Zero Emission

Electric Transit Bus in Manitoba

Prototype Electric Transit Bus Development and Demonstration
Final Report

Research Partnerships & Innovation
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Executive Summary

This report discusses the development and demonstration of the prototype electric transit bus within Manitoba. This project has been one of the most important advanced-vehicle innovation activities within Manitoba in recent history, beginning more than six years ago and continuing into the present. The project involved five initial partners: Government of Manitoba, Mitsubishi Heavy Industries, Manitoba Hydro, New Flyer Industries and Red River College. Significant additional expansion and follow-up activities have also occurred. This report summaries the project, including formulation, major activities, results, major successes and lessons learned, and major follow-up activities.

1.0 Introduction

The prototype electric transit bus development and demonstration has been one of the most important advanced-vehicle innovation activities within Manitoba in recent history. This highly successful and multi-faceted project began over six years ago, and has led to a number of related and additional follow-up activities, as well as significant direct and indirect benefits.

The five partners in the project have been: the Government of Manitoba; Manitoba Hydro, Manitoba's Crown-owned electrical utility; Mitsubishi Heavy Industries (MHI), a major international energy technology company based in Japan; New Flyer Industries, the largest transit bus manufacturer in North America and based in Winnipeg; and Red River College (RRC), Manitoba's largest post-secondary polytechnic institution.

The partners of the project had earlier confirmed the desire for a public-domain final report to be prepared by Red River College regarding the prototype bus, as well as project results. As described later (in Section 7.1), the most important follow-up activity with the prototype bus has been the pilot fleet trial involving four second-generation electric buses operating in-service with Winnipeg Transit, and with funding support from Sustainable Development Technology Canada (SDTC). The prototype bus project and associated assets were incorporated in this latter project. Given that the follow-up SDTC demonstration itself is now nearing its formal completion date (i.e., Fall 2017, although with potential for extension), this final summary report on the prototype bus is timely.

This final report has been prepared through the Research Partnerships & Innovation (RPI) department of RRC, which has been involved with the project since its inception. The report provides an overview of the project, as well as summarizing major aspects and results of work. It also describes the relationships with other related and additional activities that have occurred so far. Given the intent of this report to provide primarily a public-domain overview, specific proprietary technology details covered by non-disclosure agreements (NDA) are not described.

2.0 Project Background

Background on the development of the project is provided in the following sections.

2.1 Electrified Public Transit

Electrification of public transit is hardly new, with a diverse variety of electric systems already in place across North America and around the world. Electric operations have included a variety of subway, light-rail, tram-trolley and rubber-tire trolley bus systems, with a common feature in all cases of the vehicles being essentially tethered to an electrical supply network. The distinguishing innovation in modern electric bus technology has been the development of advanced lithium ion batteries, and associated battery-based electric transit buses. These buses have all been either based on existing diesel bus gliders, or involve new configurations that closely-resemble existing diesel buses. They are much more similar in terms of operation to diesel buses, especially compared to tethered trolleys.

Early development of battery-based electric buses largely paralleled the development of advanced battery technologies. A Transportation Research Board (TRB) report of 1998 listed a total of only 133 battery electric buses to be present in the U.S. by that time (Arcadis, Geraghty & Miller 1998). Only one of these buses involved a 40-foot full-size, but it was used for mail, not passengers. The preponderance of

20 to 30 foot buses was due to the use of primarily lead-acid and some nickel-cadmium batteries, which due to relatively higher weight and lower energy storage capacity severely limited bus operational capabilities.

During the late 1990s through early 2000s, much of the focus for advanced bus motive technology within North America had been toward hybrid and fuel cell buses (Eudy and Gifford 2003). Hybrid technology incorporating batteries gained prominence as their use continued to increase (Clarke et al. 2009), and also with the movement toward nickel-metal hydride as the preferred battery. The focus on fuel cells reached an apex by 2010, with the small-fleet deployment by BC Transit of twenty hybrid fuel cell buses, notably manufactured by New Flyer, used in conjunction with the 2010 Winter Olympic Games in the Vancouver area (Eudy and Post 2014). While not directly battery-based, developments in both these other areas helped to significantly increase both exposure to and experience with electrical operation of buses.

Lithium ion batteries first entered commercial markets in 1991, albeit starting with smaller consumer electronics, but progressively moved to a forefront position for consideration in vehicle motive operations, especially as costs declined and performance continued to improve. Battery chemistries based on lithium ion have come to dominate in both electric cars and electric buses. Initial developments toward lithium ion based battery buses occurred in a number of locations around the world during the 2000s, notably including Korea, China, Japan and the U.S.

2.2 Project Genesis

The genesis of the project in Winnipeg was the signing of a Memorandum of Understanding (MOU) in 2010 between the Government of Manitoba and MHI (Government of Manitoba 2010). The MOU involved eight potential areas of collaboration on renewable energy. Notably, the first area for collaboration was identified as, "electrification of transportation and recharging infrastructure projects."

MHI had been already undertaking development of a larger-format, prismatic-cell lithium ion battery, including implementation of a verification-scale commercial production plant in Nagasaki, this to confirm the viability of further larger-scale production (MHI 2010). At the same time, MHI also began developing specific initial products for market that would use the new battery. These included energy storage systems (ESS) for grid electricity support (Hashimoto et al. 2007), heavy-duty hybrid forklift trucks (Ogawa et al. 2010), and, most relevant to this project, heavy-duty transit buses (Kakuhama et al. 2011).

MHI also had been already well aware of capabilities within Manitoba, including New Flyer, the largest manufacturer of transit buses in North America. This was because of earlier discussions that had occurred relating to wind power, in which MHI has been also active. MHI's bus-related activities to that point had been solely within Japan, and the ensuing project in Winnipeg allowed them to participate in and explore opportunities in the North American electric transit bus market, which was just beginning to emerge at that time. Lastly, regarding MHI involvement, it is important to note that they made the decision in

2014 to exit the lithium ion battery manufacturing business (MHI 2014). MHI concluded an agreement in April 2014 to sell their lithium-ion rechargeable battery business assets, including machinery, to Taiwan-based Delta Electronics.

3.0 Formulation, Objectives and Timelines

The basic outline of the project as originally conceived, is provided in the following sections.

3.1 Project Formulation

The major announcement of the project formation and associated financial commitments was made in April 2011 (Government of Manitoba 2011). The total value of the project, as announced, was $3 million, with contributions of $1 million cash and/or equivalent each from the Government of Manitoba, Manitoba Hydro and MHI. The formation of the Electric Vehicle Technology and Education Centre (EVTEC) at RRC was also announced at the same time. Separate provincial funding support directly to EVTEC amounted to approximately $600,000 over three years (Parsons and Hoemsen 2012). As described later, this entity within RRC formally acted as the funding administrator for the prototype bus project.

The intent was also noted to have the prototype bus operational within one year, followed by two years of further testing. Before June 2011, an overall project agreement was signed by all the partner organizations. This milestone denoted the actual beginning of the project. Relevant NDAs had been also signed by the project partner organizations.

