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A Practical, 70-90% Electric Bus without Overhead Wires

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Abstract

Lithium titanate (Li4Ti5O12 or LTO) batteries have two properties that enable a new type of urban bus system: rapid charging and long cycle life. By placing a rapid charger at both ends of a bus route, LTO equipped hybrid buses can run most of the time (70-90%) in electric-only mode. A rapid charger fills the batteries each time a driver reaches the end of route. Existing hybrid diesel-electric buses with backup diesel generators are used to prevent stranding. This Rapid Charge Hybrid (RCH) approach requires virtually no changes to existing hybrid bus designs or fleet behavior, and requires little additional infrastructure.

Keywords: bus, fast charge, public transport, series HEV, lithium battery

1 Introduction

Recent advances in battery technology are enabling novel solutions to existing problems. A rapid charge hybrid (RCH) system which allows urban transit buses to substitute electricity for diesel in a practical manner using existing technologies with minimal changes to existing fleets is described here. If the electricity comes from renewable sources such as wind and solar, then RCH is a sustainable transit system.

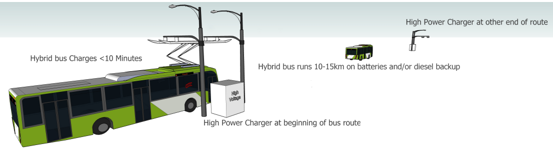
1.1 Background

Using electricity to power urban bus fleets is a proven, well researched technology. In the past almost all successful electric buses have used overhead wires (trolleybuses) to provide electric power. While this has worked well, it has become politically difficult to convince cities to erect the required network of overhead wires. In fact, many trolleybus systems have been dismantled and replaced by diesel buses, and only a few new trolleybus systems are being proposed. However, trolleybus fleets have many documented advantages compared to diesel bus fleets. These include fewer public health impacts, less noise, less pollution, and improved sustainability.[1]

Combining the flexibility of diesel buses with the advantages of electric buses has long been an elusive goal with several attempts having been made in the past[2]. However, with the new nano technology lithium titanate (LTO) batteries, this goal can now be realized easily, with minimal design risks and few changes to fleet operations.

2 System Description

The proposed RCH system is simple. High power opportunity charging stations (~250kW) are added to the end of a bus route, and serial diesel-electric hybrid buses with LTO batteries are deployed. When the driver stops for his “layover” time of 5 or 10 minutes at the end of the route, the batteries are rapidly charged. With the extraordinarily rapid charging ability of these batteries, it is possible to pump enough charge into the batteries in this time to run a route of 10 - 15km in the “electric-only” mode of a serial hybrid bus. Secondly, the long cycle life of LTO batteries permits a practical battery lifetime.[3]



This system uses a normal serial hybrid bus with LTO batteries substituted for the usual traction batteries. This means that if the bus runs out of battery power, the hybrid diesel generator can take over to run the bus indefinitely on diesel alone. These non-battery exceptions might occur, for example, if the driver is running late and doesn't have time to charge, or if it is a hot day and the air conditioner is on. If the system is sized so that normally the bus can run 100% in all-electric mode, then including exceptions, the bus should easily run 70 – 90% in all-electric mode overall.

Opportunity charging is practical in urban bus systems because of their fixed routes. Other systems with fixed routes such as refuse trucks should also be able to apply this system.

3 Advantages and Disadvantages

3.1 Advantages

- Converts a 100% diesel hybrid bus to a 70-90% electric bus, with all of the attendant, well-documented benefits of electrification.[4]

- Infrastructure is tiny compared to that of a trolleybus or tram system: just two small charging stations at each end of the route. Only a relatively small amount of construction or planning is needed, with no overhead or under-vehicle wires required along the route.

- Uses existing technologies with very little engineering cost or risk. Suitable hybrid buses already exist[5], as well as the required high power chargers[10]. Large LTO battery cells with the needed specifications are commercially available now[3].

