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# Autonomous Battery Drive in Trolleybuses: an Overview of Practical Examples

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**Abstract**

Battery electric buses are believed to be means of transportation of the future. However, despite the continuous development of electrochemical batteries technology and the multitude of electric buses on offer, it is still no proved solutions that can be widely used. Charging is the one of the weakness point of the electric buses. Trolleybuses are alternative for them. Especially, trolleybuses equipment with traction batteries for autonomous drives can split advantages of electric buses and classical busses. Paper presents two examples of trolleybus systems, which exploits hybrid trolleybuses.

**KEY WORDS:** *electric bus, trolleybus, traction batteries, Eliptic, emobility*

## 1. Introduction

Despite the continuous development of electrochemical batteries technology and the multitude of electric buses on offer, it is still not possible to exploit electric buses in urban transport on all-day route operation without the necessity of charging them. Therefore it is necessary to build contact charging stations. This results in substantial financial outlays connected with the construction of charging stations, and in the necessity to extend the stopping time at the terminals [1-4]. The alternative solution is the so-called In Motion Charging (IMC), also called the Slide-In system [6]. It consists in building an infrastructure allowing for charging vehicles in motion, most often with the use of overhead contact line (Fig. 1) [5]. A prototype route based on the IMC functions in Landskrona (Sweden) within the existing trolleybus network. In the IMC system a part of a transport route is covered by overhead contact line which is used to charge traction batteries. The vehicles move the remaining part of the route, i.e. the part where there is no contact line, with the use of battery supply. This allows for charging the vehicle without the necessity of excluding it from traffic, thus increasing the flexibility and functionality of the system.

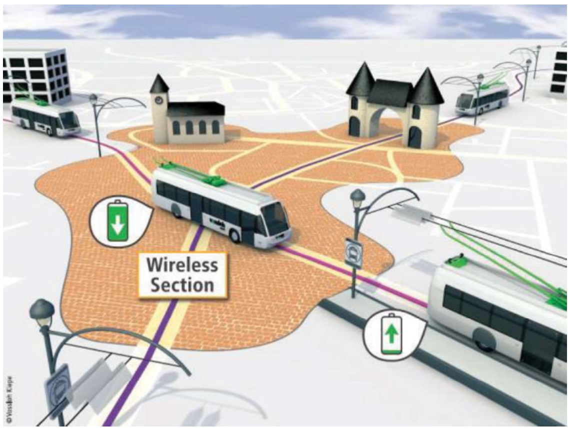


Fig. 1 The idea of In Motion Charging system (IMC) [© Vossloh Kiepe]

## 2. Trolleybus Transport System of Gdynia

The city of Gdynia, Poland, exploits an extensive, 50-km-long trolleybus network, which is serviced by 85 vehicles. The trolleybus system is operated by Przedsiębiorstwo Komunikacji Trolejbusowej Sp. z o.o. (PKT). In order to increase the reliability of trolleybus transport in 2009, the first vehicles equipped with a battery autonomous drive system were introduced into operation.

### 2.1. The First Generation of Traction Batteries in Gdynia - NiCd Technology

The first two trolleybuses equipped with auxiliary battery drive Solaris Trollino 12 MEDCOM, with electrical accessories manufactured by the Polish company Medcom, were put in operation in 2009. Another 25 trolleybuses of the same type were purchased one year later, financed by the Regional Operational Fund [7, 8].

The trolleybuses are equipped with NiCd STH 800 batteries obtained from SAFT (Figs. 2, 3). The capacity of the batteries with 168 cells is 80 Ah, which equals 16 kWh. This capacitance allows to run 2 - 4 km in autonomous regime. The total weight of the battery equipment, DC/DC converter included, is 800 kg. The maximum power when running the vehicle by using the traction batteries is 70 kW. This allows the vehicle to be run at a speed up to 40 km/h and with acceleration 0.4 m/s$^2$.


Fig. 2 Solaris Trollino 12 Medcom trolleybus

Fig. 3 Traction NiCd batteries (right) and DC converter (left)

## 2.2. The Second Generation of Traction Batteries - Li Ion Technology

Experience in operating trolley buses equipped with traction batteries has confirmed the value of this solution. However, a small capacitance of NiCd battery not allowed for a wider use of the auxiliary drive, especially in standard schedule operation. Therefore, it was decided to purchase vehicles equipped with newer technology batteries. Since 2015 vehicles with high-capacity lithium-ion batteries with the capacities of 40 kWh and 69 kWh have been introduced into exploitation (Figs. 4, 5, Table 1).

