ADVANCING PUBLIC TRANSPORT

KNOWLEDGE BRIEF

INFRASTRUCTURE FOR IN MOTION CHARGING TROLLEYBUS SYSTEMS

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INTRODUCTION

Battery electric trolleybuses with In Motion Charging (IMC) are highly effective technology with huge economic and environmental potential: High passenger capacity, an infinite range, uninterrupted 24/7 operation, the flexibility of off-wire service and energy-efficient emission-free travel. IMC is particularly suited for high-pace, high-volume operations, such as long vehicles operating at high frequency or at elevated commercial speeds on electric bus rapid transit (e-BRT) routes, in challenging environments requiring strong air conditioning or heating. When operating large fleets with short sections of lean and inexpensive infrastructure, IMC offers favourable Total Cost of Ownership (TCO), reliability and energy efficiency.

This Knowledge Brief gives an introduction to battery trolleybuses with In Motion Charging, 'the reinvented trolleybus 2.0', and provides a specific focus on the infrastructural needs and challenges. This publication follows from the Knowledge brief "In Motion Charging Innovative Trolleybus", published in 2019.

Newly installed e-BRT line in Italy

IN MOTION CHARGING INFRASTRUCTURE: INTERFACE TO THE TROLLEYBUS

IMC is based on proven trolleybus systems that are largely standardised and operating in almost 300 cities across the world. Global standardisation allows trolleybuses from any bus manufacturer to operate in any city worldwide.

The specific IMC interface between the bus and infrastructure is mainly specified by:

- An IMC onboard charger
- The IMC current collector system with two poles
- A reconnection funnel
- A pair of overhead wires (contact lines)
- The power supply

ONBOARD CHARGER

IMC onboard chargers require only a basic rail substation for power supply, with no need for a charging protocol for communicating with the vehicle. IMC technology is standardised, flexible and robust in comparison to the different standards currently applied in any off-board charging battery buses, whereby chargers require specific protocol for communicating to the vehicle's battery management system.

IMC trolleybuses charge according to the same global standard, with no protocol at all: Charging intelligence is on board, with onboard chargers drawing power from the wire according to the battery's needs. Several IMC trolleybuses can charge simultaneously and independently while operating under the same wire. Tendering is easier due to the absence of risk of a technological lock-in.

Basic rail substations used for IMC are proven technology with high reliability and a lifetime exceeding 40 years, positively affecting TCO calculations and representing a sustainable investment.

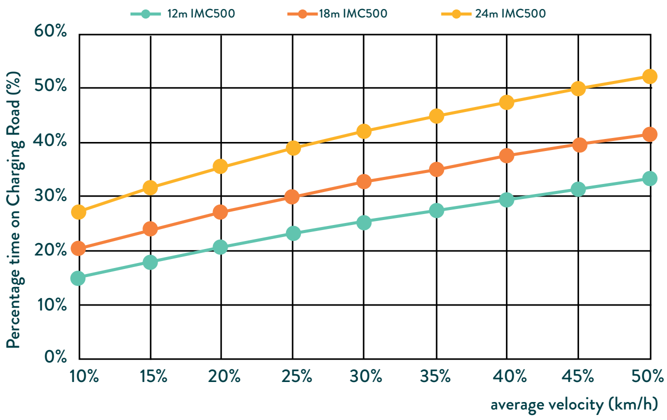
CURRENT COLLECTOR SYSTEM

The current collector system for IMC trolleybuses follows one globally proven standard. The U-shaped heads follow the course of the wires and guide the poles while the vehicle is in motion. See image below.

RECONNECTION FUNNELS AND CONTACT LINES

IMC trolleybuses reconnect to the wire after going through a section without contact lines. Reconnecting is automatic during passenger boarding at the bus stop and takes between 3-15 seconds.