3.2 Project Team Members and Roles

The main roles and responsibilities of each of the five project partner organizations are summarized as follows:

Government of Manitoba

- Financial support for the project;
- Overall coordination of activities, including coordination of consortium group meetings and communications, supporting project planning and development;
- Legal support for agreements, as well as any associated safety approvals;
- Insurance and overall liability issues; and
- Project "image" support, including project-specific communications brochures.

Manitoba Hydro

- Financial support for the project;
- Charging site locations, and associated infrastructure preparation to accommodate battery charging systems;
- Power supply arrangements; and
- Additional technical support on electrical systems and options.

Mitsubishi Heavy Industries

- Advanced lithium-ion battery packs to operate the prototype bus;
- Technical support regarding specialized component technologies; and
- Financial support for the project.

New Flyer Industries

- Technical leadership on prototype bus development;
- Bus technologies, primarily glider system with associated design modifications;
- Electric drive train components and auxiliary support systems;
- Overall systems control and vehicle communications;
- Platform integration of technologies into single operational unit; and
- Operational and maintenance support, including maintenance and driver training.

Red River College

- Administration of project funds, this through EVTEC;
- Base of operations, as required, for bus development and demonstration activities;
- Technical support to New Flyer on prototype bus development;
- Technical support with Manitoba Hydro on charging technologies;
- Battery pack assembly and monitoring (see Section 7.2); and
- Operation of prototype bus during Phase 3 demonstration (see Section 3.4).

Activities that were not outlined in the original scope for RRC, but were later added (Hoemsen 2015), are described in Section 7.2.

3.3 Project Objectives

The main objectives of the prototype bus project, outlined by Hoemsen (2015), were to:

- Develop an operational prototype battery-electric transit bus;
- Utilize advanced technologies in the prototype bus, both from MHI, regarding their lithium-ion batteries, and from New Flyer, regarding their advanced Xcelsior glider platform;
- Demonstrate operation of the prototype bus, including in conjunction with on-route rapid-charger technology;
- Test operational capabilities under Manitoba's extreme climatic conditions; and
- Use the demonstration of the prototype bus as a showcase for other potential markets in North America.

3.4 Project Timelines (Original)

The project was originally intended to last approximately three years in total. The project involved three identified main phases, outlined as follows, with all phases structured around progress with the prototype bus:

- Phase 1: Prototype bus development and construction, which was intended to be complete within approximately one year from start.
- Phase 2: Prototype bus shake-down testing, which was intended to require less than one year after the completion of the prototype bus.
- Phase 3: Limited-run operational demonstration of the prototype bus, involving high-selected route conditions and only selected passenger audiences lasting less than one year. The specific intended activity in this case was identified as shuttling selected Manitoba Hydro staff between their downtown headquarters

and facilities on Taylor Avenue in South Winnipeg. As described later, this operational run was indeed employed.

Further potential for demonstration of the prototype bus on a suitable public route in for-fare service was discussed as a further Phase 4 operation. However, this was really only expressed at the time as a desired optional activity, if possible. This latter activity was not undertaken with the prototype bus itself, but was fully realized with the follow-up SDTC demonstration described later in Section 7.1.

4.0 Major Project Activities

Major project activities as they occurred through the progress of the project are described in the following sections.

4.1 Development of Prototype Bus and Rollout

The prototype bus employed New Flyer's advanced Xcelsior glider platform, using a standard 40-foot bus size. The development activities to transition the bus to electric operation, including electric drive implementation, battery integration, HVAC (heating, ventilating and air conditioning) and other auxiliary systems, were all completed within one year, as originally projected. The official rollout of the operational prototype bus occurred in early June 2012 (Government of Manitoba 2012a).

As outlined in a descriptive brochure released at the time of the rollout (Government of Manitoba, 2012b – refer to Appendix A), the main features of the prototype bus included the following:

Figure 1: Photograph of Operational Prototype at Rollout Event (June 1, 2012)

- Total electrical energy storage capacity of 120 kWh using MHI's advanced batteries. The battery pack incorporated 8 modules, each rated for 15 kWh. The batteries were all physically located in the rear compartment of the bus, where the diesel engine would be normally located. A battery management system (BMS) was also incorporated to constantly monitor and manage the battery system.
- Siemens Electric Drive System implemented. In this case direct current (DC) power from the batteries is converted to 3-phase alternating current (AC) power to drive the traction motor. The system also incorporated regenerative braking, using the motor to act as a generator to recover energy, just like in conventional hybrid vehicles.
- HVAC involved an electrically driven air conditioning system to cool the bus when needed, electric heating for moderately cold temperatures, and for very cold conditions, a liquid-fuel heater to warm the passenger cabin using a small amount of fuel, this in order to help maintain bus range during winter.
- Other auxiliary systems including power steering and air compression were directly powered electrically. In all cases, as well as the AC system, high-voltage DC power is converted to AC power and supplied to each major system separately. This allowed each system to operate efficiently, with minimum power consumption. The bus also involved a high-voltage converter to supply 24-volt DC power for interior fans, lights, etc.
- In order for its battery pack to be recharged, the prototype bus needs to be connected to a DC charging system. The bus had the capability to use two different technologies, a slower overnight charging system, suitable for within a bus garage, and an on-route, rapid-charger system. As noted earlier in Section 3.3, one of the objectives of the project was specifically to demonstrate on-route charging of the prototype bus.

An overview photograph of the operational prototype bus, this taken as part of the rollout event in June 2012, is provided in Figure 1.

4.2 Shake-Down Testing

The prototype bus was operated for roughly one and a half years for shake-down testing. Essentially this involved test driving around the vicinity of Winnipeg, but without passengers, to confirm

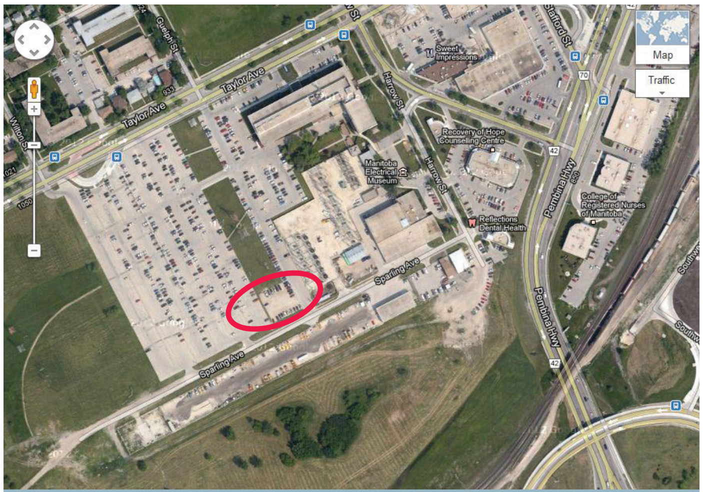


Figure 2:
Manitoba Hydro Site for Phase 3 Rapid Charger Station Installation

Figure 3:
Manitoba Hydro Rapid Charger Station Installation for Phase 3

the operability of the bus in actual use. A variety of minor issues were identified and resolved, primarily by New Flyer, through the course of this work. The test period lasted longer than anticipated, primarily as a result of delays in the acquisition and implementation of the on-route rapid charger needed for Phase 3.

