Hybrid buses with continuous energy transfer from tram network

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Abstract
Expanding cities need to cope with significant challenges to provide good mobility, while at the same time minimizing congestion, emissions and noise. Compared to combustion vehicles, electric vehicles have higher energy efficiency, reduced local emissions and are quiet, and can therefore ease the above challenges. Unfortunately, the energy density in batteries is relatively low; therefore they would be both expensive and heavy to achieve a corresponding range of conventional vehicles. This case study has therefore examined the possibilities, ambiguities and requirements for utilizing Gothenburg’s existing tram network as energy source for en-route charging of buses. A conceptual technical solution has furthermore been presented to enable the connection to the tram network. It is also recommended to implement smart control of the vehicle’s energy consumption in order to optimize the network power utilization without additional infrastructure investments.

KEYWORDS:
Hybrid bus, en-route charging, tram infrastructure.

Introduction
Expanding cities need to cope with major challenges for creating and providing sustainable mobility for all groups in the society. Cities also need to minimize congestion, air emissions and noise to reduce environmental impact. The transport sector is one major cause of the problem and needs to be changed in order to achieve increased sustainability. Compared to conventional vehicles, electric vehicles have improved energy efficiency and greatly reduced local emissions. Therefore, electric vehicles have high potential to contribute to a solution to the urban challenges and reaching a higher degree of sustainable mobility.
Unfortunately, the energy density of batteries is relatively low compared to traditional fuels; a battery capable of providing a range equal to a conventional vehicle’s would have to be both expensive and heavy, especially for public transport vehicles with long daily mileage. For urban public transport buses, with an electric drivetrain, the battery size could be reduced if charging is available frequently at bus stops. This has been demonstrated in several cities with different technical solutions, where the buses are charged while standing still [1][2][3][4]. However, if charging requires the vehicle to be standing still it affects the timetable, decreases value adding time and possibly also implies costly new or adapted charging infrastructure. A proposal is instead to use an existing tram network, like the one in Gothenburg, as a source of energy to enable buses to charge also while driving, known as en-route charging. In Gothenburg today, buses already share the same lanes as the trams during parts of the routes. If buses were charged via the existing tram network, the investment need for new charging infrastructure could be kept low and the vehicles could be operated for a longer time in electric mode. Where en-route charging is not possible or adequate, the vehicle may use energy from the on-board battery or the internal combustion engine, favourably complemented with extra charging at bus terminus.

En-route charging of a bus with rubber wheels is proposed to be made possible by using a custom pantograph, called a current collector, to connect to the overhead line, see illustration in Figure 1, and a current return arm to connect to the rail. The technical solution is a combination of technologies used for trams and trolley buses. It is reminiscent of trams that are normally connected to the overhead line through a pantograph, however with the difference that the current is fed back via a current return arm connected to the rail instead of through the metal wheels. What distinguishes this bus to a trolley bus, apart from being capable of follow a tram network, is the flexibility added by not being bound to a certain route.

![Figure 1: Fictive illustration of a bus with a tram pantograph](image)

The case study [5] described in this paper aims at exploring the possibilities and investigate as far as possible the ambiguities and requirements for utilizing the Gothenburg tram network as...
an energy source for en-route charging, in order to increase the electric range and reduce the need for energy storage in batteries. The paper’s emphasis is on describing the devices needed to connect to the tram network, the bus prerequisites and the infrastructure constraints.

In the following chapters of this paper, the term bus describes a bus with a fully electric or hybrid electric drivetrain used for propulsion. In this specific case study, a hybrid bus has been used, however the technology is applicable for other types of electric vehicles as well.

**Methodology**

The paper has followed a case study methodology [6] with the goal of solving a real-world problem where the user’s need of the application is in focus. A case study explores a particular subject of interest in a “real life” context from multiple perspectives [7]. The study usually involves the phases; defining research question; determining data gathering and analysis techniques; data collection; evaluating and analyzing data; and result sharing [6].

The case study method used in this paper is inspired by the action research methodology, which is a process where participants works together to link action, theory, practice and reflection in the search for practical solutions to problems that concern people, individual persons and communities [8]. The work process followed, in this particular case study, is described in Figure 2.

![Figure 2: Work process for the case study in Gothenburg.](image_url)

The initial phase in case studies is to define the research question in order not to be overwhelmed by the volume of data [9]. In this study, the research question was defined based on the identified demand for an increased number of electric vehicles to reduce pollution and noise in the city center.