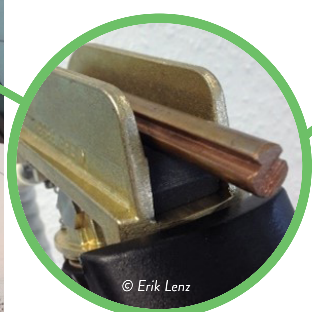
However, the amount overhead wires (contact lines) required for In Motion Charging is a major question for any operator. The graph below shows the different vehicles lengths and the percentage of running time under overhead wire depended on commercial speed. The amount of wire required mainly depends on power transfer (here 500kW), vehicle length and velocity. For example, a 24m double articulate trolleybus, at an average commercial speed of 18km/h, would only need approximately 35% of its running time as charging time using overhead wire. As an example, a 500kW power transfer enables 200kW of battery charging even when going uphill, while at the same time providing full 240kW power to two motors (2x120kW) and powering in parallel auxiliaries such as heating or air conditioning. If the vehicle speed is lower under overhead wires, the time for charging gets longer and therefore the need of wires along the route gets reduced even more.



Percentage of running time under overhead wire vs. commercial speed

The articulated IMC500 trolleybuses in Solingen, Germany, only needs 33% overhead wires of the total running time, resulting in only 23% of route length.

Re-wiring with connection funnel on Shanghai's route 71 BRT, taking less than 5 seconds



Vehicle current collector head with copper overhead wire

Transparent funnels in Villeneuve, Switzerland, are less visually intrusive

DESIGN OF IN MOTION CHARGING INFRASTRUCTURE

A holistic economic and ecologic analysis of demand is required when designing a city's IMC infrastructure. This includes aspects of overall operational robustness, regarding both temporary service alterations and future network expansion scenarios.

Avoiding expensive equipment such as switches, crossings and turning loops roughly halves average overhead wire infrastructure costs per kilometre. Similarly, reducing the overall length and complexity of overhead wire reduces the setup and maintenance costs of IMC infrastructure in comparison to traditional trolleybus systems. Digital cloud-based technology also allows for monitoring system energy management and actively contributes to stabilising the power grid.

STANDING CHARGING VERSUS IN MOTION CHARGING: CHARGING POWER AND BATTERY SIZE

Strategically, wiring battery bus routes contributes towards minimising the battery size and weight allowing approximately 10% more passenger capacity compared with high power opportunity charging. Reducing the battery size is based on two reasons:

1. Wires shorten the range, where the battery gets discharged (here from 10km to 7km), therefore the range requirement is lower.

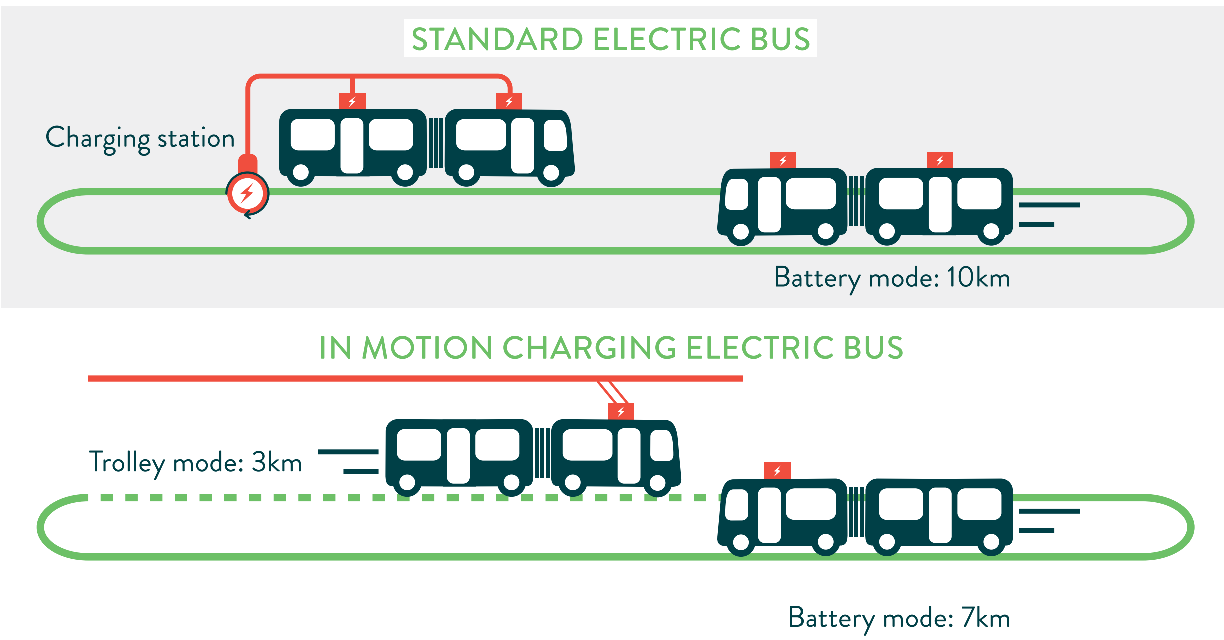
2. Having less available charging time requires increased charging power and consequently increased battery size.

