

# **Technical Report – Hybrid Technology**

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## List of Acronyms

ECM	Electronic Control Module, computer control on engines or transmissions
VOC	volatile organic compound
hp	horsepower
EPA	Environmental Protection Agency
eq.	equivalent
GHG	greenhouse gas
CAP	common air pollutant (VOC, NO <sub>x</sub> , SO, particles)
UTSP	Urban Transportation Showcase Program
STM	Société de transport de Montréal
STO	Société de transport de l'Outaouais
TCM	Transmission Control Module, computer control on the Allison hybrid transmission
VCM	Vehicle Control Module, computer control for the parameters related to vehicle operation, in the case of a bus equipped with the Allison hybrid system

## Definitions

Hybrid	Diesel-electric hybrid bus, consisting of a diesel internal combustion engine combined with an electric motor and generator.
Control	Control bus: conventional diesel powered bus, also called a standard bus in this project, whose recorded readings are compared with the readings for the hybrid bus.
Topodyn	Software used to program the ZF transmission in standard buses.

## Summary

As part of the Urban Transportation Showcase Program (UTSP), the Société de transport de l'Outaouais (STO) and the Société de transport de Montréal (STM) became partners to develop a joint public transit project with the main objective of testing a series of measures intended to reduce greenhouse gas (GHG) emissions.

One of the UTSP components, led by the STM, consisted in measuring the environmental impact of its hybrid diesel-electric buses by comparing them with standard diesel buses. To do this, the STM put eight hybrid buses and six standard diesel buses of the same model into service on the same bus routes for a whole year. The same process was implemented by the STO in Gatineau with two hybrid buses and seven standard buses. A large volume of data was gathered to provide a comprehensive measurement of the reduction in fuel consumption generated by using hybrid buses, and therefore the production of GHGs.

The hybrid technology (on the Nova Bus 2008 models) made it possible to reduce fuel consumption by an average of 30% compared with a conventional power technology. The average speed of the buses monitored during the project was about 18 km/h, while the average number of stops was 3.8 per kilometre. The average temperature during the year of the project was 6.6°C (from -29°C to +33°C). Analyses of the results showed that this technology is particularly advantageous when the average operating speed is relatively low and the distance between stops is short.

The percentage that fuel consumption was reduced with hybrid buses (Nova Bus 2008) translates into a reduction in GHG emissions of almost 36 tonnes annually for a bus that travels about 70,000 km per year. This annual reduction of 36 tonnes of GHGs per hybrid bus is equivalent to removing more than seven individual vehicles from the roads. In fact, a vehicle that travels 20,000 km/year produces about 5 tonnes of GHGs per year. In particular:

- EPA 2007 compliant engines do not emit a significant amount of particles or total hydrocarbons (THC);
- The hybrid power system emits 5% more nitrogen oxides (NO<sub>x</sub>) than the standard power system and 36% less carbon dioxide (CO<sub>2</sub>).

The analysis tools that were developed during the study enable public transit corporation managers to assess the impact that the use of hybrid buses would have on the fuel consumption of their bus fleet. All they need to know is the total average speed, and the total average fuel consumption<sup>1</sup> to be able to use the tables presented in this report. Managers can thus determine whether hybrid power would be adaptable to their operating conditions.

Other technologies were also tested through this study and proved to be promising. Replacing the hydraulic ventilation system with a low-voltage electric system made it possible to reduce GHG emissions on both hybrid and standard buses, while optimizing the transmission programming on standard buses helped to reduce GHG emissions on regular buses. These modifications require a minimal investment.

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<sup>1</sup> The total average speed and total average fuel consumption are data that are available from the ECM on the Cummins engine.

# 1 Context and objective



The Urban Transportation Showcase Program (UTSP) is a Transport Canada initiative that is part of the Government of Canada's Action Plan 2000 on Climate Change. The Société de transport de l'Outaouais (STO) and the Société de transport de Montréal (STM) participated in this program jointly by developing a public transit project. As part of the project, various measures were tested in order to reduce greenhouse gas (GHG) emissions.

One of the UTSP components involves hybrid technology. It was led by the STM. In order to measure the environmental impact of putting hybrid diesel-electric buses into service, a meticulous methodological approach was followed. The STM put 14 buses fitted with a data acquisition system into service, consisting of eight hybrid buses and six standard diesel buses of the same model. The buses ran along the same routes for an entire year. The same exercise was carried out by the STO in Gatineau with two hybrid buses and seven standard buses.

A very large volume of data was gathered in order to compare the performance of a hybrid bus with that of a standard bus. The data made it possible to precisely measure the factors influencing fuel consumption, and consequently GHG emissions. The extent of the database makes it possible to reduce the margin of error of the results and to make the results applicable to many conditions.

In 2006, intra-urban transit buses generated more than 284,000 tonnes of GHGs in Quebec.<sup>2</sup> Although this corresponds to only 0.3% of total GHG emissions in the province, it is important for public transit corporations to be proactive in addition to being leaders in environmental issues in order to offer transportation that is as "green" as possible.

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<sup>2</sup> Office of Energy Efficiency (OEE), Natural Resources Canada.

## 2 Methodology

Studies on the impact that hybrid buses have on GHG reduction have already been carried out in several North American and European cities. However, the variety of conditions in which these studies were completed made the results hard to compare. For instance, the hybrid bus was not the same model as the control bus, or the number of stops per kilometre or bus speed were not the same in both cases. These results, which sometimes contradict the benefits of hybrid technology, make it more complicated for operators who would like to acquire a fleet of hybrid buses.

