

Design, calibration and real world data of an electric school bus

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Short Abstract

A fully electric school bus was designed, built, calibrated and tested in active service in Canada's northern climate. The vehicle, designed for the severe cold climate, is currently used to replace an equivalent diesel powered bus and is able to cover the same routes with similar performance. The emphasis of the paper is going to be on the calibration process to maximise driver "feel", allowing untrained diesel bus drivers to operate this EV with minimal adaptation. The paper will reveal real world data from continuous operation over a period of many months.

1 Introduction

Lion bus is a school bus manufacturer located in Canada. It has designed, from the ground up, a new vehicle in the past 5 years. This vehicle, in its diesel powered variant, already boasts a lot of innovative features unseen in this industry. From its composite material outer shell to its single piece roof, the company is already known to offer disruptive technology to this market.

Lion bus has given the mandate to the Innovative Vehicle Institute to be part of the design and prototyping team that lead to an all-electric version of its school bus. It has been built during the summer of 2014. The first units have already logged many thousands of kilometer of test and active revenue service. A second engineering phase has been carried out in the summer of 2015 to re-design the battery pack and optimize for large scale manufacturability of the vehicle.

This paper will cover the mechanical and electrical architecture of the vehicle, the calibration process, a summary of the acquired data over many months of operation, as well as the performance envelope and results of the ongoing on-road tests.

2 Architecture

2.1 Layout and speed gearing

The electric version of the bus retains most of the diesel counterpart frame and architecture. The most notable differences are the multiple battery packs located within the frame rails as well as the centrally located traction motor without any reduction gearbox. The rear axle differential serves as the only speed reducer between the high-torque permanent magnet motor and the wheels. This layout has been simulated compared to using an additional speed reducer or even a multi-speed gearbox. The usage of a heavier, larger, higher torque motor delivers enough efficiency gain to compensate for much smaller motor size possible by more mechanical reduction. The benefits of this direct drive topology has already been published during a Mobility Electric Canada conference as well as during SAE 2012 Electric Powertrain

Technologies Symposium [1]. Since battery quantity and therefore price is the major driver in the total cost of an electric vehicle, this topology has been selected to reduce the cost of batteries.

Table 1: Energy consumption in kWh/km in various cycles for a transit bus[1]

Cycles	ideal	Multi Speed	Single Speed	Direct drive
Manhattan	2,00	2.4	2.3	2.25
Orange county	1.52	1.86	1.81	1.70
UDDS HD	1.48	1.66	1.66	1.52
	100%	118%	115%	109%

All auxiliary components such as the DCDC converter, chargers, hydraulic power unit, etc are located under the front hood, in place of the diesel motor and transmission. This layout allowed to minimize modifications to the existing diesel powered chassis while promoting component accessibility.

2.2 Chassis deflection and vibration

The entire front plate that supports all of those components has been mounted on mechanical isolators to minimise vibration induced to those auxiliaries. This mechanical insulation also serves as a way to limit torsional efforts induced in the components. A FEA simulation was performed to assess the possible flex of the ladder frame. Since those vehicles have a high ground clearance and can often climb on curbs or other obstacles, a 3 wheel-down load case has been used. It is fairly possible to imagine such a bus with one front wheel off the ground during tight manoeuvres in school yards or during tight turns on centre divided boulevards. A maximum deflection of many centimetres has been accounted for. The same strategy to minimise chassis forces being propagated to components has been used to design the motor mounts. The motor support system has been designed to reduce vibration propagation to the chassis as well as eliminate stresses induced by chassis deformation. The all-aluminium permanent magnet motor must not transmit forces from one frame rail to the other and act as a rigid cross member.

2.3 Weight distribution

The location of the motor has been selected to free as much as possible space for batteries underneath as well as to move weight on the rear axle. The double wheel rear axle can be loaded up to 9500 kg compared to only 4500 kg for the front axle. A precise weight distribution must be observed to allow maximum payload, to carry as many children as its diesel counterpart.