Fig. 4 Trolleybus Solaris Trollino 12 MEDCOM No. 3091, Route 172 in Gdynia. Photographer: Karol Grzonka


Fig. 5 Rear part of a Solaris Trollino 12 MEDCOM trolleybus, 3 battery modules (black boxes) and the charging system (a grey box in the upper part of the apparatus) are visible

Table 1

Technical data of batteries in Solaris Trollino 12 MEDCOM trolleybuses for Gdynia

| | |
|---|---|
| Producer of electrical equipment | MEDCOM |
| Power of the traction motor | 175 kW |
| Number of battery modules | 3, parallel |
| Total capacity of batteries | 69 kWh |
| Single module capacity | 23 kWh / 36 Ah |
| Wehicle weight | 13 tons |
| Number of seats | 30 |
| Total number of passenger places | 45 |
| Maximum voltage of a module | 728 V |
| Maximum continuous output power of a module | 64 kW |

Table 2

Technical data of Solaris Trollino 12 SKODA trolleybus for Landskona

| | |
|---|---|
| Producer of the mechanical part | Solaris Bus &Coach |
| Producer of electrical equipment | ŠkodaElectric, |
| Type | Solaris Trollino 12 |
| Length of vehicle | 12 m |
| Power of traction motor | 160 kW |
| Wehicle weight | 13,6 tons |
| Number of seats | 27 + 3 |
| Total number of passenger places | 58 |
| Voltage of traction batteries | 450 V |
| Total capacity of batteries | 54 kWh |

## 2.3. Measurement Performed in Gdynia Trolleybus Network

Due to very good characteristics, the possibility of autonomous trolleybus drive is used not only in emergency situations, but also when there is insufficient stock on bus routes. In such situations battery trolleybuses often function on bus routes, using for charging purposes the overhead contact line which covers the common sections of the routes. This was done on the largest scale from the 29th June to the 1st July 2016 when, in connection with the organization of the Open'er Festival, there was a considerable shortage of vehicles in bus transport, and trolleybuses equipped with high-capacity lithium-ion batteries were servicing some bus routes in Gdynia and Sopot, for example routes S, 159 and 172 (Fig. 4). Using their auxiliary drive, the vehicles were able to cover long sections of the routes, sometimes as much as 29 km. Based on the measurement data obtained at the time when bus routes were serviced by battery trolleybuses consumption in individual operational modes has been established. The values for the catenary and battery operational modes, as well as the values of energy consumption for traction purposes and the total energy consumption value have been set. The realised measurement were collected by GPS logger devices in trolleybus vehicles [11, 12]. The main issue connected with dimensioning the IMC systems is to establish the minimum coverage of a public transport route with catenary. Collected data allowed to set requirement for IMC and can be used for construction of the new systems. When servicing bus routes, the trolleybuses covered, on battery supply, the sections whose length varied between 0.5 km and 29 km. Battery charging from the traction network took place during the operation. This allowed for collecting the data which make it possible to establish boundary parameters of both battery and catenary drive for the vehicles charged in the IMC system:

1) the drive with traction battery supply allowed for establishing the range of a vehicle autonomous mode (Fig. 6);

2) the drive with traction network supply and simultaneous charging of traction batteries allowed for establishing the parameters of the traction battery charging process (Fig. 7).

Analysis 1 makes it possible to established the battery capacity required for covering a given route section, while analysis 2 allow for establishing the parameters of the catenary section where battery charging takes place.

Currently trolleybuses are equipped with an on-board charging system supplied from the catenary, with the power of 70 kW, which allows for fast battery charging with the 1 C current. Systems which charge batteries with much higher current, even 5 C, are currently applied more and more often in modern electric buses. Thanks to the linear dependence, the obtained results may be used to estimate the charging times and the minimum relative length of a route under the catenary for other operational conditions. In the case of charging vehicles in the IMC system with the use of trolleybus collectors, current capacity of these collectors constitutes a limitation. The maximum charging currents in motion and during stopping time are 200 A and 150 A respectively, which corresponds to respective charging power of 120 kW and 90 kW. These values should therefore be regarded as boundary values with regard to the IMC system. In the case of charging with the power of 120 kW, it is sufficient to cover only 22% of the route length with catenary. The above measurements refer to springtime, when energy consumption is 1.3 kWh/km. During the winter season the total energy consumption may increase even to 2.3 kWh, which results in a greater degree of traction battery discharging and longer charging time. In such a case, using a 120 kW charger, it is necessary to cover 33% of a route with catenary, while in the case of currently used charging systems, this value rises to 46%. Table 3 presents the comparison of charging times and the equivalent lengths of catenary sections for various operational conditions and different charging powers.