- Buses use current diesel fueling infrastructure. The operator can run the same routes and schedules as current diesel buses. Charging is done at the route ends, where ordinarily there are no passengers. Passengers will never have to wait while the bus is being charged at intermediate stops. Additionally, if a charging stop is missed, the bus can continue indefinitely using the diesel generator.

- Integrates easily with existing diesel bus systems, especially if the system already uses hybrids. The operator can gradually add more RCH buses over time, phasing out pure diesel buses or non-chargeable hybrids as they age.

- Additional power for accessories such as air conditioning on hot days is always available from the backup diesel generator. The batteries and charging system can therefore be sized for normal days.

- Flexible trade-offs between electricity and diesel can run the full spectrum. An operator can decide to weight his percentage usage of electricity anywhere from 0 – 100% by changing how much layover (charge) time is built into the bus schedule.

- Intelligent charging can be coordinated with the electric supplier to avoid charging when there is a high electrical demand, and diesel power can be substituted during these peak times.

3.2 Disadvantages

- The bus charges during the day at full day electrical rates in competition with many other electrical users. However, this system is true for trams, electric rail, and trolleybus systems as well. This can be alleviated by coordinating charging with the electric utility to avoid or reduce charging during peak demand periods.

- Power draw is very high (>200kW), intermittent, and will likely be located in outlying residential areas where bus layovers already exist. It is likely that power substations will be shared with residential users, so care must be taken that there is enough capacity in the substation to handle the added load. Potentially, batteries, flywheels, or other storage devices could be located at the charging station to even out the load.

- Battery replacement. While these batteries have a very high cycle life, they need to be replaced when they lose capacity. However, since these are serial hybrid buses, and can run in hybrid mode whenever needed, the operator can decide at what point (80%,70%, 50% capacity loss) to replace the batteries.

4 Comparison Relative to Other Urban Bus Transit System Types

4.1 Compared to Diesel

Fleet operations for the RCH system are very similar to current diesel fleet operations. They can use the same diesel fueling infrastructure, routes and timetable. The only difference is that the drivers will stop at a rapid charger at the route ends during their layover time whenever possible. Adding this small change results in a shift from 100% diesel to 70-90% electricity use.
Converting from diesel to an RCH system shifts a bus system from using 100% diesel fuel to one using primarily electricity. No large electrical infrastructure, overhead or roadbed wires, route changes, or changes to fleet operations are required.

4.2 Compared to Hybrid

Hybrid buses have been shown to be anywhere from 10 – 30% more fuel efficient than pure diesel buses[5]. This reduces the amount of local pollution as well as CO_2 emissions by the same percentage. However, they are still 100% powered by diesel.
Adding LTO batteries and rapid charging to a series hybrid converts it to a RCH bus. This relatively simple change converts a 100% diesel bus to a 70%-90% electrically powered bus.
Additionally, hybrids currently cost considerably more than diesel buses, which reduces their attractiveness to operators. Changing to RCH will make hybrid buses much more attractive to municipalities and bus operators, accelerating the transition to sustainable public transportation.

4.3 Compared to 100% Battery Buses

The RCH battery size is much smaller than that required for a 100% battery bus that is charged only at night. Since the battery is charged every hour or so, the battery can be sized for a one hour runtime instead of 18 hours. If a bus runs 18 hours a day, the battery can be 1/18th the size. This translates into tremendous cost and weight savings. Unlike a 100% battery bus, an RCH bus cannot be stranded by running out of battery power. The diesel generator is always available to run the bus. This might be necessary if routes are temporarily changed due to an event, if there is a power failure, or if the charging stations malfunction.
Accessories such as air conditioning (A/C) and heating can be run without worry. On very hot days the diesel generator can run to provide enough power for the A/C.