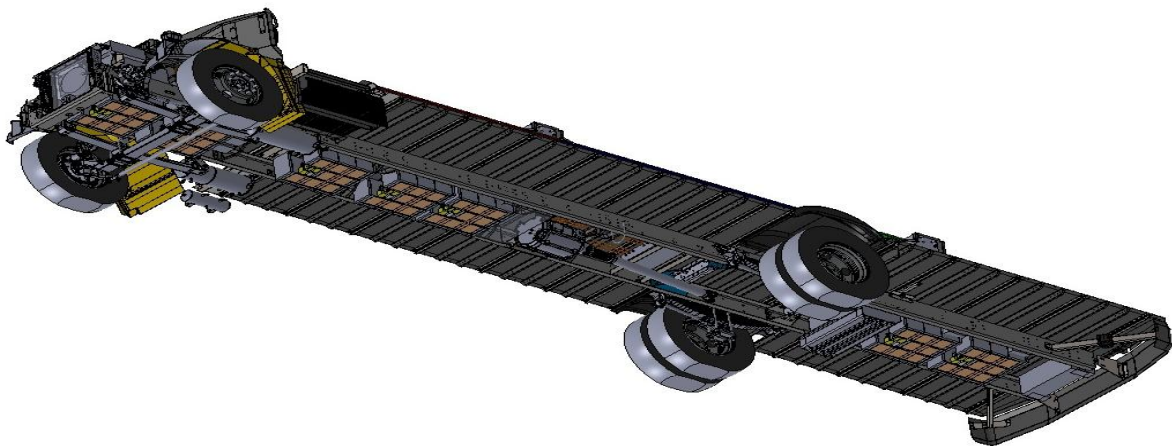


Figure 1: CAD of the first prototype, underside

3 Prototype simulation and sizing

3.1 Simulation

A reliable model of the diesel bus has been built using the Advisor simulator [2]. The model was perfected by gathering real route operations using an Isaac Instrument data logger. The exact road profile, speed as well as fuel consumption has been captured. From vehicle drawings, weight measurements as well as coast down test, the model was built. The same routes have been “played back” in the simulator and the model has been adjusted until outputs matched the captured power and consumption of the real bus. By using the same simulator, with an ideal battery and infinite motor, electric motor power and torque requirements have been determined. The participation of TM4 as a partner in the project has allowed to pick the most suitable motor in the direct drive line-up [3]. The exact power and losses maps of the selected motor and inverter have been used to model the drivetrain within the simulator.

3.2 Battery sizing

A target range and route type has been selected by the bus manufacturer to represent the toughest reasonable route for its electric bus. Running this route in the simulator with the correct drivetrain model allowed to assess the energy requirements, therefore the sizing of the battery. Simulations have shown a reasonable average energy consumption of 0.8kWh/km of operations, yielding a minimal usable battery pack of 80kWh for a 100km range. It is important to remember that school bus routes do not vary over time and are precisely known. Also, the long “down time” between the morning runs and afternoon runs allows for mid-day charging. The vast majority of school bus runs are less than 100km daily, but depending on the targeted route, some flexibility was needed. Since the battery pack architecture consists of parallel full voltage packs, they can be populated or not, depending on the intended range for that specific vehicle. It has to be noted that a single pack is not powerful enough to saturate the traction motor. Therefore, at least 2 packs must be installed. The final design allows for 2, 3, 4 and 5 packs of 26kWh usable to be installed, giving a usable range of anywhere between 65 km and 162km. The most common setup is targeted at 4 packs, giving over 130km of range. This range has been validated many times in the hilly region of the lower Laurentian, north of Montreal, by the Lion bus test driver. With this configuration, routes of 110km can be used with some reserve. The packs have been designed with a voltage range contained between 300V and 400V. This common voltage range allows the use to automotive components, typically less expensive than higher rated components. By running cycles in the simulator with a model of the actual cell used in the packs, the heat rejection has been precisely evaluated. With these numbers, the mechanical battery pack design team has been able to choose the appropriate cooling and heating scheme. Since the motor power versus pack capacity is a small ratio, the C-rates are fairly low. In the typical 4 pack configuration, a peak C-rate of 1.25:1 is the maximum possible. In automotive applications, a typical car has a motor of around 80kW and a pack of 24kWh, resulting in a C-rate of over 3:1. Since most battery losses are squared to the current and we operate at small currents, battery losses are very small. Therefore, a simple sealed forced air cooling scheme has been selected. Its performance has been validated in a climate controlled chamber while cycling the packs with an Aerovironment AV900 test equipment. The targeted regions of operation for these busses can be as high as the 56th parallel, in northern Alberta. The pack must be able to operate with ambient temperatures as low as minus 40°C. A powerful electric air heater with a system of blowers and baffles allows every battery module to stay at an even temperature. While the vehicle is being charged the cells are raised in temperature between 10°C and 20°C, giving it some thermal inertia to minimise the heating requirements while driving and by utilizing energy from the grid. Once on the road, the system will start heating again the cells at a lower temperature, minimizing the impact on range.