The main feature of the methodology used in this study is the compatibility between the results gathered for the hybrid buses and the standard buses, as well as the amount of data collected. This approach has the benefit of producing precise, coherent results, and extensive applicability, and the volume of data gathered makes the margin of error very small. The methodology followed is described in the following sections.

### 2.1 Type of bus

In this study, the performance of hybrid buses was compared with the performance of regular diesel buses. To do this, the STM acquired eight hybrid buses and six standard diesel buses. The diesel buses were called the control buses. The hybrid buses and the control buses were identical since they were the same model and year of make. Only the components specific to the power systems were different. In the case of the STO, nine buses took part in the study: two hybrid buses and seven standard diesel buses.

The STO and STM hybrid and control buses were made by Nova Bus, model Nova LFS. The hybrid buses were fitted with the parallel EP40 hybrid electric system made by Allison Transmission. The general characteristics of the buses in this study are given in Figure 2-1.

**Figure 2-1 General characteristics of the Nova LFS bus**



Structure	Stainless steel
Outer shell	Fibreglass and thermoplastic skirt panels
Length	12.2 m (40 ft)
Width	2.6 m (102 in)
Height	3.1 m (123 in)
Wheelbase	6.2 m (244 in)
External turning radius	12.2 m (40.1 ft)
Electric system	Volvo Bus Electronic Architecture (VBEA)
HVAC system	MCC standard - Thermo King or Carrier air-conditioning
Engine	Cummins ISL 250 hp standard - Cummins ISL 280 hp
Transmission	ZF 6HP554C standard - Voith or Allison available
Front axle disk brakes	ZF RL85 - Rigid axle
Rear axle disk brakes	ZF AV-132
Brakes	ABS with traction control
Fuel tank capacity	454 litres (120 US gallons)

The general characteristics applied to the hybrid and control buses used by the STM and the STO. However, some characteristics were specific to certain buses. For instance, the STO's buses had air-conditioning, whereas the STM buses were not air-conditioned.

In addition, the engines in the STM and the STO buses assigned to the UTSP did not all meet the same standards. While the engines in the hybrid buses and some STO control buses met the EPA 2002 standard, the engines in the STM buses complied with the EPA 2007 standard. The engines were all CUMMINS ISL models. The engines in the STO buses assigned to the UTSP were all 280 hp.<sup>3</sup> As for the 14 STM buses assigned to the UTSP, the eight hybrid buses and three control buses had 280 hp engines, while the other

<sup>3</sup> The abbreviation "hp" stands for horsepower.

three control buses had 250 hp engines. Note that all the buses in the STM's fleet are equipped with 250 hp engines. When the hybrid power systems were ordered for the project, they were offered with 280 hp engines only. The STM therefore decided to acquire 280 hp and 250 hp control buses to be able to do a cross analysis of the results. The specific characteristics of the STM and STO hybrid buses are shown in Table 2-1.

**Table 2-1 Characteristics of the hybrid and control buses used by the STM and the STO**

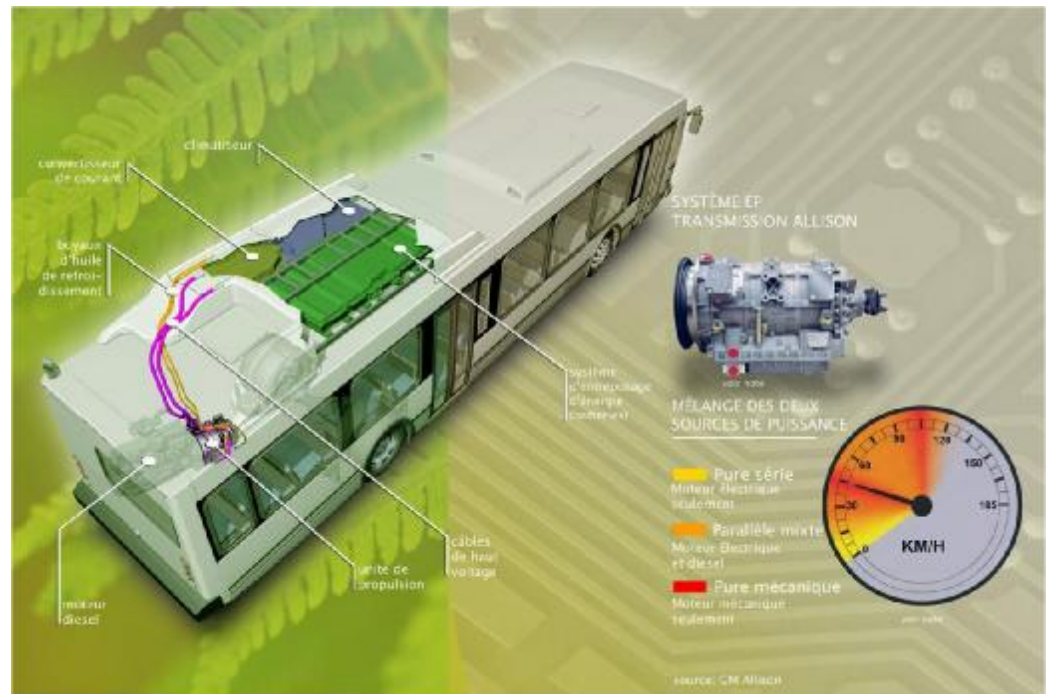
Corporation/ Identification	STO-control 2006	STO-control 2007	STO- hybrid 2006	STM- control 250 hp 2008	STM- control 280 hp 2008	STM- hybrid 280 hp 2008
Delivery date	2006-April	2007-May	2007-May	2008-Jan	2008-Jan	2008-April
Total average km per bus on March 31, 2009	185,000	88,000	87,000	82,000	82,000	52,000
Model	Nova LFS	Nova LFS	Nova LFS HEV	Nova LFS	Nova LFS	Nova LFS HEV
Engine	Cummins ISL 8.3 l	Cummins ISL 8.9 l	Cummins ISL 8.3 l	Cummins ISL 8.9 l	Cummins ISL 8.9 l	Cummins ISL 8.9 l
Programming	280 hp	280 hp	280 hp	250 hp	280 hp	280 hp
Standard/EPA	2002	2007	2002	2007	2007	2007
Transmission	ZF-Ecomat	Voith	Allison EP40	ZF-Ecomat	ZF-Ecomat	Allison EP40
Air-conditioning	Carrier	Carrier	Thermo King	N/A	N/A	N/A
Total weight (kg)	12,670	12,100	13,560	12,200	12,200	13,383