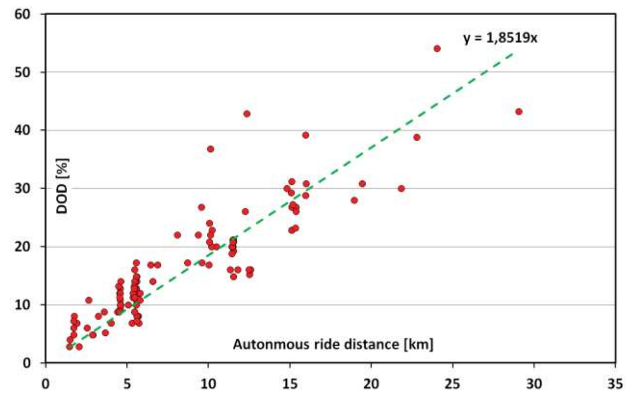


Fig. 6 Dependence between the length of autonomous drive and battery discharging resulting from it

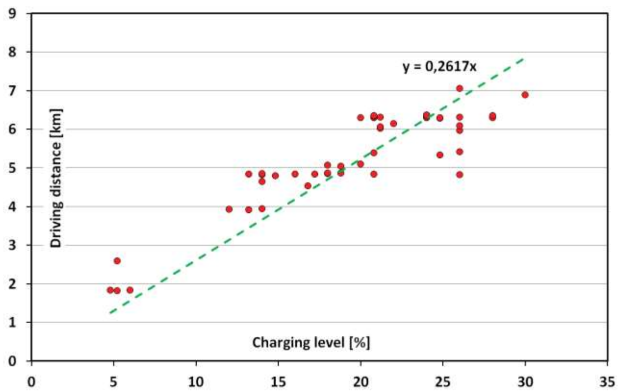


Fig. 7 Dependence between the degree of traction battery recharging and the distance required for battery recharging

Based on the conducted theoretical estimate and measurements, it can be stated that this value falls within the range 22% to 46%, depending on technical and operational conditions (Fig. 8). Taking into consideration the development of battery technologies and the necessity to dimension supply systems with a safety margin, the results obtained for the current of 200 A and energy consumption in wintertime should be regarded as reliable. Therefore it is suggested to assume the following guidelines for boundary conditions when designing the IMC systems:

1) Minimum coverage of a public transport route with catenary should be 33%. Due to the possibility of disturbances occurring in traffic or of the energy consumption increasing above the normative value, the terminals should be equipped with a system allowing for charging traction batteries in emergency situations (unless there is catenary at these terminals). Moreover, the route should be additionally verified with regard to the time needed for a vehicle to cover a catenary section in relation to the total travel time, which should be at least 33%. This would allow for avoiding the situation where the velocity of a vehicle moving along a catenary section is much higher than in the case of a catenary-free section, which would make it impossible for the batteries to be charged up to the required level. Such situation may also occur when a catenary section is located along dedicated traffic lanes, while a catenary-free section is located in a congested district of the city.

2) If the above conditions cannot be fulfilled, then the minimum catenary coverage of 50% should be assumed. This is the situation where there is no possibility either to charge vehicles at terminals or to extend the stopping time for charging purposes.

3) If the catenary coverage is at the level of 30%-32%, modification of the public transport route should be considered, so as to extend the catenary section.