3.3 Motor sizing

Motor sizing has been performed using the same technique, but increments in available power are not as fine as when designing a battery pack. A more powerful than needed motor has been selected to provide sufficient torque. It is currently able to climb grades of over 15% loaded at GVW and over 20% empty. The motor can provide 200kW peak of mechanical power as the diesel bus only gives 200hp. From this diesel rating, you have to remove transmission losses, cooling fan losses, power steering and alternator load, etc. Acceleration tests have been performed with both vehicles and power has been limited on the electric bus to give the same performances as the diesel version.

4 Calibration

4.1 Motor power

Power calibration of the motor has yielded an optimal number of 135kW. With this power setting, the electric bus exhibits the same accelerations as the diesel bus. This was the guiding principal of all the calibration process, to behave as closely as possible to the diesel version.

4.2 Regenerative braking

The calibration of the control algorithm has been performed to minimise driver learning while preserving energy efficiency. The regenerative braking as well as creep and hill holding features make the vehicle very easy to drive and demand minimal adaptation time to the driver. Most professional drivers feel comfortable after only a small test run in a parking lot, being ready for revenue service with minimal training. It behaves like an automatic transmission equipped bus and delivers very fine low speed driving accuracy, to help in slow and tight school yard manoeuvres. The regenerative braking is done with a dual stage strategy. First, there is an amount of counter-torque applied at lift throttle. It simulates engine compression but with a more refined control.

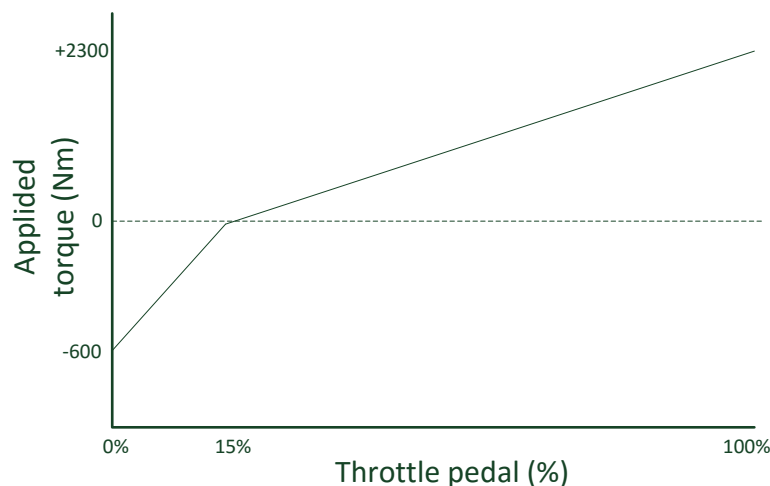


Figure 2: Torque vs throttle pedal position

By using this scheme, the driver can control the amount of “light” regen braking he wants just by applying light throttle. Since the vehicle controller does not assert the brake lights, those are purely done with a switch on the brake pedal, the application of a higher counter torque would not be safe. This counter torque also fades as the vehicle slows down. Less and less regen braking is applied as the vehicle slows down and the driver needs to apply some mechanical brakes. This is done for 2 reasons. First, it is important to keep the mechanical braking system clean and free-moving. This braking at low speed allows to keep the discs rust-free, prevents the calliper pistons from gripping and also keeps the friction surfaces dry, ready for an emergency braking. The second reason is that the friction braking allows a much greater precision and pedal feedback to the driver, allowing him to slow down to a complete stop smoothly with total control. The slight loss in recoverable braking energy is not very important. The amount of energy available at very low speeds is only a fraction of what was already captured at higher speeds.