4.3 Rapid-Charger System Implementation

An important element of the project was implementation of a rapid-charger system that could be used for intermediate rapid charging of the prototype bus batteries while on-route, i.e., not having to periodically return to the bus garage for charging. Initially, discussions were led by Manitoba Hydro and RRC, although looking more from the perspective of first principles. This was due to the lack of such specialized equipment available in the market, as well as the lack of any consistent standards for high-power battery charging systems. Given a desire to not implement one-off technology for the demonstration, i.e., without later commercial support or follow-up product, this tactic was switched toward having discussions with existing electric systems manufacturers to investigate their interest in this area, and the potential to assemble a unit of suitable power capacity of around 300 kW for the Phase 3 operations. These latter discussions were coordinated by New Flyer from the consortium, and led to the engagement of Eaton Electric, a major international supplier based primarily in the U.S., to manufacture a suitable unit.

The Eaton rapid-charger, which they termed their "hyper-charger" product, was modular in nature. The system, as supplied, incorporated two modules, packaged into a single NEMA 3 type enclosure. Each module had an output current capacity of 250 A, with maximum voltage of 800 V, translating to a maximum power output of approximately 200 kW per module. As such, the overall system capacity was up to a maximum of approximately 400 kW. This was more than what was deemed necessary for the prototype bus. Also, given the modular nature involved, additional modules could be added later as required to boost output, or to ensure redundancy. A powered overhead rail was selected to supply the DC power to the prototype bus, specifically using an already-existing product called Busbaar supplied by the European manufacturer Opbrid. An extendable pantograph on the prototype bus itself was selected to make the final connection.

In order to facilitate Phase 3 operation of the prototype bus (noted earlier in Section 3.4), the initial recharging site was selected to be located at the south end of the employee parking lot at 820 Taylor Ave., on Manitoba Hydro property. This area was clear of any overhead obstructions and away from routes for any heavy equipment, ensuring the overhead arms of the charging unit would not be exposed to potential damage. Ample electrical connections were available at this site. An overhead view with the approximate location of the selected site is highlighted in Figure 2.

A rough elevation view of the setup of the charging station is illustrated in the photograph in Figure 3, with the prototype bus also included and about to be charged. The main components in order from left to right are as following:

- Pad-mounted distribution transformer, which involved a relatively specialized three-phase unit to step down from 24 kV to 480 V, the operating voltage of the Eaton unit (i.e., U.S. voltage level);

- Pad-mounted service entrance enclosure, which was manufactured locally;
- Pad-mounted Eaton charging unit itself, which shows twin exhaust stacks, one for each module; and
- Opbrid charging rail to connect to vehicle, mounted on a concrete foundation.

Some concrete piles were required to support the overhead arms, which would remain in place, but the rest of the equipment was set up in a way so as to simplify relocation. Manitoba Hydro employed a standard "tub" mounting arrangement, with one unit each for the distribution transformer, the service entrance enclose, and the Eaton charger. This approach in each case involved excavating a sufficient hole, filling with adequate aggregate to form a base, wooden members then laid down to form a base floor, inverted fiberglass tub installed on top of the wooden members, and lastly the equipment mounted on top of the tub. Wiring access in all cases is from underneath and is not constrained by the direction involved. A final, smaller unit that was part of the installation but not visible in Figure 3 behind the bus, was the communications enclosure. A direct communications cable coupling was involved between the bus and the charger, as described later. Movable concrete barriers were also incorporated at the site to form the driveway for the prototype bus.

The rapid charging station for Phase 3 operation was completed by mid-2013. The Eaton rapid-charger unit, which involved quite new technology, progressed through a number of teething issues during initial installation. Problem issues were corrected, after which the unit performed well. A more important, but non-technical problem developed later on. Eaton Electric announced that effective September 2015, they were exiting the commercial electric vehicle charging station manufacturing business. This included ceasing all activity on their electric bus hyper-charger systems, on their direct current fast chargers (DCFC) for electric cars (i.e., Level 3 charger systems), and on their Level 2 commercial electric car chargers (i.e., 220 V, 16+ A). This decision was for business reasons, and although it did not directly impact the demonstration, it had longer-term implications.

A further important aspect of the rapid charger set-up was that communication between the bus and charger was effected through a physical cable. As such, this required that for each charge event, the driver would have to leave the bus, open both the communications box and a panel near the rear on the side of the bus, and insert the cable, stored in the communications box, into a selected slot in the bus itself. This approach was undertaken given that it was both simple and reliable. However, it was understood to be undesirable in terms of full-scale transit system operation. Communication between the bus itself and the charger system was progressively enhanced by New Flyer.

As a side note, New Flyer early on developed a simplified "shop-charger" unit suitable for the prototype bus, although outside the formal project. This system provided the ability to more slowly charge the bus overnight. It was partly an interim solution until the rapid charger was ready, and also was mobile in nature, providing recharging capabilities for demonstrations of electric buses in other diverse locations later on. With the transition to the larger SDTC project, four shop-chargers based on this initial unit were implemented at Winnipeg Transit's garage, again providing over-night recharging capability as required.

Lastly, there had been consideration within the project to potentially look at the concept of battery-swapping as an alternative to rapid charging. Such a concept, however, was not found to be practical in this case. It was not pursued further.

4.4 Demonstration Testing

In order to validate the operation of the prototype bus (and rapid charger) with passengers, albeit in a more controlled environment, it was regularly operated during Phase 3 on a dedicated route, essentially as a shuttle. The bus carried limited-access passengers, as opposed to unrestricted general passengers as would be typical for regular transit operation. This provided an important incremental step towards regular operation in proving the vehicle.

A public announcement regarding the Phase 3 demonstration activities was made midway through completion, in May 2014 (Government of Manitoba 2014). This announcement event was also used to signal the impending start of operations later that year on the expanded SDTC demonstration, described later in Section 7.1.

The prototype bus travelled between Manitoba Hydro's new headquarters building at 360 Portage Ave. and their facilities at 820 Taylor Ave. The only people permitted to ride the bus were Manitoba Hydro employees and other authorized personnel. This simplified the licensure and insurance for the bus, given that it was not involved in any commercially

available conveyance service. The total round trip in this case was approximately 15 km, undertaken approximately once every hour on the half-hour. The bus was thus meshed with other shuttle vehicles undertaking the same regular route, with the other shuttle vehicles providing back-up redundancy as a precaution. The prototype bus was recharged as required using the rapid charger located at the rear side of 820 Taylor Ave., as noted earlier.

In order to facilitate this operation, the bus was registered for operation within Manitoba through Manitoba Public Insurance, with RRC as the vehicle registrant. The prototype bus was appropriately insured for Phase 3 operation using a standard policy from Manitoba Public Insurance. Given the much higher value of the prototype bus beyond the vehicle-value of a standard policy (i.e., $50,000), an extension policy was also secured. Both policies were obtained by RRC, as the vehicle registrant.