Charging while standing is non-productive waiting time and this idle charging time should be as short as possible. With IMC, the wire gives time to charge while productively transporting passengers. In the image below, 3km wires results in 12 minutes charging, assuming 15km/h vehicle velocity. With that time and 200kW charging power, sufficient energy can get recharged.

With standing charging, the idle stand still time has to be minimised. Cutting the charging time in half to 6 minutes consequently requires doubling the charging power for the same 40kWh recharging, resulting in double battery size while preserving the same battery lifetime. Batteries are limited on charging power and double charging power leads to double battery size. Besides, having a smaller battery for lower range means that they get charged faster.

The highest possible efficiency is achieved while operating under the wire, since the energy goes straight from the infrastructure directly into the motor, bypassing the batteries and avoiding the energy loss from charging and discharging. With IMC500, only 70% of the traction energy is needed for off-wire operation. During the 30% operation under the wire, the air conditioning can function at maximum to condition the vehicle perfectly for the off-wire operation, saving the energy stored in the battery for the traction.

To summarise, **IMC requires less energy from the buffer batteries and allows for longer charging time.** In contrary, with standing charging, the trolleybus needs to be 100% charged before operating. Since passenger capacity depends on available space and the restriction on axle load, lighter smaller batteries mean more passengers.



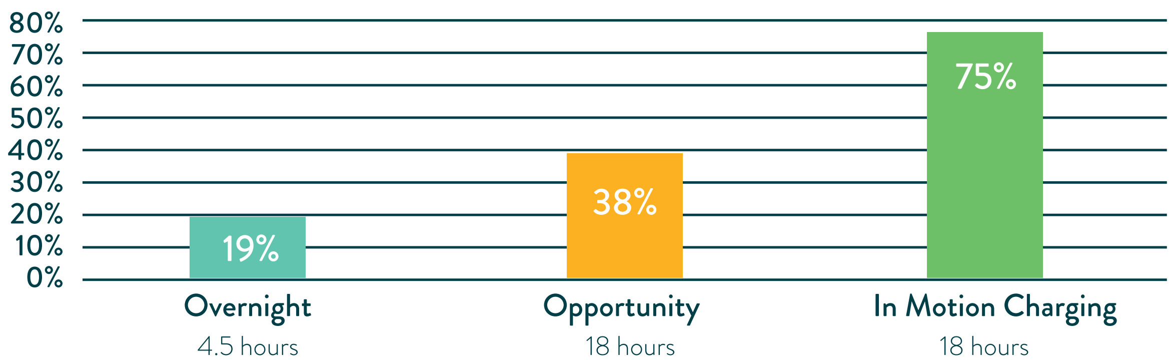
IMC requires much smaller on-board batteries, thus less vehicle weight, and allows to entirely skip unproductive vehicle charging standstill times

A different comparison can be done with overnight charging, where overall grid power demand is four times higher than IMC. The graphs below show the different utilisation rates and power demand. **IMC offers the highest utilisation rates and least power demand from the grid.**