The hybrid power systems use electric components to transfer, recover and collect energy. They are hybrid diesel-electric drivetrains comprising a diesel internal combustion engine and electric motors and generators. The system consists of four main electromechanical parts:

- The drivetrain (Allison EP transmission) that contains the gears and two electric motors;
- The electric energy storage system (ESS), consisting of a roof-mounted nickel metal hydride (NiMH) battery weighing about 400 kg;
- The dual power inverter module (DPIM) that manages the flow of current between the transmission and the battery;
- The two logic control modules (also called the TCM and VCM computers) supplied by Allison that manage the drivetrain system.

More details about the hybrid technology and the technical characteristics of the hybrid buses used by the STM and STO are provided in Appendix A.

**Figure 2-2 Location of the components on a Nova Bus hybrid bus**



convertisseur de courant = current converter  
 climatiseur = air-conditioner  
 boyaux d'huile de refroidissement = cooling oil hose  
 moteur diesel = diesel engine  
 unité de propulsion = drivetrain  
 câbles de haut voltage = high voltage cables  
 système d'entreposage d'énergie (batteries) = energy storage system (batteries)

Système EP Transmission Allison = Allison EP Transmission system  
 Mélange des deux sources de puissance = Blend of two sources of power  
 Pure série = Pure electric  
 moteur électrique seulement = Electric motor only  
 Parallèle mixte = Parallel mix  
 Moteur électrique et diesel = Electric motor and diesel engine  
 Pure mécanique = Pure mechanical  
 Moteur mécanique seulement = Mechanical engine only  
 voir note = see note

## 2.2 Deployment of hybrid and control buses

The STM's first control buses were delivered in late January 2008. The first hybrid bus was delivered on February 13, 2008, while the STM's other hybrid buses were delivered between mid-March and early April 2008, and were put into service for passengers on April 21, 2008. The control buses had already been operating with passengers since February 2008.

The routes on which the hybrid and control buses ran were chosen according to the information available in the documentation concerning the performance of hybrid buses. The documentation suggested that hybrid technology would perform best in conditions

where the average speed is relatively low and where stops are frequent. Consequently, bus routes in downtown Montreal were chosen. Also, in order to assess the impact of the topography, routes passing close to Mount Royal were selected. Finally, to have a large amount of variability in terms of average speed and number of stops, some buses ran on routes that served less dense areas.

The STO acquired its two hybrid buses almost one year before the STM acquired its buses. Service with passengers started on March 23, 2007. Data acquisition on the hybrid and control buses started in late February 2008, or at the same time as data acquisition for the STM buses. The corridor chosen by the STO consisted of its green bus route along Gréber/Fournier/Maisonnette/Portage Bridge/Ottawa, called the "Ligne verte." This corridor is 9 kilometres long with 49 stops. About 50 buses travel along this route per hour during the morning rush hour, with service provided by three regular bus routes and seven express routes. About 10,000 trips are carried along this axis daily.

For fuel, the STM buses used biodiesel composed of 95% petro-diesel and 5% biodiesel produced from animal fat and recycled vegetable oil. The STO used 100% petro-diesel as fuel.

## 2.3 Measurable parameters



A large volume of data was collected in order to measure the performance of the hybrid and standard buses and clearly understand what influences this performance. Bus performance is measured primarily by fuel consumption. Some factors that cause fuel consumption to vary are well known, such as the average speed, distance covered and average acceleration. In addition, in order to properly understand the operation of the diesel engine and the battery in the hybrid system, the amount of energy of these two systems was also recorded. In all, more than 30 parameters were measured. The main ones were:<sup>4</sup>

- Fuel consumption in litres/100 km;
- Average bus speed;
- Distance travelled;
- Average acceleration;

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<sup>4</sup> The complete list of parameters is presented in Appendix B.

- Average outdoor temperature;
- Dwell time;
- Operating time of the diesel auxiliary heating;
- Average engine speed of the diesel engine;
- Amount of electric energy generated by the hybrid system;
- Operating time of the compressor for the pneumatic system;
- Demand on the accelerator and brakes;
- Current on the standard 24-volt charging system.