Next, a consortium of experts and stakeholders were set up to the assignment. The ambitions were to include entities with expertise within several disciplines ranging from a technical level up to an overall system perspective both on the vehicle and the infrastructure side. A system solution was identified through discussions and verified against regulations and
descriptions of closely related technologies. To define subsystem requirements and prerequisites, each partner prepared to gather additional data implicating the system solution.

The participating expert group consisted of engineers from heavy vehicle industry, institute researchers from the electromobility field, a strategist for environmental questions within the local public transport company, and representatives from the Transport authority in Gothenburg. Subsystem requirements and prerequisites were generated based on an analysis of the identified areas: case study vehicle capabilities, conceptual technical components for current collection, vehicle classification, infrastructure limitations, and other unidentified impacts of the new type of vehicle. A Volvo 7900 Hybrid was used as reference vehicle in the case study. The participants used the results in order to develop a technical solution but also to revise the system solution when necessary.

Data was collected during approximately six months. The technical solutions were based on interviews, existing solutions for closely related applications and literature studies. The physical meetings with participants are listed in Table 1. Open-ended questions were prepared for the meetings to identify possible solutions but still allow unrestrained and free responses as all potential implications and restrictions to the new technology were not known beforehand.

Table 1: List of the physical meeting with participants held during the study.

<table>
<thead>
<tr>
<th>Post</th>
<th>Entity</th>
<th>Type of interview</th>
<th>Date 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategist environmental questions</td>
<td>Västrafik (local public transport company)</td>
<td>Discussion, Brainstorming, Emails</td>
<td>June</td>
</tr>
<tr>
<td>Senior Manager Public Affairs</td>
<td>Volvo Buses (heavy vehicle industry)</td>
<td>Telephone meetings, Open ended interviews</td>
<td>August September November</td>
</tr>
<tr>
<td>Senior Product Manager Global Product and Marketing</td>
<td>Volvo Buses (heavy vehicle industry)</td>
<td>Open ended interviews, Emails</td>
<td>September November</td>
</tr>
<tr>
<td>Senior Product Manager Electromobility</td>
<td>Volvo Buses (heavy vehicle industry)</td>
<td>Open ended interviews</td>
<td>September November</td>
</tr>
<tr>
<td>Electrical System Engineer</td>
<td>Volvo Buses (heavy vehicle industry)</td>
<td>Telephone meetings, Emails</td>
<td></td>
</tr>
<tr>
<td>Signal planner</td>
<td>Trafikkontoret (the transport authority)</td>
<td>Structured interviews, Brainstorming, Emails</td>
<td>June August</td>
</tr>
<tr>
<td>Traffic planning</td>
<td>Trafikkontoret (the transport authority)</td>
<td>Discussion, Brainstorming, Emails</td>
<td>May</td>
</tr>
</tbody>
</table>

Some meetings were held together with several experts in a workshop environment in order to capture the expert’s common experience and best practices. In addition to the interviews, the interviewees had the possibility to describe additional conclusions in text to avoid misinterpretations and confirm data internally within the entity. The working process was
iterative with follow-up email conversations and phone meetings after the physical meetings. When a technical difficulty was identified that concerned the overall system solution, new work process iteration was started with a new revised system solution idea.

The following chapter presents the identified prerequisites and results for the proposed overall system solution. It is important to note that the concluded concept is in an early stage of progression and has to be experimentally verified by demonstration.

**Identified prerequisites and results**

*Current collector and current return arm*

Since the bus does not have metal wheels, a current return arm is essential to be able to follow the rail and complete the electrical circuit. Similar techniques have been developed to demonstrate how a truck can conductively retrieve power from a rail in the roadway while driving [10]. A current collector is required to connect to the overhead line above the vehicle. Today, the overhead line is positioned in a zigzag pattern (approximately ± 400 mm) from the imaginary centre above the rails to distribute the wear evenly on the contact strip of the current collector.

A current collector is therefore proposed, which resembles a tram pantograph, with lateral movability to compensate for the flexibility of the bus. The lateral movability could be achieved by adding additional two-way joints, as shown in Figure 3 suggested by Ranch and Snygg (2011) [11], or mounted on a linear drive. A flat and wide current collector, like the tram pantograph, ensures that the existing overhead line brackets, like in Gothenburg, could be used and do not need to be replaced.