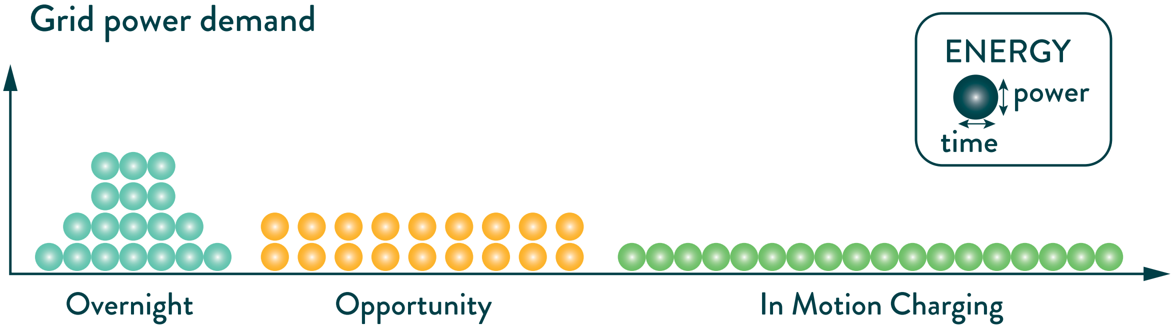
For building feeder substations, the installation cost depends also on the distance to the power grid. Building underground power lines to opportunity charging stations in dense city areas can result in significant costs. With IMC, the location of feeder substations is more flexible since they can be located at any point along the overhead wires, allowing for optimal distances to the grid. In other words, the costs of underground power lines can be minimised and utilise the lines as overhead contact lines.

Opportunity charging at a terminus stop in Solingen with an IMC bus, an additional element that can extend off-wire range in specific cases, further adding flexibility and combination options with opportunity charging to the IMC system

Infrastructure utilisation rates



Grid power demand



Infrastructure utilisation rates for different charging systems

ANALYSIS OF ROUTE AND NETWORK TOPOGRAPHIES

Besides demand estimation and its projected evolution, an analysis of network topography is key. Due to comparably low vehicle weight and the possibility for continuous operation, IMC trolleybuses are particularly suitable for network sections with:

- High demand and/or high frequency e.g. mid- to high-capacity corridors where several routes overlap, making best use of the infrastructure.
- BRT applications operating large vehicles e.g. double articulated buses, low operational cost and quick setup times.
- High daily mileage: There would be no need to recharge while standing along the route, and no unproductive recharging times at terminal stations even with heating and air conditioning.
- Hilly terrain: An external supply of energy means less batteries and lighter vehicles operating in a more economic and ecologic way.
- Or any combination of the above.

Implementing IMC can be particularly interesting when bundling several routes sharing common wires, since the utilisation increases and the investment in these sections with overhead wires faces comparably quick returns on investments.

The significantly longer lifespan of IMC vehicles, combined with their lower maintenance costs, results in a lower TCO that in many cases does not only offset the upfront investment in overhead wires, but rather profits from it.

GOVERNANCE

In many countries, trolleybuses are traditionally classified as railways, which has implications for awarding concessions and operational permits. Switching to IMC, trolleybuses can run for significant periods off-wire, which brings them much closer to other bus propulsion modes. Funding mechanisms for battery e-buses should therefore be applicable to IMC buses as well.

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Shanghai's Route 71: High-capacity BRT

URBAN DESIGN AND INTEGRATION

IMC Trolleybuses do not require complex chain catenaries, but simple double wiring that is visually unintrusive and can either be well hidden or elegantly integrated into an urban context as a deliberate visual element.

However, visible public transport infrastructure has always had a psychological function in urban design. It signals the availability of reliable and sustainable urban connections. For a better exploration of opportunities in a given context, UITP advises active collaboration with urban designers and leading architects.

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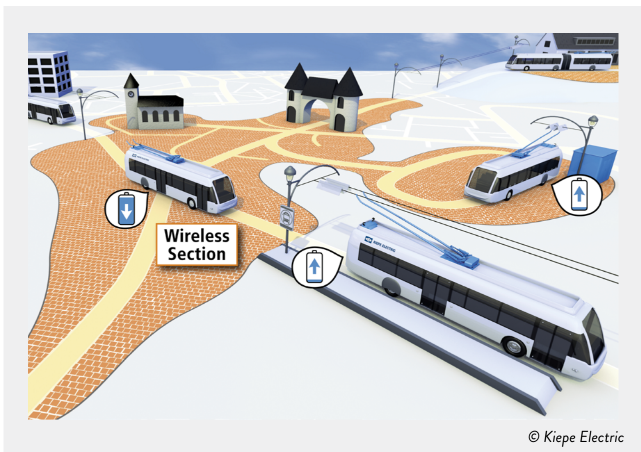
Integrating infrastructure into urban design in Pescara, Italy

New town planning and suburbanisation can be addressed with route flexibilisation and are ideal for IMC since it relies on the efficiency of common trunk routes while allowing for full flexibility serving local communities. Due to its unique advantages such as low investment costs and quick setup times, UITP suggests for IMC trolleybuses to be generically included in setup plans for Sustainable Urban Mobility Plans (SUMPs).