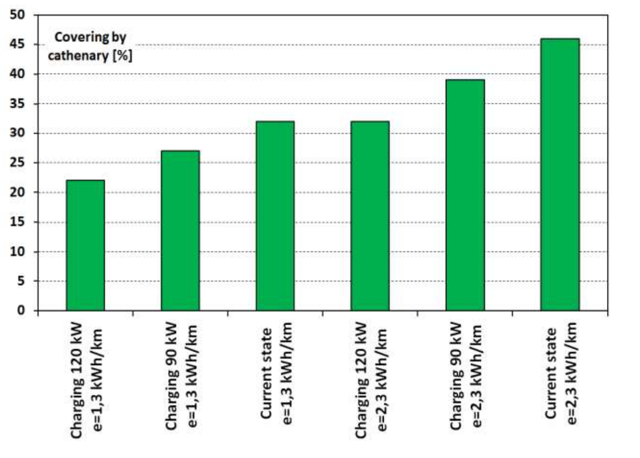


Fig. 8 Minimum catenary coverage for various operational conditions and charging conditions

## 2.4. Schedule Operation of Trolleybuses on Line 29

The concept of servicing Fikakowo with trolleybus appeared in 2005. Initially there was planned to build a trolleybus overhead line, however difficult terrain conditions (narrow streets) and opposition of some residents slowed down the design. With the introduction of trolley batteries with NiCd batteries in 2009, the concept of the line on Fikakowo [11] with traction batteries using was proposed again. Due to insufficient technical parameters of batteries, it would be necessary to build a traction cathenary on the part of the route. The introduction of trolleybuses with Li-Ion batteries enabled trolleybus to operate without the need for a overhead cathenary lines.

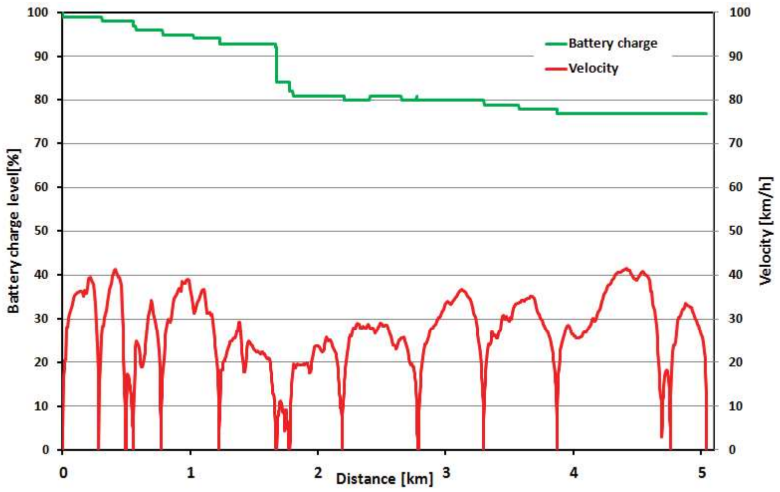


Fig. 9 Example battery driving registration for line 29

Fig. 10 Charging of traction batteries from 400 VAC grid on a terminus

Line 29 is an all week line. The section without traction network is 3 km long (1,5 km one way), however, due to the limitations resulting from automatic connection to the traction network, battery mode is 5 km long. Fig. 9 shows an example of battery work registration. The battery is discharged around 20%. The registration was made in January 2017 at a low outdoor temperature and a strong heating operation. This results in significant power consumption for heating purposes, which results in significant battery discharge during stay in terminus. In summer conditions, the discharge rate of the battery will be much lower. The Fikakowo loops also is equipmented with 3 × 400 V AC charging station (Fig. 10).

## 3. Slide–In System in Landskrona

On 27 September 2003 a completely new trolleybus system was opened in Landskrona (Sweeden), which received the number *3* in the existing public transport system. It connected the new railway station, the city center and the harbor. Length of line was 3 km. Originally operated by *3* Solaris Trollino 12 trolleybuses produced in cooperation with the Hungarian GANZ company [1, 4].

The trolleybus line proved to be a very good solution and quickly became the backbone of the city's transport. The increase in passenger traffic caused the decision to purchase a fourth trolleybus, that was put into service in 2010. There have also ideas to extend the trolleybus transportation system. However, the small transport operation on the bus lines made unprofitable extension of the traction network. The solution of this problem was an auxiliary drive that enabled the trolleybus to move on sections without traction cathenary [6]. This project was made possible by the SlideIn project.

Slid-In is funded by the EU's LIFE + program. The main partner in the project is the University of Lund. The other partners are: Skånetrafiken, ÅF (Landskron transport operator), Motivationshuset, Volvo Powertrain and E.ON [13]. The budget was estimated at 1.6 million euros, and its implementation time is September 2011-December 2015. The task of the project was to make the SlideIn's electrobus, test it in operation and evaluate the results. Due to geographical localisation and favorable conditions, it was decided to operate the electrobus in nearby Landskrona and to use its trolleybus network for charging (Fig. 12).