Because of requirements for payment of Manitoba Retail Sales Tax upon the time of any vehicle registration, a waiver was obtained from the Minister of Finance for Manitoba. The same waiver was also provided for the four second-generation electric buses as part of the follow-up SDTC project, described later. All the bus drivers for the Phase 3 operation were hired by RRC.

5.0 Utilization and Performance of Prototype Bus

The uses and monitored performance of the prototype bus through the course of the planned demonstration are described in the following sections. Additional research-related activities undertaken that were not outlined in the original scope are described later in Section 7.2.

5.1 Overall Travel, Energy Consumption and Emissions

The original plan for the prototype bus, as described earlier, was to operate for approximately three years. The prototype bus is still in operation after roughly five years, which is well beyond initial expectations. As discussed later, the prototype bus is still currently licensed for operation and insured with Manitoba Public Insurance.

In terms of travel, from an overview perspective, the prototype bus by May 2017 had logged total cumulative travel of just over 33,000 km. A significant portion of this travel was accumulated during the regular Phase 3 operation. By September 2015, after completion of Phase 3, it had logged almost 21,000 km (Hoemsen 2015). As such, during its first three years of operation the bus travelled roughly 7,000 km per year, and during the past roughly two years has travelled roughly 6,000 km per year. The overall travel distance undertaken is a relatively large value for a prototype vehicle, but on an annual basis represents less than 15% of the normal annual travel of a transit bus in actual service (i.e., about 50,000 km per year).

The energy consumption performance of the prototype bus was also monitored relative to seasonal conditions, with summary results as follows (Hoemsen and Friesen 2013):

- Approximately 125 kWh per 100 km when no heating or air conditioning employed (i.e., spring or fall);
- Approximately 185 kWh per 100 km when air conditioning fully engaged (i.e., summer); and
- Approximately 310 kWh per 100 km when full heating employed (i.e., winter)

The high electricity consumption for the bus during cold weather, i.e., roughly 250% of baseline requirements, is highly consistent with observed significant increases seen for light duty battery electric vehicles (BEV) in cold weather operation within Manitoba (Delos Reyes et al. 2016). This significant increase in energy consumption emphasized the importance of using an auxiliary heating system during very cold conditions in order to preserve battery capacity for motive travel. Based on the above values, and including auxiliary heating, the average electricity consumption for the prototype bus was estimated to be around 160 kWh per 100 km, including travel in all seasons.

Even though the prototype bus was involved solely in development and demonstration activities, a rough estimate of greenhouse gas (GHG) emissions reductions can be made based on cumulative travel (i.e., 33,000 km as noted above). Also, the performance of the prototype bus gives guidance as to emissions reductions that could be expected for fleet operations based on using the technology. Assumptions and calculations for GHG emissions reductions are provided in more detail in Appendix B. As described in Appendix B, the extent of emission reductions depends significantly on the basis of calculation, and on the extent of travel, whether in total for the prototype bus, or in the case of fleet-based performance projections of electric buses.

In terms of the prototype bus itself, over its life, it has achieved total GHG reductions in the range of 53 to 77 tonnes, depending on calculation method. In terms of projections for fleet operation, three cases are calculated, based on annual travel and depending on calculation method, as follows:

- Lower annual travel of 35,000 km per year translates to annual GHG reductions in the range of 56 to 82 tonnes per year;
- Average annual travel of 50,000 km per year translates to annual GHG reductions in the range of 81 to 117 tonnes per year; and
- Higher annual travel of 70,000 km per year translates to annual GHG reductions in the range of 113 to 164 tonnes per year.

It is obvious from these results, irrespective on the basis of calculation that electric buses produce very significant emission reductions, roughly 98%. Diesel buses are large vehicles consuming large quantities of diesel fuel, and represent individually significant emission sources. When considered on a consistent basis compared to light duty vehicles, a single electric bus is equivalent to transitioning as many as 20 cars from fossil fuel to electricity, in terms of reductions. This analysis emphasizes the importance of electrifying transit fleets.

An additional notable feature of the prototype bus has been its quiet operation. Initial estimates of noise levels were undertaken with the prototype bus. Preliminary results showed noise levels of roughly 50 dBA for idle operation (with all background systems operating), roughly 56 dBA for idle operation (with compressor operating), and roughly 61 dBA for full-throttle acceleration (Hoemsen and Friesen 2013). More definitive third-party evaluation of noise levels was undertaken for one of the second-generation electric buses as part of Altoona testing as described later (Pennsylvania State University 2015). The latter results were highly positive, in particular compared to competitor bus models.

5.2 Phase 3 Operations

The Phase 3 demonstration of the prototype bus, shuttling Manitoba Hydro employees, lasted for approximately six months. This started in March 2014 and continued until August 2014. Due to the timing involved, the prototype bus thus experienced operation in both cold winter and warm summer conditions. This was the most extensive and intense operation of the prototype bus over its entire life so far. The bus operated well over this period.

5.3 Public Awareness and Promotional Activities

The prototype bus was used in conjunction with a variety of public awareness and promotion activities. Firstly it participated in two major announcements events directly associated with the project. Both involved operation, and providing rides for dignitaries and media:

- Initial unveiling of the prototype bus in June 2012; and
- Highlighting of Phase 3 demonstration operation in May 2014, including showcasing of the rapid charger system at Manitoba Hydro's 820 Taylor Ave. location.

Both of these events were well covered by the local media, including a variety of radio, television and video spots.

In terms of additional promotional events, in January 2013, New Flyer transported the prototype bus to Los Angeles, California. While there, it participated in a demonstration trial event as part of a procurement process underway for electric or other "super-low-emissions" buses by the City of Los Angeles. In July

2012, the prototype bus was on display at a Car and Heavy Truck show event at RRC. Again, in June 2014, the prototype bus participated as part of a public vehicle "Show and Shine" event at RRC. In June 2015, the prototype bus was used for shuttling delegates as part of the Canadian Urban Transit Association annual meeting held in Winnipeg that year. The most recent promotional activity involving the prototype bus was in May 2017, as part of the Science Odyssey event at the University of Manitoba.

By 2014, the second-generation electric buses, part of the SDTC project, had begun to be completed, and, given their more developed nature, ended up being preferentially used for individual promotional and demonstration events. One of the second-generation buses was also used for Altoona testing, as discussed later in Section 6.1.

With the transition of the project to the larger SDTC demonstration, which began on-route operation in November 2014, it had been intended for the prototype bus to be available on loan to the City of Winnipeg until all four of the second-generation buses had been delivered. As it turned out, however, the prototype bus was not required for this purpose. An intended significant later promotional use of the prototype bus was to shuttle dignitaries to an opening event at Assiniboine Park Conservancy as part of the 2016 Energy and Mines Ministers Conference (EMMC) in August of that year. In this case, the prototype bus was tied up with some other research activity, described later, and one of the second-generation electric buses was used instead.

In terms of coverage in academic journals, a peer-reviewed article by Li (2016), reviewing electric bus development activities around the world, specifically noted the electric bus project in Winnipeg. Also, the California Air Resources Board in a 2015 report on technology status for electric heavy-duty vehicles, noted bus activities in Winnipeg (CARB 2015).