## 2.4 Instrumentation

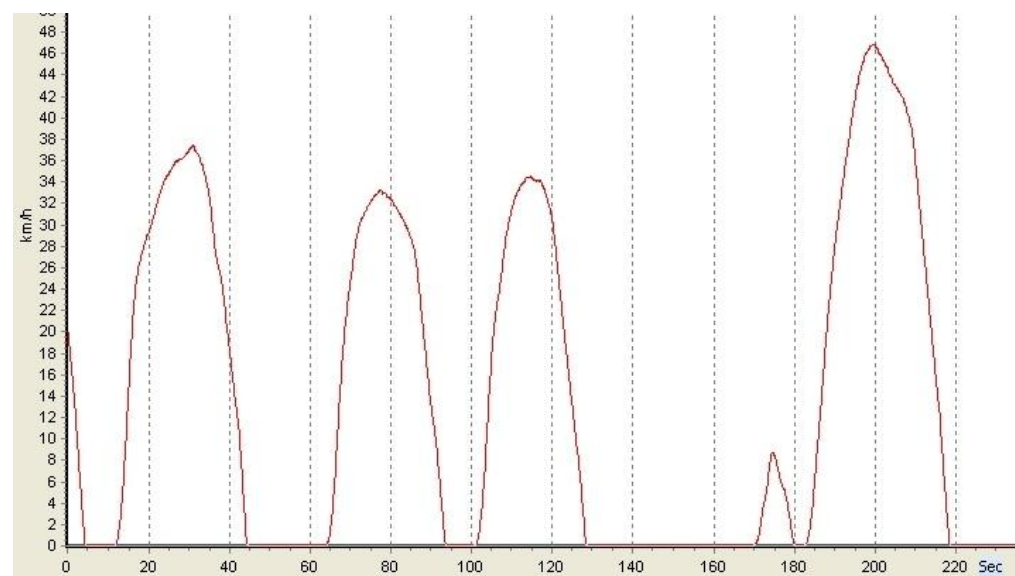
In all, more than 30 parameters were measured continuously for one year on the hybrid and control buses. More than **20 billion items of raw data** were compiled. To record all these data, an advance data acquisition system provided by ISAAC Instruments Inc., a Quebec company, was installed on the STM and STO hybrid and control buses. This system continuously recorded the data related to drivetrain operation, along with anything related to bus operating conditions.



The ISAAC data acquisition system was installed at the back of the bus, under the outside illuminated display panel. The data were transferred by wireless modem when the buses arrived at the transit centre. Every bus therefore gathered more than 14 MB of data per day.

Gathering such a large amount of data through the ISAAC system nonetheless made analysis complex. Figure 2-3 illustrates the type of results obtained by the ISAAC data acquisition system.

**Figure 2-3** Simplified example of the results of the ISAAC data acquisition system



Initial analyses made it possible to observe that all the stop-and-go cycles had the same characteristics, although their values changed in each cycle. As shown in Figure 2-3, which presents several stop-and-go cycles, each cycle starts with a speed of 0 km/h, increases to a maximum, and then drops back down to 0 km/h to stay there until the next start. This general cycle represents all the events that a bus could encounter, such as the travel between two bus stops followed by the time for passengers to get on and off the bus, or the incessant stop-and-go of driving in traffic. In this report, these cycles are defined as "hops."

For every hop, it is possible to calculate the key values such as average speed, average acceleration and fuel consumption. Furthermore, since the parameters presented in the previous section are gathered for each hop, it is possible to evaluate the impact of the hop. For example, it is possible to determine the impact of outdoor temperature on fuel consumption by comparing the fuel consumption of all hops that have the same average speed, but at different temperatures.

To help with analysis, the Matlab<sup>5</sup> software was used and a set of logic commands and interactions were programmed. The result is an information matrix of all the parameters related to a hop. This matrix was developed with the participation of the Centre national de transport avancé (CNTA). For each hop, it includes the results calculated for various measured parameters. Analyzing the information contained in this matrix makes it possible to predict the fuel consumption of both types of buses evaluated depending on variable operating conditions.

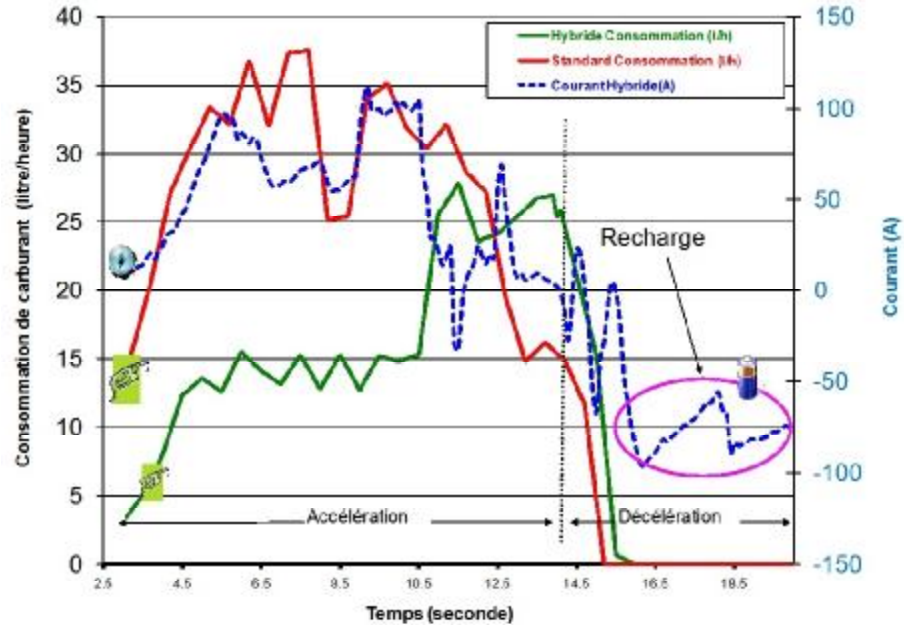
Figure 2-4 shows the fuel consumption in a typical hop for a hybrid bus and a control bus (in litres per hour), along with the current used by the hybrid vehicle's battery (in amperes). Certain characteristics of a typical stop-and-go can be observed that are similar to the 5 million stops documented during the project. They show acceleration up to 50 km/h for a control bus and a hybrid bus. The following information can be deduced:

- Fuel consumption of the control bus reaches a peak value of 37 litres per hour (0.01 litre/second) during this acceleration;
- Peak fuel consumption for the hybrid bus is in the order of 27 litres per hour (0.007 litre/second);
- Total fuel consumption during this phase was 1.3 litres for the control bus and 0.35 litre for the hybrid bus.

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<sup>5</sup> Matrix calculation software produced by Mathworks Inc.

**Figure 2-4 Comparison of fuel consumption and flow of electric current – Nova 2008 hybrid and control bus**



Consommation de carburant (litre/heure) = Fuel consumption (litres/hour)

Temps (seconde) = Time (seconds)

Courant (A) = Current (A)

Recharge = Recharge

Accélération = Acceleration

Décélération = Deceleration

Hybride Consommation (l/h) = Hybrid consumption (l/h)

Standard Consommation (l/h) = Standard consumption (l/h)

Courant Hybride (A) = Hybrid current (A)

It can be seen that the fuel replacement energy for the hybrid vehicle during this acceleration is provided by the battery. During deceleration, the battery's amperage sign inverses, indicating that it is the regenerating phase. The two electric motors in the transmission become a generator at the same time as they are slowing the vehicle.

For more information on the ISAAC data acquisition system, see Appendix B.

## 2.5 Personnel training

The mechanical and electrical maintenance personnel for the hybrid buses at the STM, and the engineering personnel received one week of training given by a specialist from Allison Transmission. The training covered basic maintenance and safety related to the high voltage electrical system, as well as diagnostic and repair methods in case of malfunction.

The drivers at Centre de transport LaSalle, the location of the hybrid buses, received three hours of training that included the theory of the hybrid system and driving practice. The training was developed by the STM's training personnel.

At the STO, all drivers received theoretical and practical training that lasted 1 hour and 15 minutes. Note that all new STO bus drivers receive this training.

## 2.6 Tests at the Environment Canada laboratories

A series of laboratory tests was carried out to analyze the performance of the hybrid and control buses under controlled conditions. The fuel consumption and polluting emissions were measured and compared. These tests were also used to calibrate the ISAAC data acquisition system in terms of fuel consumption to be able to accurately determine the relationship between fuel consumption and polluting emissions. The diesel used in the tests of the STO and STM buses was biodiesel composed of 95% petro-diesel and 5% biodiesel produced from animal fat and recycled vegetable oil.

The "Manhattan" bus cycle was used for the base comparison because it is well known in the urban public transit industry. Therefore, for a typical route, the bus must run on the rollers of a dynamometer at a controlled steady speed with the same number of stops and starts. This approach makes it possible to compare the distance travelled, accelerations, maximum and average speeds, and dwell times with much greater reliability. All the exhaust gases are sucked in and processed by a complex chemical analysis system. This makes it possible to establish the concentration of the various pollutants and the average fuel consumption of the bus for the type of route covered. Figure 2-5 illustrates the laboratory tests.

**Figure 2-5 Tests at the Environment Canada laboratories**



In all, 10 tests were carried out. To measure the impact of summer and winter temperatures on the performance of hybrid and regular buses, tests were carried out at +20°C and -20°C. Finally, since the STO buses are equipped with an air-conditioning

system, tests in which the AC was turned off and when it was on high were done. The list of the conditions for the 10 laboratory tests is given in Table 2-2.

**Table 2-2 List of tests in the Environment Canada laboratories**

Temperature	Bus	Air-conditioning
+20°C	STM hybrid	
+20°C	STM control 280 hp	
+20°C	STM control 250 hp	
+20°C	STO hybrid	Without air-conditioning
+20°C	STO hybrid	With air-conditioning
+20°C	STO control 280 hp	Without air-conditioning
+20°C	STO control 280 hp	With air-conditioning
-20°C	STM hybrid	
-20°C	STM control 280 hp	
-20°C	STM control 250 hp	

## 2.7 Controlled tests on an outdoor track



In late August 2008, the outdoor track at the PMG Proving Ground in Blainville, Quebec, was used for controlled fuel consumption tests of the STM's hybrid and control buses (see Figure 2-6). A closed circuit track is a tool that allows vehicles to be driven safely without having to worry about the vehicle traffic that is common on public roads. The proving ground allows vehicles to travel for set distances at controlled speeds, such as having two buses operating at the same time and in the same way without being interrupted by signage, intersections or the interaction with other vehicles.

The proving ground tests evaluated the following points:

- Establish fuel consumption trends depending on the number of stops per kilometre;
- Establish fuel consumption trends depending on the load carried;
- Measure the combined effect of the load and number of stops per kilometre;
- Obtain comparable results for the hybrid and control buses;
- Identify any other significant aspect that could potentially be observed during the tests in service with passengers.