![Figure 3: Design of an active current collector, suggested by Ranch and Snygg (2011)](image)

We also suggest dual current return arms underneath the vehicle to connect to the rails. Dual current return arms will enhance the contact, especially on a bumpy road or if there are objects on the rails. Dual return arms are also necessary to allow switches to function correctly. In Gothenburg today, some switches for changing drive path direction is configured
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In such a way that short-circuiting of the two rails could trigger the switch. On trams, the metal wheels are used to short-circuit the rails. For a bus, short-circuit needs to occur through the current return arms, unless there is an alternative communication method to change the drive path direction.

The current return arms should ensure a connection to the rails before contact with the overhead line is established. This provides protection against a potential difference to occur in the vehicle towards the ground, which otherwise could be a risk if there is a connection to the overhead line and a failure in the insulation. The current collector should correspondingly be lowered automatically if the current return arms have lost the connection to the tram rails. For safety reasons, the current return arms may not protrude from the vehicle side, as this could be dangerous for pedestrians. A current collector could, unlike the current return arms, protrude from the side of the vehicle since it is not estimated to harm neither people nor the surrounding environment, as it will have room within the normal path of the tram pantographs.

Sensors are needed to identify the rails and position the current return arms. The sensor information about the rail position in relation to the bus could also be used to calculate the approximate position of the overhead line. Positioning the current collector close to an imaginary centre above the rails, regardless of the bus's position could avoid the risk of tearing down the overhead line, see Figure 4. To further protect against an overhead line accidently being torn down, for example when the bus makes a sharp turn and crosses the overhead line in the opposite direction, a maximum allowed angle between the bus’s driving direction and the rails should be implemented. If the angle is exceeded, the current collector should be retracted.

![Figure 4: Current collector guidance based on the position of the current return arms.](image)

It is also proposed that, on a rigid bus, the current collector and current return arm should preferably be placed aligned with each other near the rear axle of the bus. The rear of the bus
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follows the rails better than the front part, particularly in curves, as the bus needs to take a wider turn to compensate for the vehicle length.

Vehicle requirements

The electronics and batteries on board the bus are sensitive and could be damaged if it is supplied with wrong voltage or current. Using the tram network for continuous power supply to the vehicle without any filter or converter would imply that the vehicle is subjected to a high degree of voltage fluctuations. Fluctuations in the tram network can occur when a tram accelerates, which results in a voltage drop, or when a tram brakes and feeds back energy. High current or surge due to a short circuit or lightning strike could also affect the vehicle. Another difficulty with en-route charging, is maintaining a continuous contact to the rails and overhead line. A bad connection can result in disturbing sparks and risk of unintentionally retracting the pantograph. This is also true to some extent for trams but would especially be the case for the more flexible bus.

As a result, two major subsystem requirements were identified in order to retrieve the energy from the tram network for continuous charging of the bus. The first requirement is to ensure that the vehicle and the energy storage system receive accurate and continuous voltage and current. The second requirement is to ensure that safety requirements are fulfilled for proper grounding and insulation.

To comply with the subsystem requirements it is therefore proposed that dual layer insulation or more should be mandatory to assure isolation between chassis with 600 V components and the bus’s body. On trains and trolleybuses today, all components are at least double insulated to ensure that anyone who touches the vehicle is not exposed to an electrical shock. In practice this means that the high voltage components on the vehicle are contained within an insulation envelope surrounded by the component casing. The principal difference between the Volvo hybrid bus and a bus that could connect to the tram network is described in Figure 5. During en-route charging voltage converter with galvanic separation on board will also be a necessity to manage and control the voltage levels and voltage fluctuations according to the requirements of the electronic components. The galvanic separation is required to isolate the bus chassis from the body and thus protect passengers and other road users in case of failure in the insulation. Additionally, filters and super capacitors need to be taken in consideration for this type of charging to compensate for any temporary connection losses. As it is today with vehicles that are only adapted for stationary charging at dedicated charging stations, the components for insulation and the system for monitoring the insulation (IMS) are placed instead inside the infrastructure and are not required on each vehicle. A vehicle adapted for en-route charging will therefore be more expensive due to the additional components.
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![Diagram of hybrid bus with continuous energy transfer](image)

**Figure 5**: Left: Schematic diagram of a bus with double isolated components connected to the tram infrastructure. Right: A hybrid bus with the power regulated at the charging station where any current leakage is continuously measured and monitored.