Lastly in terms of promotion, two significant video segments were prepared regarding the prototype bus, one by RRC and one by Manitoba Hydro. Both of these videos are still available through Youtube on the internet, as follows, and can be still publicly viewed:

- RRC public video on prototype bus demonstration: https://www.youtube.com/watch?v=4nZxPO8ddMY
- Manitoba Hydro public video on prototype bus demonstration: https://www.youtube.com/watch?v=QptoGWmnEy4

6.0 Successes and Lessons Learned

Major successes and lessons learned from the prototype bus are summarized in the following sections.

6.1 Project Successes (Direct and Indirect)

The project generated a number of important major successes. Directly, the project achieved all the goals as were originally outlined:

- Prototype battery-electric transit bus was completed, fully-integrating MHI's advanced batteries with New Flyer's advanced Xcelsior platform;
- Prototype bus was demonstrated in conjunction with on-route rapid-charger technology;
- Prototype bus proved it could be successfully operated under Manitoba's highly variable climatic conditions; and

- Demonstration of the prototype bus was used as a showcase to promote the technology in other potential markets across North America.

The prototype bus was literally the first modern, battery-based electric bus to be completed by a domestic manufacturer in Canada (i.e., in 2012), not imported into the country. Also, the on-route rapid charger was the first bus rapid-charger system to be implemented in Canada and the highest power rapid-charger to be operated to date for any battery-electric vehicle in Canada (i.e., in 2013). As had been desired, some further business relationships developed between MHI and New Flyer, for example as part of the follow-up SDTC demonstration. MHI provided battery packs for two of the four second-generation buses. This, of course, did not continue, but because of MHI's decision to exit the battery manufacturing business in 2014.

An important concrete outcome is that the subsequent expansion of the project with SDTC directly involved the realization of a production model bus based on the prototype within a relatively short period of time, i.e., within roughly three years from the start of the prototype bus project. The prototype bus was more exploratory by its nature, and provided an important learning experience. As such, by the time of the follow-up SDTC project, New Flyer had already transitioned design to the more standardized XE40 model bus that is now an important component of their product line (New Flyer 2017).

As also mentioned earlier, one of the second-generation buses from the SDTC demonstration was used for Altoona testing. This involves extended performance and reliability evaluation lasting over one year, undertaken by an independent testing organization associated with Pennsylvania State University. Such testing is required for all transit bus models sought to be eligible for funding under the U.S. Federal Transit Administration. All reports on these tests are available in the public domain, including for the New Flyer model XE40 (Pennsylvania State University 2015). The results of the Altoona testing confirmed the solid performance characteristics of the XE40 product, in particular compared to competitor models (i.e., test results also publicly available).

The success of the demonstration was to a significant degree due to successful project coordination, and cooperation between partners. The partnership that developed between the various organizations worked very well. As an important note, regular meetings were held involving project partners, ensuring that all were up to date on developments.

The success of the prototype bus development and demonstration was also an important factor that led to RRC receiving a major and prestigious national award from the Natural Sciences and Engineering Research Council of Canada (NSERC 2016). The college received a NSERC 2016 Synergy Award for Innovation (Category 4: College). This was based on a series of on-going collaborative projects involving RRC and Manitoba Hydro, of which the prototype bus was specifically noted.

6.2 Lessons Learned

Developments regarding the rapid-charger system, particularly charging protocols, likely represented the most important lessons learned as part of the prototype bus project. Rapid charging has also remained the area of greatest uncertainty in the more general progress of battery-electric buses overall. When the project began, there was very little experience anywhere with rapid charging of batteries at high power levels. It was also clear from the start that individual transit authorities were seeking a one-stop shop solution, not wanting to deal with different and independent providers of buses and charging-equipment.

As noted earlier in Section 4.3, in order to secure a practical operating rapid-charger for the prototype bus, the consortium shifted away from an initial design approach based on first principles to engaging with a major electric systems manufacturer, Eaton Electric. An important anticipated implication was that into the future they could potentially act as an ongoing technology partner as market applications increased. This

was similar to relationships that had already developed between charging system providers and electric car manufacturers.

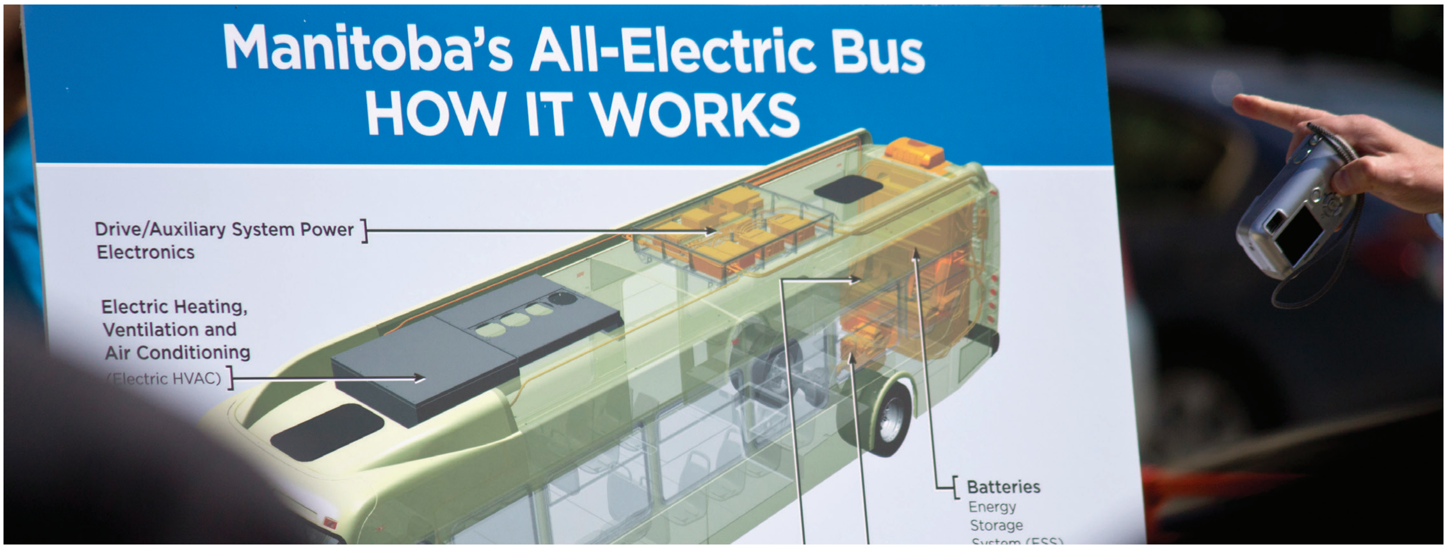
As also noted earlier, the system from Eaton Electric worked well, but a major unanticipated issue arose. Eaton Electric exited the high capacity and commercial charging equipment market in 2015, essentially leaving the equipment as an "orphan" system, without further support. More subtly, the communications and charging protocols involved were of a proprietary nature, not necessarily compatible with other technologies.