4.4 Compared to Plug-in Hybrid

Charging a battery dominant hybrid vehicle at night makes sense for cars or light duty cycle buses like school buses. However, for a bus that runs 18 hours a day, 7 days a week, storing enough electricity to run all day would require more than 360kWh. A lithium battery (100Wh/kg)[6] of this size would weigh about 3600kg, whereas the equivalent fast charge 20kWh would weigh 18x less, or 200kg. This difference is equivalent to almost 68 100kg passengers.

The RCH system is similar in principle to a night-time plug-in hybrid, with the difference being that charging occurs much more frequently with the RCH system. With this frequent charging, a heavy duty bus can run most of the time in all-electric mode, without having to carry enormous batteries.

4.5 Compared to Trolleybus and Tram

An RCH system has no overhead wires or large electrical infrastructure. Avoiding the political issues of adding a network of overhead wires makes an RCH system much easier to sell to a community than a trolleybus or tram system. Besides much smaller initial planning and investment costs, the expensive maintenance of the overhead wire network is also avoided. Routes can be changed much more easily since there is no fixed track or overhead. Due to this lack of infrastructure, an RCH system achieves close to 100% electric transit (70-90%) operation much more easily and quickly than building a trolleybus or tram system.

Trolleybuses do have some advantages however. They are 100% electric, handle steep hills well, and do not require the added weight and complexity of a battery pack and backup generator. In areas where it is possible to set up the overhead wires, trolleybuses and trams may still be preferable to an RCH system.

4.6 Compared to Super Capacitor and Flywheel Buses

There have been several attempts to create a similar system using either super capacitors[7] or flywheels to store energy, with rapid charging occurring at intermediate stops. More frequent charging is required for these systems because of the lower energy storage capability of super capacitors and flywheels.

The advantage of super capacitors and flywheels are their very fast charge time and practically unlimited number of recharges. The disadvantage is more frequent charging which means more charging stations. More stations means more infrastructure, more planning, less route flexibility, and possible route slowdowns if a bus has to stop to charge, even if there are few passengers boarding. The bus will still need a backup generator in case of a missed charge, or a large A/C load.

5 Enabling Technology

5.1 LTO Batteries

LTO batteries are the critical advance that makes this system possible. While LTO batteries don't have the energy storage capacity of some other lithium chemistries[3][6], it is their properties of rapid charging and high cycle life that make the RCH system practical. These batteries are available today, and charging tests using large 35kWh packs [8] have shown that sustained high rates of charging and discharging are possible using conventional thermal management techniques.

Even with the very low internal resistance of LTO batteries, it is very important to control cell temperatures to increase battery lifetime. High temperatures will reduce cycle life[3], while low temperatures reduce cell capacity. Large 600V packs of 50aH AltairNano cells (35kW) that control temperature at the cell level have been cycled rapidly using symmetric fast charge and discharge hundreds of times with no problems. According to the test engineer[8], temperature rise is actually greater during the discharge portion of the cycle than during the charge portion. Since an RCH bus will have a much longer discharge time than charge time, this should pose no operational difficulties.

5.2 Serial Hybrid Buses

The other critical enabling technology is the design maturation of serial hybrid buses. A great deal of engineering has gone into making these buses cost-effective, efficient and reliable. Combining these road-tested buses[5] with LTO batteries and rapid charging stations is all that is needed to build an RCH system. Indeed, adding rapid charging to an existing serial hybrid bus makes for a much better value proposition for bus manufacturers, and should increase their hybrid bus sales substantially. Note that only a hybrid bus that can operate for long periods in “electric only mode” can be used as an RCH. This feature is typically found only in serial hybrid buses as opposed to parallel hybrids.

6 Design Considerations

6.1 System Sizing

For the RCH system to work, it must be possible to transfer a large amount of electricity to the batteries in a short amount of time. In Granada, Spain, for example, it is typical for buses to stop at their layovers around 7 – 12 minutes[9] in order to maintain schedules and minimize “bunching” of buses.