The maximum target speed between stops is 50 km/h. When the number of stops per kilometre increases, the maximum speed between the stops decreases, which is similar to what is observed in regular service. The tests were conducted with a varying number of stops per kilometre, with a maximum of 10. A reduced set of tests was also conducted with a maximum speed of 70 km/h with no more than two stops per kilometre.

**Figure 2-6**      **Controlled tests on at the Blainville proving ground, Quebec**

	<p>The proving ground tests were conducted on a control bus and a hybrid bus at the same time.</p>
	<p>The instruments in the data acquisition system made it possible to have a computer screen telling the driver the precise distance (to 0.01 km) in real time between stops, the speed reached and the acceleration measured by one of the accelerometers.</p>
	<p>During the tests at the PMG proving ground, the passenger load was simulated using bags of sand. The tests were carried out over several days with an empty load or the equivalent of 20, 40 or 60 passengers.</p>

## 2.8 Service life

In addition to measuring the fuel consumption of the hybrid and control buses, the acquisition and maintenance costs must be estimated in order to compare the service life of these two types of buses. This part of the study was carried out with the participation of the Marcon group. The cost analysis is separated into two components:

- The bus acquisition, operation and maintenance costs;
- The introduction and integration costs.

The main components on the hybrid and diesel buses for which a difference in the preventive maintenance and replacement costs must be taken into account are the starter, transmission, energy storage system, engine, current inverter and cooler.

In addition, it is possible that some installations could require modifications, namely because the hybrid bus is heavier and higher than a standard bus. If this is the case, the cost of modifications such as the capacity of the cylinders, door height, bus wash height, clearance between the cylinders and roof structure, etc, must be considered.

## 2.9 Driver and passenger survey

A survey was carried out among CT LaSalle bus drivers for their reactions to their driving experience on the hybrid buses.

STM passengers on the hybrid buses were also surveyed. The survey was conducted during the winter of 2009.

## 3 Analysis of the results

The analysis results are generally presented in terms of fuel consumption. These data were measured during all the tests in order to compare the performance of the hybrid and control vehicles. The GHG emissions are directly proportional to fuel consumption. In the case of diesel, one litre of diesel used by a bus emits about 2.7 kg of GHGs.<sup>6</sup> A drop in fuel consumption therefore represents a similar proportional reduction in GHGs.

The hybrid technology was compared to the standard diesel technology according to three types of tests:

- Tests at the Environment Canada laboratories;
- Controlled tests on a proving ground;
- Tests in service with passengers compiled over one year.

The results are presented in the following sections.

### 3.1 Results of tests at the Environment Canada laboratories

The results from the tests at the Environment Canada laboratories provided the first comparison data obtained during the UTSP project. These tests made it possible to measure the concentrations of polluting gases released by the hybrid and control buses operated by the STM and the STO. All the results are presented in Appendix C.

As mentioned in section 2.6, 10 tests were carried out on the standardized "Manhattan" bus cycle using variable temperature and bus configuration conditions. The tests were conducted at an average speed of about 11 km/h and the maximum speed reached was about 41 km/h. The average number of stops was seven per kilometre travelled. It is important to note that an Environment Canada employee operated the bus; although this person attempted to reproduce the same accelerations and conditions between buses, there is still a slight variability in the results. The values obtained are therefore not absolute values.

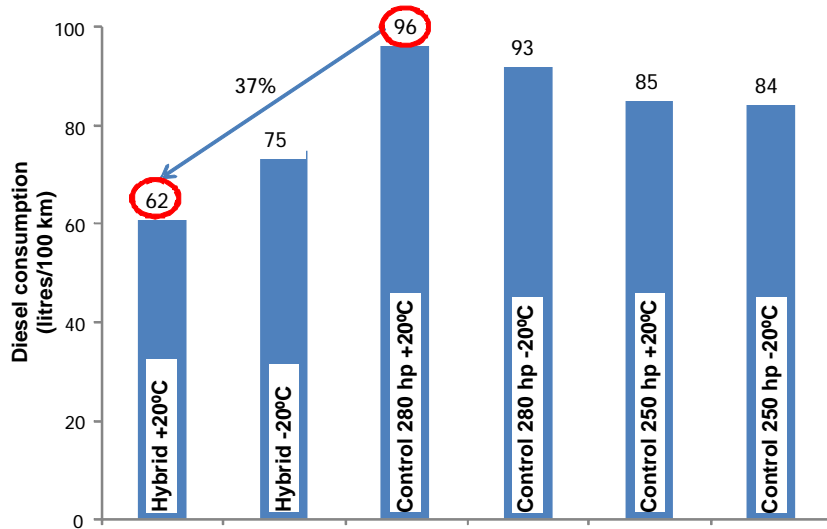
The comparison of fuel consumption between the STM's hybrid and control buses is shown in Figure 3-1 while the results for the STO's buses are shown in Figure 3-2.

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<sup>6</sup> According to ISO 14064-1 standard, see Appendix F. This is the amount of GHG emissions at the exhaust and not the emissions from the "well to the wheel."