The vehicle was designed as a standard trolley bus with enlarged traction batteries enabling the vehicle to move on a section without traction. The power source is lithium batteries with a capacity of 54 kWh and a voltage of 450 V (Table 2). They allow the run 20 km without supply from cathenary. The schematic diagrams for lines *3*, *4* and *5* are shown in Fig. 11. Trolleybus was designed to operate on bus lines *4* and *5* in the following work regime:

1) trolleybus service on line *3*, charging from trolleybus cathenary, trolleybus goes two cycles (Fig. 11, red line);

2) operation on bus lines *4* and *5* powered from traction batteries (Fig. 11, black and orange lines).

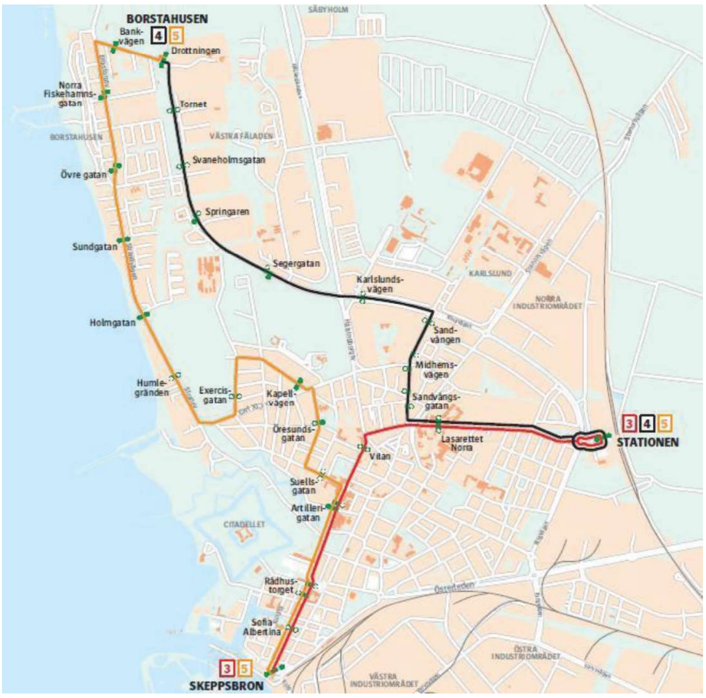


Fig. 11 Trolleybus system in Landskrona, line *3* - standard trolleybus line; lines *4* and *5* - battery operation [14]

During daytime operation, 70% of the total operation distance are powered by traction batteries, and only 30% of the trolleybus is routed using the overhead contact line. The operation of the trolleybus has fully confirmed its strengths. Line coverage of only 30% of the length of the traction network enables operation in electric mode. The maximum discharge of the battery has been observed at 40%, which means that there is sufficient storage capacity in case of traffic disturbations.

Fig. 12 Slide – In trolleybus in Landskrona

## 4. Summary

Despite the fact that the number of cities exploiting electric buses in urban transport is increasing, the existing systems are test systems, and there is still no agreement among the users with regard to optimal and universal solution for electric buses. The issue of charging is one of the biggest problems. On the other hand, trolleybus transport in numerous cities is considered to be outdated. The In Motion Charging system makes it possible to combine the advantages of trolleybuses and electric buses.

The IMC system makes it necessary for only 33%-50% of the route to be electrified. What is more, in case of common sections on many public transport routes, there is a possibility that the overhead contact line is used by vehicles operating on a number of routes. This solution is particularly suitable for the existing trolleybus networks and allows for more effective utilization of the infrastructure. Moreover, in many cases it may be justified to construct brand new public transport systems based on the IMC, particularly in connection with using dedicated traffic lanes for buses.

Slide-In system in Landskrona and 29 line in Gdynia are ready to use examples of modern city transportation systems. Hybrid battery trolleybuses are alternative for pure battery buses or diesel hybrid busses. Especially the have can be implemented in cities, which exploit trolleybus systems. What is more, in the cities where tram network is already exploited, there is a possibility to use the elements of the tram infrastructure when constructing the catenary for the IMC system.

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