The present technology is fine to use the refill method. The handling of the fuel in a station or terminal does not impose any issues. However, the overall efficiency for such technology of fuel cell and flow battery is still low, therefore for tram system needing relatively high power, the overall efficiency discount the investment's decision.

X. Conclusion

This short paper presents an overview of energy storage impacts on light rail development in the context of clean and efficient mass mobility as a component of the smart city of the future, and is the first stage on a longer project.
Trams are appropriate in both capacity and efficiency terms while having lower investment requirements than heavy rail and other forms of light rail. They also have a lower environmental impact in urban situations than even electric buses, because of the levels of particulate matter created.

Onboard energy sources reduce or eliminate the disruption, time and cost of installation, maintenance and the aesthetic impact of overhead wires for conventional trams. Different cell chemistries were summarised alongside supercapacitors and hybridised formats.

Of the methods for providing and replenishing on-board storage that were considered, namely conductive and wireless charging, battery swapping and refilling with a consumable energy medium, battery swapping has the least attraction. The conductive and wireless charging each have trade-offs on time required and facility cost, but can be done while in-service under favourable conditions. Like battery swap, refilling needs to be done at service facility such as the depot, and offers long term potential.

Currently therefore, pending the anticipated further development of power and energy densities, replenish, discharge and energy loss rates, the most appropriate energy storage solution for a given tramway network at a particular point in time will depend very much on the characteristics of the network such as frequency of stops, timetabling, terrain, passenger density and surrounding traffic densities. Details of these dependencies will form the next phase of this research.

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APPENDIX

EMISSION SPECIES / PROPULSION SYSTEM	NO	NO_2	CO	CO_2	SO_X	Carbon PM	Tyre PM	Brake PM (non	Road material PM	Fe/FeO_X PM	O_3
Petrol (gasoline)	1	1	1	2	0	1	1	1	1	1	1
Diesel (fossil)	1	2	1	1	0	1	1	1	1	1	1
Petrol (gasoline) hybrid	0	0	0	0	0	0	3	3	2	2	1
Diesel Hybrid	0	0	0	0	0	0	3	2	2	2	1
Petrol (gasoline) plug-in hybrid	0	0	0	0	0	0	3	2	2	2	2
Diesel plug-in Hybrid	0	0	0	0	0	0	3	2	2	2	2
Hydrogen Fuel Cell Electric Vehicle	0	0	0	0	0	0	3	2	2	2	2
pure Battery electric vehicle	0	0	0	0	0	0	3	1	3	1	1
LPG/CNG	0	0	0	1	0	0	1	1	1	1	1
LPG Electric hybrid	0	0	0	0	0	0	2	1	2	1	2
High capacity diesel bus *[75 passengers]*	1	2	1	2	0	1	1	1	1	1	1
High capacity diesel hybrid *[75 passengers]*	0	1	0	1	0	1	2	1	1	1	2
High capacity battery electric *[75 passengers]*	0	0	0	0	0	0	3	1	3	1	2
Medium capacity HFCE bus *[60 passengers]*	0	0	0	0	0	0	1	1	1	1	2
High capacity trolley bus [75 passengers]	0	0	0	0	0	0	1	1	1	2	1
Conventional Tram (305 passengers)	0	0	0	0	0	0	0	1	0	3	2
Battery tram (305 passengers)	0	0	0	0	0	0	0	1	0	2	2
Autonomous electric pod (2-seat)	0	0	0	0	0	0	2	1	+	1	2
Autonomous electric pod (6-seat)	0	0	0	0	0	0	2	1	+	1	2
Autonomous electric pod (6-seat & 6-standing)	0	0	0	0	0	0	2	1	1	1	2

Urban Pollution Characteristic Matrix

Notes

1. Information sources are the most current UK/EU available, in the interests of future planning, and do not necessarily include legacy technologies; a separate study could be undertaken to represent a contemporary traffic mix.
2. Urban Euro 6b data are assumed (typical actual results, not regulatory limits), for personal or public passenger transport vehicles
3. Only low sulphur / unleaded fuels are considered as these are the only fuels available for road transport in Europe.
4. Electric power is rated as zero combustion emissions for urban street level pollution assessment. A further, additional, assessment using current or worst-case mix of renewable/fossil electric power generation should also be added for scientifically balanced comparison.
5. Whole-life environmental impact, ethical materials sourcing and disposal, are not considered as UK urban street-level pollution issues
6. Judgements are made on the basis of equivalent utility, i.e. number of seats, luggage capacity and ability to match urban and extra-urban traffic speeds but a minimum range usable range of 150 km for electric urban use.
7. An average weekly occupancy (load factor) of 25% for cars, 45% for buses and trams is assumed
8. The assessment does not take into account effect of vehicle type on congestion, nor effect of congestion on vehicle type, nor traffic priority management.
9. Observations of hybrid buses in London have noted considerable need to boost batteries using their engines several times during a shift.
10. Taxis (including Uber, Lyft, etc.) are not covered in this version: they are mostly comparable technically with private vehicles, but have one less seat available for users, and use road space and energy when not carrying a fare. However, hybrid taxis are likely to need to boost batteries using their engines several times during a shift.
11. A similar table could be compiled for goods vehicles
12. Regenerative braking is assumed for all hybrid and full-electric vehicles, but this may be unrealistic for pure continuous overhead-wire systems.
13. HC/VOC emissions at filling stations are not included – these are uncommon in central urban areas, and are localised.