Ongoing progressive upgrades were made by New Flyer to the rapid charger system, both through the course of the prototype bus demonstration, and into the subsequent SDTC project. Most importantly, the significant practical experience gained by New Flyer helped them become directly involved in, and encouraged general industry directions towards, standardization of transit bus charging. A number of relevant organizations have been involved in helping to coordinate these directions, including: Society of Automotive Engineers (SAE), which is an international automotive-related standards organization; Electric Power Research Institute (EPRI), which is the major electric-industry research organization in the U.S.; and the Canadian Urban Transit Research and Innovation Consortium (CUTRIC), which is a recently formed research-organization under the auspices of the Canadian Urban Transit Association (CUTA). Various bus and electric equipment manufacturers have also become involved. Most directly relevant to the rapid charger system is the developing standard SAE J3105 (SAE ND). Additional relevant standards are also under development, including for plug-in chargers and wireless chargers (New Flyer 2016). Similar work on bus charging standardization is also underway in Europe.

A second major area of learning was in the selected battery capacity to be used for transit buses. The battery capacity of the prototype bus, being 120 kWh, was essentially defined by what could be reasonably provided by MHI at the time, and was not based on any assessment of customer needs within the North American market. In their electric bus brochure, New Flyer (2017) notes that variable battery capacities, ranging from 100 kWh to 480 kWh, can be accommodated by the XE40 model but with the standardized model involving 200 kWh. The standard battery pack, being able to satisfy most transit authority requirements, is thus roughly 70% larger than the original prototype bus.

A third, but relatively subtle, area where lessons were learned was regarding auxiliary heating. Originally, it had been intended that the prototype bus be completely renewable in nature, with auxiliary fuel being 100% biodiesel, usually denoted as B100. When combined with Manitoba's already clean electricity grid, the prototype bus then would have been 100% renewably powered. Notably, such renewable liquid fuel was available via a licensed non-commercial biodiesel system already at RRC, this employing used canola oil from all the College's cooking and culinary arts operations. Using 100% biodiesel, however, turned out to be highly problematic. B100 is known to act as a "penetrant," similar to well-known commercial products like WD-40. This made the sourcing of acceptable equipment tricky and expensive. Further, all transit authorities, including for example Winnipeg Transit, have capability for diesel refueling, including indoors, given the relatively high flash point of conventional diesel, which is a noted safety feature. On the other hand, B100 is a more limited special product that is expensive to source, and further requires separate and specially designed refueling infrastructure, given its aggressive properties.

As a practical compromise, it was determined that the prototype bus, and indeed the further second-generation buses, would use regular diesel fuel blend for auxiliary heating. This is safe and readily available fuel that also normally incorporates some biodiesel, typically in the range of 2% to 5%. This is obviously not purist in terms of being completely emissions free, but as noted earlier in Section 5.1 and in detail in Appendix B, the contribution of diesel fuel used for auxiliary heating is trivial, with overall emission reductions of roughly 98% compared to a conventional diesel bus even when the auxiliary heating fuel is included. Auxiliary heaters, typically involving catalytic operation, are dramatically more efficient for producing heat than diesel engines, and further, due to catalytic operation, produce negligible quantities of other engine-related pollutant emissions. This facet of emission reductions for the electric buses also led to an important realization. Within Canada, it would be more practical to deliberately define zero emission vehicles (ZEV) in terms of no emissions being produced from motive operation, as opposed to no emissions produced from the vehicle as a whole. This subtle change



practically recognizes the reality of cold weather and the need for vehicle heating within this country.

A fourth area in terms of lessons learned was regarding taxation implications for demonstration vehicles. A relatively significant cost that initially had not been anticipated in the project budget of the prototype bus was the Retail Sales Tax that is due upon formal registration of any vehicle for operation. This was a relatively easy item to overlook. Initially, the prototype bus was operated through shake-down testing using a "dealer" plate under New Flyer, but this needed to change for the Phase 3 operation, which was described earlier. Given the relatively high value of any demonstration vehicle, like the prototype bus, the amount of tax is also very high, i.e., current Manitoba rate of 8% of vehicle value. The Government of Manitoba was a partner in the project, and once this issue was identified, their involvement facilitated approaching the Minister of Finance to secure a tax waiver. As such, when the prototype bus was formally registered by RRC, no tax was due. Similar tax waivers were also provided for the four second-generation buses.

6.3 Technology Readiness Assessment

In order to assist in the objective assessment of new technologies under development, the U.S. Department of Energy (2011) prepared a Technology Readiness Assessment Guide. The concept of Technology Readiness Levels (TRLs) was originally pioneered by NASA in the 1980s and was adapted to energy-related technologies in this case by the DOE.

TRLs overall range from Level 1 (TRL 1), corresponding to the observation of basic principles, to Level 9 (TRL 9), corresponding to a total system used successfully in expected regular full-scale operation. Based on their guidance document, in terms of the technology of an individual electric transit bus, the completion of the prototype bus, including Phase 3 operation, would best represent the completion of TRL 6. This corresponds to an engineering-scale prototype validated in a relevant (similar) environment. As follow-up, the further SDTC demonstration would represent, in terms of individual electric transit buses, moving past the completion of TRL 7, which corresponds to a full-scale system demonstrated in a relevant (actual) environment, and even potentially achieving completion of TRL 8, which corresponds to the system having been proven to work in its final form, and under expected conditions as typical for real operations. The key differences between the status levels achieved by the prototype bus versus the follow-up SDTC project stem from design finalization with the second-generation buses to a production model, and operation in actual for-fare service as is required for regular transit operation.

The approach of assigning TRLs is useful, and has been popular with a number of relevant organizations. At the same time, it is important to note limitations and key caveats in using TRLs, as for example outlined by EARTO (2014). Achieving a more advanced TRL has meaning solely in term of the state of readiness for a technology product, not necessarily whether it is economically viable or economically superior to existing or other new technologies, nor whether it is likely to be adopted by the market. Assessments of the latter, of course, involve looking at additional factors. A more important limitation in the application of TRLs, so far, is that they have only reflected the readiness of individual bus vehicles for operation. Indeed, many transit operations have been actively involved in the testing of small numbers of electric buses, typically over short periods of time. Current transit systems, however, involve complex network operations, and have been largely based on and built up around the characteristics of conventional diesel buses. Moving to an overall system that can accommodate fully or nearly fully electric bus operation still requires significant additional work.

7.0 Follow-up Activities

Several important follow-up activities that resulted from the prototype bus project are described in the following sections.

7.1 Transition to SDTC Demonstration

In 2012, New Flyer, with the support of consortium partners, applied for and was awarded additional funding from Sustainable Development Technology Canada. SDTC acts as an arms-length foundation with the Government of Canada, providing investments in promising environmental-related technology products, essentially helping to bridge the gap toward commercialization.

In order to facilitate the SDTC application process, the assets and remaining activities of the prototype bus project at that time were rolled into the larger SDTC proposal. The SDTC proposal envisioned expanding activities to construct four new, second-generation electric buses, these based directly on the experience gained with the prototype bus, and also to undertake pilot operation on a suitable dedicated route with Winnipeg Transit in full-fare service operation, this including on-route rapid charging.