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IMC 'charging road' installations in industrial zones and uphill areas, and wireless in the city centre

CO-USE OF RAIL INFRASTRUCTURE

Cities with existing metro or light rail/tram systems can easily supplement their e-mobility network with an IMC system, since both systems use a DC 600V or DC 750V power supply. European Standards such as EN 50122-1 allow the common use of power supply infrastructure for both tram and trolleybus, which is proven technology. Existing substations of metro or tram systems can be extended to feed the IMC overhead wire as they are almost identical in their main components.

Generally, rail substations are dimensioned to deliver a peak power of 300% of the nominal power during a short time. IMC trolleybuses only draw power once it is available and can partly use power from the onboard batteries. A collapse of the power system is prevented by an intelligent on-board power management, detecting the line voltage in real-time and adapting the careful charging accordingly. Existing masts (poles, towers) supporting contact lines of a tram system can possibly be used to install overhead lines of an IMC trolleybus system.

An IMC trolleybus system in combination with a light rail system can be controlled from one control centre including power management. Trained staff familiar with light rail infrastructure should be able to operate and maintain the fixed installations of IMC lines with little additional training.

In addition to the technical synergies described, there are also operational aspects. Usually, metro or light rail systems cover legacy transport axes of a city. An IMC system can use the existing substations along these axes to create new, electric ring lines ideally complementing existing rail systems (e.g. Milan).

MULTIPURPOSE AND SHARED CHARGING INFRASTRUCTURE

Since electricity demand in urban areas will rise substantially due to the uptake of e-mobility, new charging solutions need to be found to supplement electricity grids locally. IMC networks can provide opportunities for Direct Current (DC) fast-charging hubs, which could encourage the use of electric vehicles (EV) without requiring too much urban space in cities.

When planning for a new IMC network, such a physical transport infrastructure should be exploited as much as possible to foster a transition towards zero-emission mobility systems. Thus, smart trolley grid elements like multipurpose use, stationary energy storage and renewable energy sources should be considered from the beginning and integrated with energy and spatial planning processes.

For example, in Arnhem, the Netherlands, the existing trolleybus network power supply is used to charge municipal e-fleet vehicles, enabled by innovative chargers drawing power directly from the DC trolley grid[1].

CASE STUDIES: IN MOTION CHARGING

Supplying large e-bus fleets in demanding operational situations has been accomplished, for example in North America. Vancouver, Canada, operates 262 IMC trolleybuses, introduced for the 2010 Winter Olympics. Starting in 2017, San Francisco introduced 278 and Seattle introduced 174 IMC trolleybuses with Li-Ion batteries.

San Francisco Municipal Transportation Agency (SFMTA) measures and publishes the mean distance between failures (MDBF) of their vehicles including trolleybuses and diesel buses. The new IMC trolleybuses MDBF surpass expectations and generally perform better than diesel buses despite IMC buses mainly operating on steep gradients and in demanding downtown areas. Besides their outstanding reliability, handling of IMC trolleybuses is comparable to conventional buses. Plus, since there are no charging issues, maintenance is sufficiently covered by a single staff member only for the full fleet of 278 buses.

Italy has the largest number of cities with trolleybus systems in western Europe and numbers are increasing, for example, with a new e-BRT line in Rimini. Pescara has recently ordered IMC buses, which will enter operation in late 2022. Genoa plans an extended, new high-capacity IMC system planning to use 24-meter bi-articulated vehicles, comparable to Linz.