The second level of regenerative braking is applied when the brake pedal is used. Since the mechanical braking system of the vehicle has not been modified in any way, not additional hydraulic pressure sensor or potentiometer has been added. Only the brake switch, used to drive the brake lights, is available to the vehicle controller to indicate the usage of the brake pedal. An additional counter torque is added progressively when this signal is asserted. The ramp and the level have been calibrated with real school bus drivers to make it as transparent and natural as possible. The overall regenerative braking scheme required many days of calibration but was an important step to make the bus behave in a natural way.

The following figure shows an actual bus run of many minutes. The plot represents the motor torque versus the motor speed, clearly outlying the two different counter torque levels.

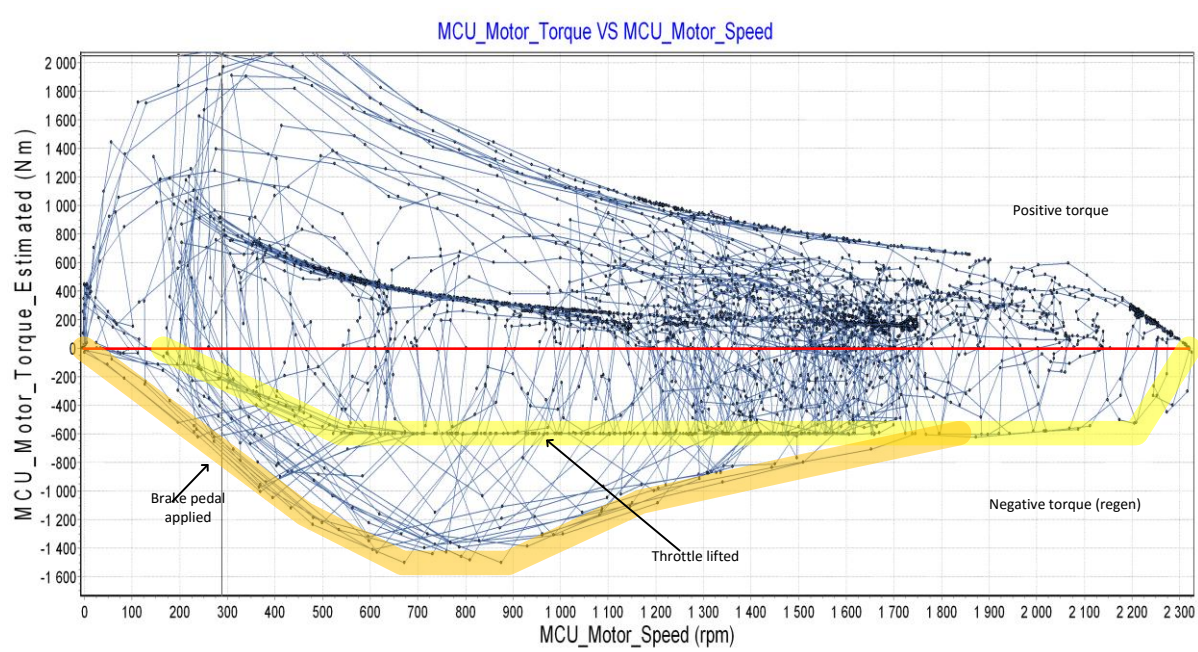


Figure 3: regenerative braking versus motor speed, 2 modes

5 Real world data

The vehicle is equipped with a data logging system that has enabled us to analyse the long term energy usage and the energy split between different systems. This data also enabled to assess the effect of weather on consumption and range.

5.1 Heating

During the simulation phase, it was clear that the range would be reduced by an unacceptable amount if the vehicle was heated with the energy from the battery packs. This vehicle has an enormous interior volume with windows all around and its front door constantly opens. Therefore, the compromise has been made to equip it with a fuel burner for vehicles operating in colder climates. This burner is replaced by an electric liquid heater for southern climates like California. Real operating data has shown that at minus 20°C ambient, the heating of the cabin consumes as much energy as the propulsion of the vehicle. Without a fuel burner, range would have been cut in half on colder days, rendering the vehicle useless.