In studies with trolleybuses, typical urban electricity usage is about 2kWh per km[1]. Therefore, if a bus route is 10km, this means that about 20kWh of power needs to be transferred for the bus to run a 10km route on electric power. If we assume a layover time of 8 minutes (0,13 hour), then to transfer 20kWh of power would require a charging power of

20Wh / 0.13 hour = 150kW

If the traction battery voltage is 500V, this then implies a current of

150kVA / 500V = 300A

This amount of power transfer is well within the operating range of modern chargers[10] and current collectors[11]. If a 50Ah cell is used, 300A corresponds to a 6C rate. Published specifications from Altair Nano[3] and full pack testing from EBus[8] indicate that a 6C charging rate is readily achievable in large battery packs using conventional cooling techniques.

6.2 Charging Station

There are a number of possibilities for charging the bus at the route ends, ranging from manually operated plugs to more complicated automated in-roadbed or overhead connections. Power transfer can be either conductive or inductive.
DC chargers of the required size are already commercially available[10].
The charging process is normally controlled by the bus CPU rather than by the charger, since typically the bus CPU has access to the state of charge, temperature, and cell balance information from the battery packs.

6.3 Safety Considerations

Fortunately, LTO batteries have excellent safety characteristics[3]. Tests have shown that these batteries are immune to thermal runaway, and will not explode or catch fire in case of an accident.
The design maturity of serial hybrids, in-service use, intensive testing and regulatory scrutiny have made the serial hybrid a safe platform on which to add rapid charging. No major design changes are needed. One issue that must be addressed, of course, is the safety of the charging station, both the fixed roadside portion, as well as the on-vehicle portion.

7 Economics

7.1 Introduction

The economics of an RCH bus system are somewhat different than those of diesel bus systems and trolleybus systems, both of which have been studied extensively[1][5]. Essentially, an RCH system displaces fossil fuel (typically diesel) in exchange for additional bus cost, charging station cost, electricity cost and battery life. In order for an RCH system to be attractive to transit operators and municipalities, overall perceived cost (including indirect costs such as health and pollution) has to be less than the alternatives.
Usually RCH systems will be competing directly against diesel bus systems, so this analysis will compare the two.

7.2 Additional Bus Cost

Since the price of an RCH bus is essentially the same as currently available serial hybrid buses, we can use these for comparison. Using an LTO traction battery pack plus the vehicle portion of the rapid charging station will likely only add a minimal amount to the overall price of a serial hybrid bus.

Current Serial Hybrid Bus: ~500.000€
Current Diesel Bus: ~300.000€

7.3 Charging Station Cost

Each charging station will cost approximately 150.000 -200.000€. However, these stations can be shared by all the RCH buses on a route. If we assume that the time interval between buses is 10 minutes, this means that 6 buses will share the same charger(s). Assuming 2 chargers per route, this works out to be approximately 400.000/6 = 66.000 € per bus. Over time this may be less, as the charging station should have a greater lifetime than the buses.

7.4 Electricity Cost

This system essentially trades electricity and battery life for petroleum. If the example 6.1, 20kWh used 18 times in a day is assumed. This equates to 360kWh of electricity used per day. At a price of 0.15€ per kW, this results in a daily cost of 360 x 0.15 = 54€ per day

7.5 Battery Life Cost

Electricity is not the only consumable. Battery life is consumed each time the battery goes through a charge/discharge cycle. Unfortunately, due to the recent development of LTO batteries, reliable real-world cycle lifetime performance in a RCH system is not yet available. However, we are able to make some rough estimates based on published cycle life specifications.

7.5.1 LTO Battery Cycle Life Specifications

From the most recent specifications[3] for the 50Ah and 11Ah LTO cells from Altair Nanotechnologies, the following can be taken:

We are assuming using 50Ah cells, 6C charge/discharge using packs with good cell level temperature control at 25° C.

100% DOD 6C charge/discharge @ 25° Cycle Life: > 9000 cycles

7.5.2 Battery Cycle Cost

Assume a cost of 100.000 € for a 35kW battery pack, and cycle it 20kW each hour.