Electric trolleybus in Linz

1 Venematech, 2018. *Vehicle fast-charger from the trolley – tramnetwork*.

Berlin, Germany, has extensively analysed the suitability of IMC, resulting in introducing it[2]. New high-performance IMC routes are also planned in Prague, Czech Republic, functionally replacing a metro line to the airport, and Bratislava, Slovakia, with double articulated trolleybuses.

New systems have also been recently introduced in Shanghai and Beijing, China, in the form of newly built BRT routes designed as In Motion Charging trolleybus operations. In 2017, Malatya, Turkey, introduced a 24m 'trambus' as an inexpensive and fast-to-build alternative to light rail.

ADVANTAGES OF IN MOTION CHARGING

- Infinity range e-bus concept (∞ e-bus) at maximum passenger capacity with heating or air conditioning
- 24/7 operation without charging breaks
- Proven robust technology, high availability, reliable e-mobility
- Fast to implement, fast to convert
- Worldwide established standard of infrastructure interface, allowing for competitive tendering
- Light and durable vehicles resulting in less energy consumption and better sustainability
- Truly sustainable and economic power concept powering the drive train directly from overhead wires, without constant double losses of energy transformation to or from batteries
- Highly effective for intensive operations
- Convenient bus operation, similar to conventional buses
- Substations can be combined with rail use and can also charge opportunity charging e-buses with on board chargers
- No need for diesel-powered vehicle heating or air conditioning

WHY THE WIRES?

- Wires reduce battery size by e.g. shorten the range of battery mode use
- Wires increase passenger capacity due to lighter batteries
- Wires give valuable charging time during operations and eliminates unproductive downtime for charging while standing
- Wires spread the power supply over time and smoothen out the grid peak power demand, actively contributing to stabilising energy grids
- IMC wires are specifically deployed in locations where highest infrastructure utilisation rates can be obtained
- Wires are sustainable having a 20-year life span, are easy to recycle and remain the initial material value afterwards, thus becoming an integral part of a circular economy. Substations and masts have a 50-year life span
- Power supply substations are based on simple and robust rail applications offered by technology providers worldwide
- Wires allow for fully powering auxiliary functions such as heating or air conditioning even in demanding climatic zones without any impact on vehicle range or performance

Uninterrupted continuous operations in Vancouver, Canada, despite the extreme cold or heat

2 The study can be downloaded here.

CONCLUSION

In motion charging is a technology combining all the best components of sustainable mobility. It performs mainly through its infinite range allowing for 24/7 service, high reliability, light and durable vehicles, high capacity, true ecologic and economic sustainability, and outstanding scalability.

Global trends show a preference for the introduction of IMC systems when upgrading to double articulated e-buses or otherwise scaling operations. This is because of the proven technology of trolleybuses combined with the highly robust and efficient IMC approach. UITP recommends IMC to be systematically considered in any feasibility study.

When a BRT-like IMC operation is introduced, existing bus routes can be switched to electric operations by having them share the IMC infrastructure on corridors where they overlap. This allows for standard 12m trolleybuses to also be charged with IMC, and can be combined with interoperable combination of opportunity charging on selected routes. This will increase the utilisation rate of the infrastructure and encourage deployment for cost-efficient, resilient, robust electrification of entire bus networks.

In addition, opportunity charging e-buses with on-board chargers can be considered for less intensive services, powered by IMC substations. The combination of the IMC and e-buses with on-board chargers will electrify the entire fleet, without having to additionally invest in depot charging.

Cities looking to introduce a light rail system should consider whether their requirements for passenger capacity can be achieved by double-articulated electric trolleybuses. New BRT IMC systems generally cost less than new rail systems, can be implemented faster, and trolleybuses are not stopped by roadworks, accidents or illegally parked cars.

Infrastructure can be built in key public transport hubs with elevated levels of traffic and ideally be connected to ensure a higher degree of energy efficiency. Using existing rail infrastructure can provide additional advantages, as common use will reduce investment costs. Besides, it allows for a faster implementation phase, supported by existing expertise of staff.


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This Knowledge Brief was prepared by the Trolleybus Committee. The Working Group involved Wolfgang Backhaus, Arnd Bätzner, Jiří Kohout, Erik Lenz, Richard Kayser and Dr. Steffen Röhlig.

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