5.2 Data analysis

A Matlab script has been written to analyse the data gathered and sent by a cellular modem to a server. The following figures show some of these results.

```
#####
__Statistics of data_matlab, eLion__
5443.1km travelled
4404.5kWh consumed
4334.1kWh consumed while moving
70.4kWh consumed stationary
29.8km/h average speed
36.9km/h average speed while moving
0.81kWh/km average consumption
0.80kWh/km average consumption while moving
0.5m/s^2 average acceleration
-0.4m/s^2 average deceleration
#####
```

This analysis over 5400km shows that the initial energy consumption simulation was very accurate, yielding and optimal battery pack size for the application.

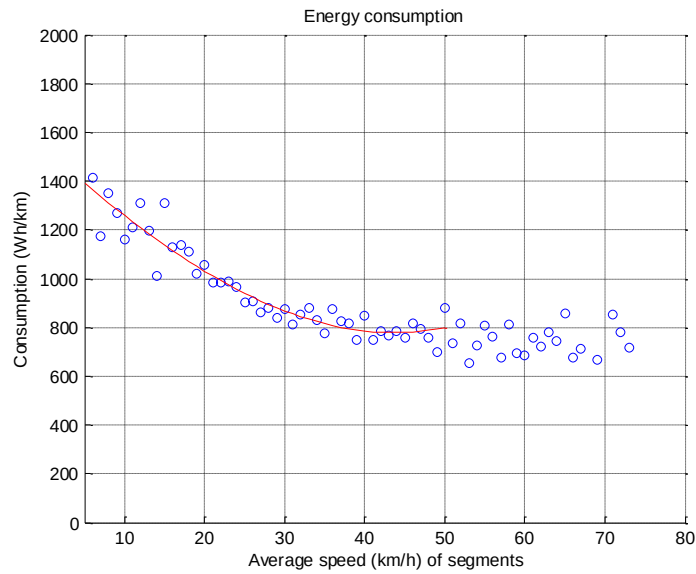


Figure 5: Energy consumption, over 5400km of operations

In Figure 5 the energy consumption per segment was plotted. A segment consists of the interval between two full stops. The trend has not been plotted over 50km/h because of the low occurrences of these segments. Figure 6 outlines those occurrences.

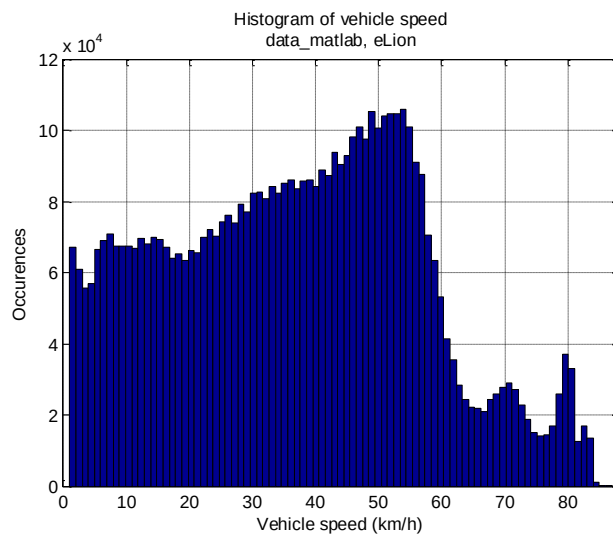


Figure 6: Average speed of segments, over 5400km of operations

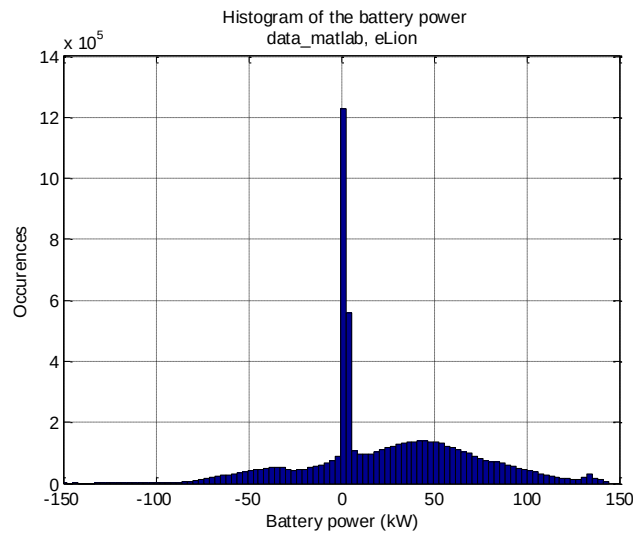


Figure 7: battery power draw, over 5400km of operations

In Figure 7 we clearly see that a lot of time has been spent with the vehicle not moving, as with any vehicle. Once in movement we can see that the average power required by the bus is around 40kW with peaks up to 140kW. Regenerative braking occurs mostly around the -30kW area but with peaks up to -140kW. The area of negative power is about 25% of the positive power area. Actual calculations show that regenerative braking allows 26% range increase.