Since we are only cycling the battery about 60%, we can increase the expected 9000 cycles by this amount to 1/0.6 * 9000 = 15.000 cycles, which gives a cycle cost of 100.000/15.000 = 6.60 € per cycle.

If the battery is cycled 18 times per day, this gives a daily battery replacement cost of 120€.

Additionally, 15.000 cycles at 18 times per day gives an approximate battery lifetime of >833 days, or >2.3 years.

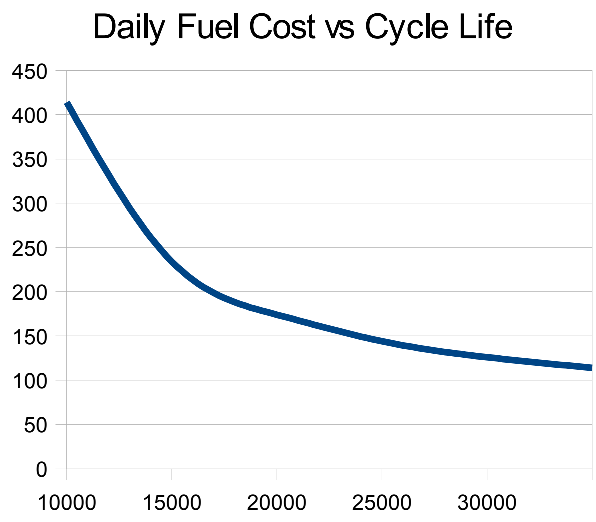
7.6 Comparable Diesel Cost

If we assume a diesel bus gets around 3.5 miles per gallon[5] (or ~ 1.5 liters per km), then at a diesel cost of 0.90 € per liter, and a route of 10km, a diesel bus would use 9€ each cycle, or 9*18 = €162 per day.

7.7 Fuel Cost Comparison

Adding the cost of electricity and cost of battery cycle life gives a daily cost of 54 + 120 = 174€ per day compared to the diesel cost of 162€ per day, making them comparable.

Note that while diesel costs and electricity costs are well known, the RCH system fuel costs are extremely dependent upon battery cycle life. Greater or lower cycle life has a dramatic impact on fuel costs. The following graph shows this dependency.



7.8 System Economics

If we assume that current fuel costs are comparable, but overall system costs are somewhat higher due to the higher bus costs and charger costs, then the decision to implement an RCH system would include indirect benefits such as improved air quality, less greenhouse gas emissions, lower street noise, better public health, energy independence, less price volatility, and energy sustainability.

8 Conclusion

A Rapid Charged Hybrid (RCH) bus system has all the well documented advantages of an electric bus system (trolleybus) but without any overhead wires. It is clean, quiet, displaces large amounts of petroleum, and is almost as easy to deploy as a diesel bus system.

While the best solution would be a 100% electric bus, this is impractical, since if a bus gets stuck in traffic with the air conditioner on, it can run out of power and be stranded. Instead, the RCH system uses existing hybrid diesel-electric buses which have a backup diesel generator that can provide enough power to run the bus on diesel alone if necessary.

This system leverages existing technology by adding LTO batteries and high power opportunity battery chargers to existing serial hybrid diesel electric buses. These buses already have electric drive and a diesel generator. All they are lacking is a way to rapidly charge the batteries at each end of the bus route. Adding this relatively simple feature converts a 100% diesel powered bus (hybrids still run on diesel), to a 70 - 90% electric bus.

Analysing fuel costs show that costs are more dependent on the cycle life of the battery than on the cost of the battery. High cycle life is critical, and if high enough, it is possible to obtain lower overall fuel costs than diesel.

As real-life experience demonstrates that these new batteries can live up to their promise of fast charging and high cycle life, RCH bus systems will be a major advance in sustainable public transportation, with virtually no changes to existing hybrid bus designs and very little design or investment risk.

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