**Supply based energy supply to vehicle**

Of the approximately 60 rectifier stations in operation in Gothenburg today, there are several which have daily problems with temporary or thermal overload. The load on the 750 V grid increases heavily during spikes of up to 10 to 15 seconds when a large amount of power is required for acceleration of the heavy trams. A single tram can require up to 850 A during acceleration. The relay protection in the rectifier station for temporary overcurrent is usually between 1500 and 2000 A with an instantaneous protection usually around 2500 A. However the feeder cables become overloaded already at about 300 to 350 kW of continuous power output. To diminish the risk of overloading the infrastructure, it is preferable that the bus charges during movement with low power, approximately 30 kW to 50 kW (roughly 70 % to 80 % of the route), rather than intermittent charging at bus stops with higher effect levels of 100 kW to 200 kW. The battery need and cost could also be reduced if the energy is not stored on board the vehicle.

To increase the possibility to introduce additional vehicles in the existing tram network we suggest using information and communication technology. Today there is no continuous communication between the tram infrastructure and the vehicles that regulates the vehicle power consumption. By communicating a rectifier stations’ load in real time, the vehicle’s power demand could be limited to the available power capacity. With smart control of the vehicle power, the tram network could be optimised based on the total available energy capacity instead of the expected maximum current demand. This solution would prevent rectifier overload and shutdown, but with the consequence of occasionally affecting the
vehicle acceleration. The amount of reduced vehicle acceleration will be situation dependent. With increased vehicle intelligence, the energy from the tram network could be used when available and internal energy storage when needed, without the need for infrastructure expansion.

Each vehicle receives the rectifier stations’ load level information via a server that collects all data from the rectifier stations in real time. The bus will need an installed computer unit, which continuously receives data from the measurement server and adjusts the power demand. The communication between the buses and the rectifier station/measurement server is performed with the appropriate wireless technologies such as high speed telecommunication with prioritized traffic or guaranteed access time.

Discussion
This paper proposes a novel solution in order to electrify to a higher degree the public transport system in the city of Gothenburg, using already existing infrastructure. The benefit of using the existing tram network, also for vehicles other than trams, is that an increased number of electric vehicles can drive an increased distance while keeping the infrastructure costs low.

Since this has been an academic study, future work should focus on demonstrating the proposed system solution, including the capability of the current collector and current return arm, to verify en-route charging from the tram network. The proposed current collector is similar to a general tram pantograph. The tram pantograph technology has been known for a long time and is no longer protected by any patent. This, together with the technology for lateral movement that is accepted for trolleybuses, simplifies the possibility to demonstrate and commercialise the technology in the future. To the authors’ knowledge, the current return arm has not been used in this type of application and will likely require more extensive development. A possible starting point could be to build on technology developed for highway en-route charging.

Retrofitting an existing Volvo hybrid bus with a voltage converter, functionally similar to those implemented in the infrastructure, would probably be a huge and costly intervention today. Looking ahead, there is a possibility that additional alternatives will be developed for dynamic charging of buses in urban areas. If it would be demanded that buses have to be equipped with safety insulation and voltage converters like the bus described in this paper, the technology could be shared. This would greatly reduce the additional cost and threshold for dynamically charging the buses from the tram network. Providing a trolleybus with the necessary equipment to connect to the tram network is one option to perform early demonstrations since the insulation technology needed is already standard in this vehicle type.
The Gothenburg tram network is by today's standards already peak overloaded at some locations. Fewer outages due to overload could be achieved with continuous monitoring, communication and smart control of the tram and bus’s power utilization. The smart control should be based on the rectifier station’s momentary load. By reducing the risk of overloading the rectifier stations, the tram network could also be utilized to a greater extent. This type of communication could be useful already in today's tram network regardless of whether buses are utilizing the same external power supply or not. As a result of the smart control, vehicle acceleration will occasionally be limited. This could be a possible implication and must be studied further.

**Conclusions**

Preconditions and requirements for an environmentally friendly transport mode, with energy supply from existing tram infrastructure, have been presented. Technical solutions have been proposed to enable a moving bus to charge from Gothenburg’s tram network. It is suggested to use information about current return arm position to determine the correct current collector position towards the overhead line. Furthermore, to utilize the existing tram network capacity to a higher degree, it is proposed that there is continuous monitoring and communication of the rectifier load and smart control of the vehicles’ power utilization. The concept investigated and proposed in this paper has not yet been experimentally verified and further demonstration is therefore recommended.

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**References**