The last analysis, in Figure 8, shows the difference of electric consumption between mild and cold climate. The increase of consumption can be narrowed down to 2 factors. First of all, snow on the road and frozen tires increase the rolling resistance significantly. Secondly, the air density at -20°C is 1.3943kg/m^3 and only 1.2041kg/m^3 at $+20^{\circ}\text{C}$. This represents an increase of about 16%. Since aerodynamic drag accounts for around 65% of the energy used by the vehicle, this factor alone represents an energy consumption increase of more than 10%.

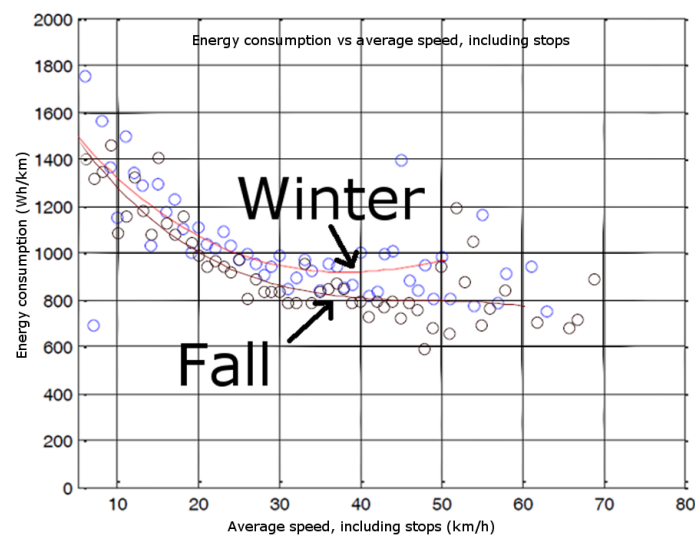


Figure 8: impact of cold weather on energy consumption

6 Current project state and future developments

An engineering phase has been carried out to ease the manufacturability of the vehicle during the summer and fall of 2015. As of march 2016 the vehicle is in full production at a rate of between one and two per week. A continuous process of optimisation and cost reduction is in place for the first few months of production, with the help of the assembly team and selected key early customers. This project has shown that an existing school bus chassis can technically be electrified. Even with a complete control over the chassis, some design compromises have been made. Therefore, the next logical step could be to design an entire new vehicle, from scratch, that would be dedicated to an electric propulsion system. This would yield a more effective vehicle, with better performances and possibly a lower cost.

Acknowledgments

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References

- [1] Christian Pronovost, SAE 2012 Electric Powertrain Technologies Symposium, *Removing the Transmission in Commercial Electric Vehicles*, October 11th 2012, Stuttgart, Germany
- [2] ADVISOR® Software, "Advanced Vehicle Simulator", <http://adv-vehicle-sim.sourceforge.net/>
- [3] TM4 Sumo HD motors, <http://tm4.com/products/direct-drive-electric-powertrain/sumo-hd/>

Authors



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Mr. Prigge is an electrical engineer, graduated from Sherbrooke University (Québec, Canada) in 2000 and has an experience of more than fifteen years in electronics and hardware interfaces programming. Having developed multiple on and off road electric vehicles of the past years, as well as simulated and modelled numerous components, he currently holds the position of R&D Director at the Innovative Vehicle Institute.



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Marc graduated in electrical engineering from l'École de technologie supérieure in 2012, where he specialised in microelectronics, digital signal processing and real-time programming. Marc has developed a battery management system, contributed to the development of multiple lithium-ion battery packs for heavy vehicles, designed electric and hybrid vehicle architectures and lead the commissioning of on-road and marine vehicles. He currently holds a position of project manager at the Innovative Vehicle Institute.