As a result of this transition, Winnipeg Transit became a new partner with the consortium. The overall value of the combined proposal was approximately $10.3 million at the time. SDTC provided $3.4 million in new funding to New Flyer (NRCan 2012 and SDTC ND). MHI's activities continued into the SDTC project as well, with them providing two 200 kWh battery packs for two of the four buses. Another battery supplier provided battery packs for the other two buses.

For the for-fare service operation, Winnipeg Transit's #20 (Watt) route was selected. This route runs laterally from west to east across the City, and was deemed to be highly suitable for operation of the electric buses. The western terminus of the route is Winnipeg's James Armstrong Richardson International Airport. Discussions by New Flyer secured cooperation and involvement of the Winnipeg Airport Authority, with the rapid charger relocated from its initial site at Manitoba Hydro to a new location at the airport, just outside the main terminal building at the normal bus route stop. Although the core charger unit remained the same as for the prototype bus, New Flyer had undertaken a variety of improvements for communication with and connection to the buses, as noted earlier. This included an improved overhead gantry. Reinstallation of the updated rapid-charger station at the new airport site was undertaken in conjunction with Manitoba Hydro, which provided electricity for the airport charging location at no cost. Some additional funding assistance for updating of the rapid charging system was provided to New Flyer by the Manitoba-based, non-profit Vehicle Technology Centre (New Flyer 2014).

Actual in-service operation began in November 2014 using the first of the second-generation buses (New Flyer 2014). Over time, the number of buses operating in service increased to fully involve all four. Formally, the in-service operation continues until at least September 2017. There is potential to extend for a longer period, based on agreement with the parties involved.

The Winnipeg SDTC demonstration represents literally the most advanced battery-electric bus project ever undertaken in Canada, and one of the most advanced in the world as a whole. This report only discusses aspects of the SDTC project as they relate to the original prototype bus, and does not provide all relevant details. Separate reporting on the SDTC demonstration is anticipated in the future.

7.2 Additional Research Activities Undertaken

Although not included in the originally identified project, RRC increased its scope of research-related activities in conjunction with both the original prototype bus and the subsequent SDTC project. RRC worked with MHI and was awarded additional funding through NSERC, using NSERC's Applied Research and Development (ARD) Level 2 funding stream. Although not all activities can be disclosed, RRC provided important support in battery pack assembly, battery management system, and battery pack monitoring for the MHI battery packs in the prototype bus and two of SDTC buses.

Although RRC's work was limited to a total of 520 kWh of battery pack capacity, through these activities RRC acted as a Tier 1 battery pack assembler, which is both a significant

and highly relevant accomplishment. Through additional NSERC funding, RRC also provided support to some additional activities with the prototype bus undertaken by New Flyer, although this work has not been publicly disclosed.

7.3 Joint Task Force on Transit Electrification

The most recent major activity following-up from the prototype bus project was the announcement in November 2015 of the formation of a joint task force by the Government of Manitoba and City of Winnipeg on transit electrification (Government of Manitoba 2015). The purpose of the task force was to examine the potential for broader implementation of electric buses beyond the demonstration activities already underway. The task force began and completed its main work during 2016. A public-oriented version of their final report was also prepared later in 2016. Release of this final report is still pending.

8.0 Future Potential Directions and Uses for Project Assets

The prototype bus development and demonstration has definitely been a significant success, and has set a number of important directions for the future. Two major assets remain that are both still actively in use: the prototype bus itself; and the core rapid-charger unit (i.e., less overhead gantry, transformers and other site elements currently at the airport charging station). Under the project agreement, a procedure to determine the final disposition of remaining project assets was included.

The prototype bus has been operational for roughly five years, and remains licensed and insured by RRC, being still the vehicle's registrant. Given its close similarity to the more modern XE40 bus models, the prototype bus has been in use with New Flyer most recently and publicly to test additional battery packs for the transit application. The prototype bus has also been associated with additional bus equipment testing work that has not yet been publicly discussed. As long as uses remain for the prototype bus, i.e., now primarily for research support, it is worthwhile to keep in operation. A number of possible alternative applications for the bus have been discussed.

The core rapid-charger has been in operation for more than four years, and remains in service as part of the SDTC project at the airport charging station. It will remain there until operation of the four-bus SDTC demonstration finally ceases. After that, however, the future of the rapid-charger is less certain. It could definitely still be used for the prototype bus or other second-generation electric buses, however, as discussed, the industry has been moving toward common charging standards. In such a developing environment, this older, "orphan" system has become largely obsoleted by technology advancement, a common issue for electrical and electronic systems.

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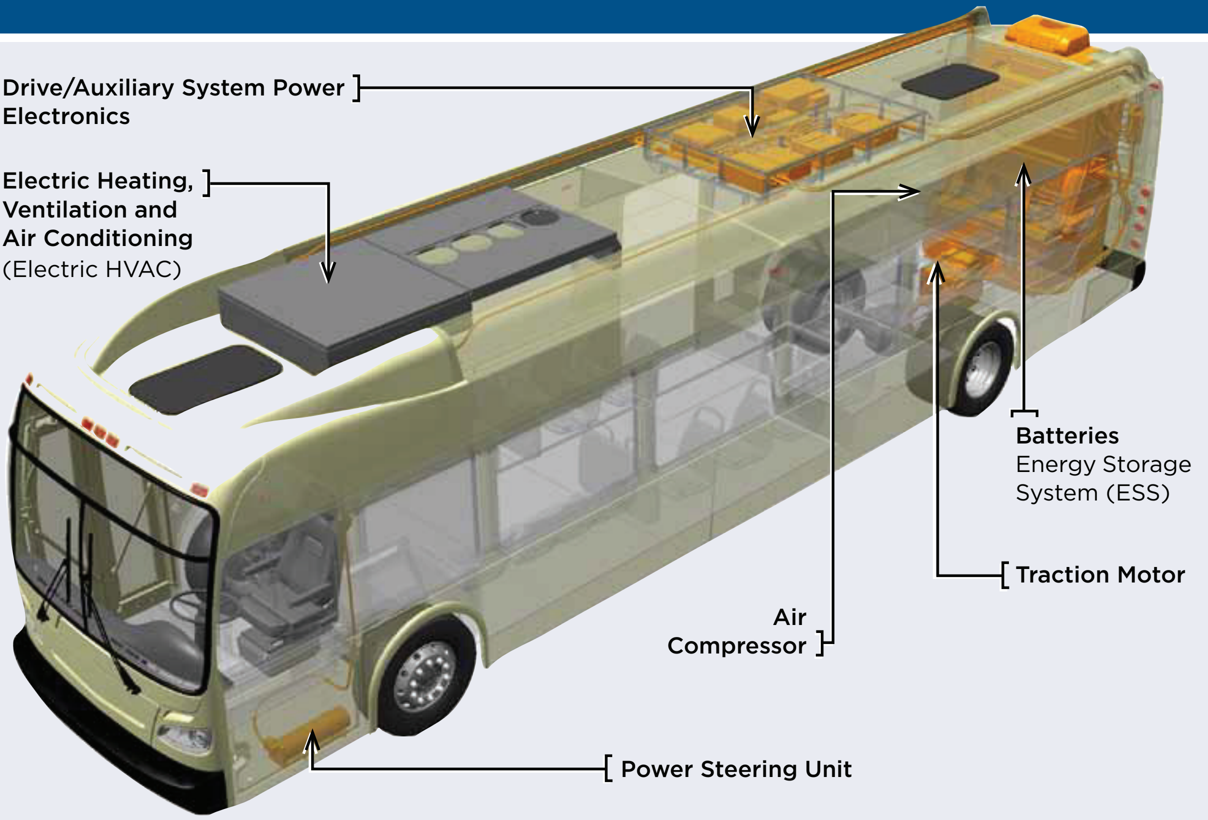
Note: ND = not dated.

Manitoba's All-Electric Bus: How It Works.

Manitoba's All-Electric Bus HOW IT WORKS



NO FUEL TANK – NO EMISSIONS

The bus is powered by energy stored in rechargeable batteries. Instead of an internal combustion engine, it's propelled by an electric motor.

BATTERIES

Up to 120 kWh of electricity is stored in high-voltage lithium ion batteries at the rear of the bus. A sophisticated battery management system constantly monitors and manages the system.

ELECTRIC DRIVE

Direct current (DC) power from the batteries is converted to 3-phase alternating current (AC) power to drive the traction motor. When braking, the motor acts as a generator to recover energy, just like in conventional hybrid vehicles.

AUXILIARY SYSTEMS

The power steering, air compressor and air conditioning systems are electrically powered. High-voltage DC power is converted to AC power and supplied to each of these major systems separately. This allows each system to operate efficiently, with minimum power consumption. The bus also has a high-voltage converter to supply 24-volt DC power for interior fans, lights, etc.

HEATING, VENTILATION AND AIR CONDITIONING

An electrically-driven air conditioning system is used to cool the bus when needed. For moderately cold temperatures, the bus uses electric heating. For very cold conditions, a liquid-fuel heater warms the passenger cabin using a small amount of renewable biodiesel. This helps maintain bus range during the winter.

CHARGING OPTIONS

The bus is connected to DC charging systems to recharge the batteries, either on route or at a transit yard. One key project goal is to demonstrate on route, rapid recharging capabilities.

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Appendix B

GHG emission reduction calculations and assumptions

Estimates of GHG emissions reductions depend on a number of assumptions:

- Extent of travel by the bus in question on a total cumulative or annual basis;
- Electricity consumption of electric bus, as well as any auxiliary fuel required;
- Fuel consumption the comparable diesel bus being displaced;
- GHG emissions associated with electricity;
- GHG emissions associated with diesel fuel blend, as well as associated diesel emission fluid (DEF) used in Tier 4, post-exhaust control systems for the diesel bus; and
- Basis for emissions calculation.

For the prototype bus itself, total travel of 33,000 km is assumed. In terms of annual bus travel for projections of fleet based emission reduction comparisons, three cases are included: (a) lower travel of 35,000 km per year; (b) average travel of 50,000 km per year; and (c) higher travel of 70,000 km per year.

Average fuel consumption for conventional diesel buses is assumed as 62 Litres per 100 km, which is based on average fuel consumption indicated publicly by Winnipeg Transit (i.e., 18 million Litres per year ÷ 29 million vehicle km per year). DEF consumption represents additionally about 2% of diesel fuel consumption. Diesel fuel contains approximately 2% biodiesel on average, based on Manitoba's current mandate requirements, and also reflected by the Federal Renewable Fuels Regulation. In the case of biodiesel, it is assumed that approximately 5% of the carbon content is fossil-based, this coming from natural-gas based methanol used in the transesterification reaction. Average electricity consumption for the prototype bus over all conditions is assumed as 160 kWh per 100 km, based on experience. An additional small amount of auxiliary fuel is assumed for heating purposes, which is diesel blend.

In terms of the GHG emissions reduction calculation methods, three bases are also considered: (a) combustion emissions, solely at the bus itself; (b) full-cycle emissions, including upstream emissions for energy and other inputs; and (c) National Inventory Report (NIR) based emissions, including only emissions that occur within the province, which effectively translates to full-cycle for electricity and combustion-only for liquid fuels.

Input Component	GHG Emissions Calculated on Different Bases		
	Combustion Only	Full-Cycle	NIR Based
Electricity	0.0 kg/kWh	0.004 kg/kWh	0.004 kg/kWh
Diesel alone	2.70 kg/L	3.90 kg/L	2.70 kg/L
Biodiesel alone	0.15 kg/L	0.50 kg/L	0.15 kg/L
Blended fuel	2.65 kg/L	3.83 kg/L	2.65 kg/L
DEF	0.50 kg/L	0.70 kg/L	0.50 kg/L

Transit Bus Option	GHG Emissions Calculated on Different Bases		
	Combustion Only	Full-Cycle	NIR Based
Conventional Diesel Emissions	165 kg/100 km	238 kg/100 km	165 kg/100 km
Prototype Electric Bus Emissions	2.4 kg/100 km	4.0 kg/100	3.0 kg/100 km
Electric Bus Net GHG Reduction	163 kg/100 km	234 kg/100 km	162 kg/100 km

Case	GHG Emission Reductions per Bus on Different Bases		
	Combustion Only	Full-Cycle	NIR Based
Prototype Bus (21,000 km total)	54 tonnes total	77 tonnes total	53 tonnes total
Lower Travel (35,000 km/yr)	57 tonnes/year	82 tonnes/year	56 tonnes/year
Average Travel (50,000 km/yr)	82 tonnes/year	117 tonnes/year	81 tonnes/year
Higher Travel (70,000 km/yr)	114 tonnes/year	164 tonnes/year	113 tonnes/year

Emissions associated with different energy and fuel inputs for the three different bases of calculations are summarized in the first table above. Electricity reflects Manitoba's approximate current grid mix, while all the others are based on fairly standard values for fuel components.

Based on these values, and associated input energy and fuel consumption rates, including auxiliary fuel used for heating in the case of the prototype bus, GHG emissions and net reductions per 100 km travel can be calculated as summarized in the second table above.

These data show that irrespective of the basis for emissions calculation, an electric bus based on the prototype operating within Manitoba achieves more than a 98% reduction in emissions on a per 100 km basis.

Using the above values, total GHG emission reductions for the prototype electric bus, if its operations had been undertaken using a conventional diesel bus, as well as annual reductions for the three projected cases of electric buses operated in transit fleets are summarized in the following table.

These results clearly show that the reductions achieved are significant, but also depend both on how much a given electric bus travels, and the basis on which the calculation is made as summarized in the third table above.

Electric Vehicle Technology & Education Centre (EVTEC)

EVTEC at Red River College is responsible for applied research and innovation projects concerning ground transportation electric and hybrid vehicles that utilize renewable fuels. EVTEC has a mission to: support electric vehicle (EV) innovation amongst Manitoba's transportation sector; enhance electric vehicle education at the College and in the region; and increase public awareness and understanding of electric vehicle technology.

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