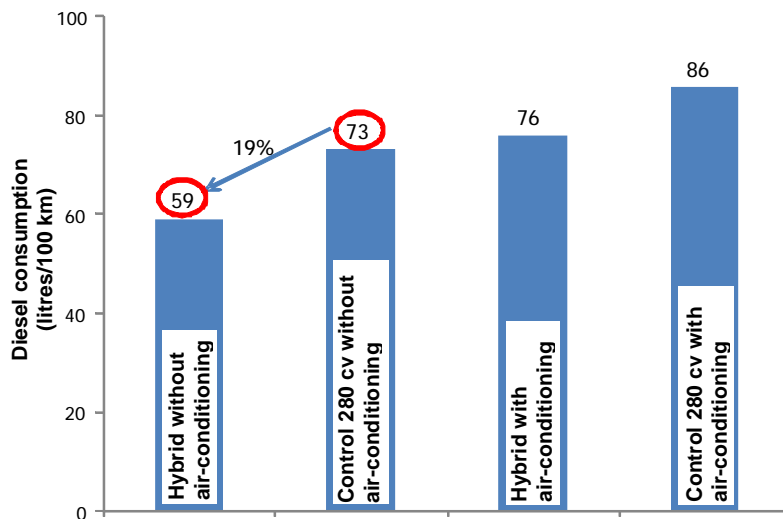


**Figure 3-1 Fuel consumption of STM buses – Results of tests at the Environment Canada laboratories (average speed of 11 km/h)**



It can be seen that at a temperature of +20°C, the STM's hybrid bus consumed 37% less fuel than the control bus, or 62 litres/100 km compared to 96 litres/100 km. It can also be seen that the outdoor temperature has an effect on the performance of hybrid buses. Fuel consumption for the hybrid bus went from 62 litres/100 km at +20°C to 75 litres/100 km at -20°C. This variation is much lower for the control buses. The difference in the rate of fuel consumption depending on temperature can be explained by a potential decrease in the battery performance of the hybrid bus, by the rate at which the hydraulic fan is used and/or even engine performance.<sup>7</sup>

**Figure 3-2 Fuel consumption of STO buses – Results of tests at the Environment Canada laboratories (average speed of 19 km/h)**

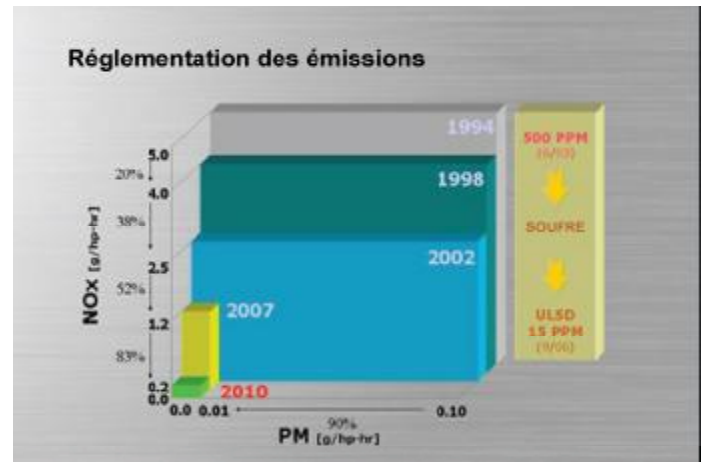


In the case of the STO's buses, the hybrid bus consumed 59 litres/100 km (without air-conditioning) compared to 73 litres/100 km for the control bus, or a reduction of 19%. This

<sup>7</sup> For the tests, the auxiliary heating system was deactivated so it did not distort the fuel consumption values.

fuel economy is less than that of the STM buses, where the hybrid bus consumed 37% less fuel than the control bus. This significant difference in fuel economy in the STM's hybrid buses compared to the STO's buses is a result of the calibration of the Cummins tandem engines and the Allison EP40 transmission.

Because the EPA 2002 generation engines are relatively polluting compared to EPA 2007 generation engines, Allison and Cummins chose to calibrate the hybrid system in this generation to optimize the reduction of CAPs. Furthermore, since the EPA 2007 generation engines were designed to significantly reduce CAP emissions, Allison and Cummins chose to calibrate the hybrid system in this generation to optimize fuel economy and consequently reduce GHGs.



Réglementation des émissions = Emissions Regulations  
Sulfre = Sulphur

The tests with the STO's buses also made it possible to measure the impact of air-conditioning on the fuel consumption of the hybrid and control buses. Activating the air-conditioning on the STO's hybrid buses resulted in an increase in fuel consumption of 12%, whereas the increase was 17% for the STO's regular buses. It is important to mention that the air-conditioning was on high during the tests, or at 100% throughout the test period. This is not representative of real conditions where the air-conditioning is intermittent in response to the rate of cooling requested.

This process also made it possible to measure fuel consumption during a long trip with a high average speed and few stops. For example, for the Montreal-Ottawa route, a distance of 230 km, in a cold season and at an average speed of 100 km/h, bus fuel consumption was about 30 litres/100 km with no distinction between hybrid or control buses. This confirms what is contained in documentation about hybrid power systems:

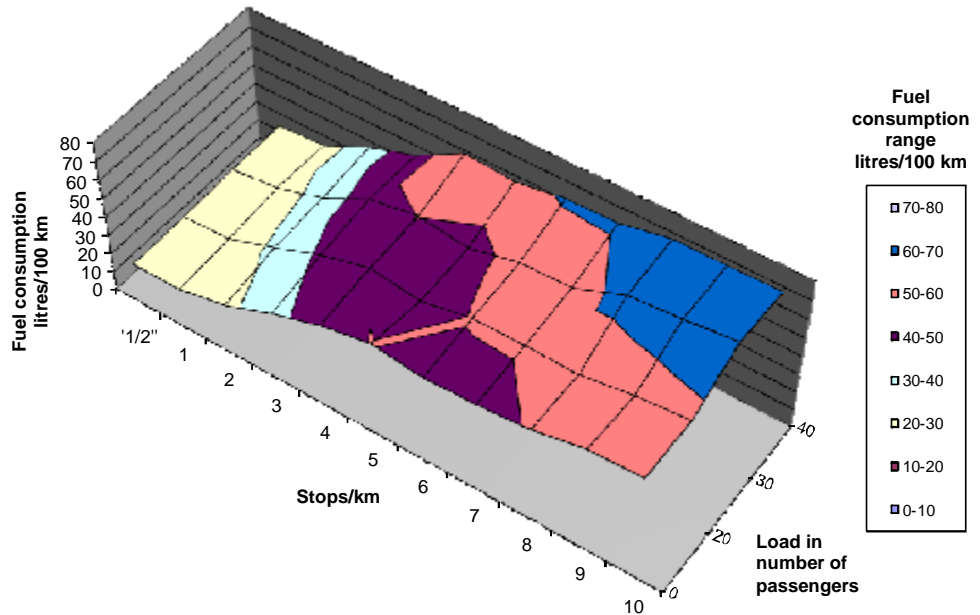
- They provide a reduction in fuel consumption at low speeds and with frequent stops;
- They have little impact at high speeds on long trips with few or no stops.

### 3.2 Results of controlled tests on a track

Controlled tests on a track were conducted at the PMG Proving Ground in Blainville, in August 2008 with the STM buses only.

The maximum target speed between stops was 50 km/h, with one stop per two kilometres, up to 10 stops/km. Each series was conducted over two kilometres to establish a representative average despite some variations in acceleration. The data retrieved from the ISAAC system were analyzed and Figure 3-3 shows the hybrid bus test results.

**Figure 3-3** Controlled tests on a track – Fuel consumption depending on the number of stops per kilometre and the number of passengers – Nova 2008 hybrid bus (auxiliary heating system consumption is excluded)



This graph shows that fuel consumption increases gradually depending on the number of stops per kilometre and the load carried.

Although the results obtained with the control bus show the same trend, they demonstrate that the driver's rate of acceleration had a much greater impact on a standard bus than on a hybrid bus. This variation distorted the data gathered on the standard bus and made it impossible to analyze the data related to the different factors studied. Furthermore, the tests made it possible to conclude that the rate of acceleration has a greater impact in the case of standard buses than hybrid buses.

### 3.3 Analysis of hybrid technology in service with passengers

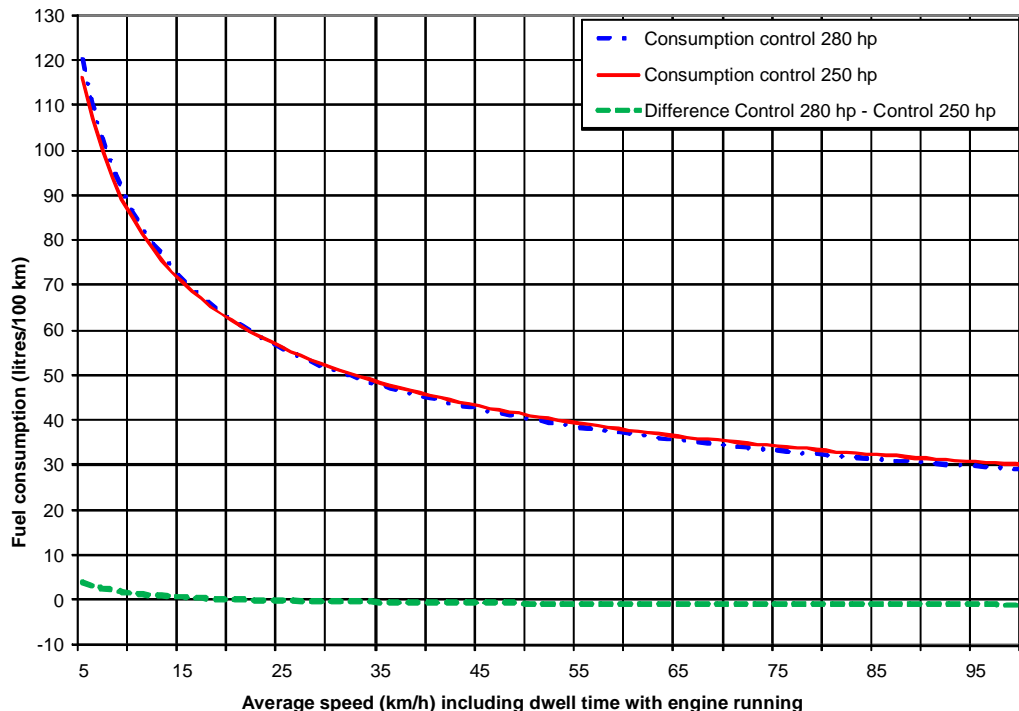
Many parameters such as average speed, number of stops per kilometre, outdoor temperature and rate of acceleration were observed using data acquisition tools. The variation in these parameters was analyzed according to fuel consumption. The graphs below show the main results obtained after one year of service with passengers.

As mentioned in section "2.1 Type of bus,"<sup>8</sup> the STM chose to equip its standard buses that served as control buses with 250 hp engines (three buses) and 280 hp engines (three

<sup>8</sup> As for the 14 STM buses assigned to the UTSP, the eight hybrid buses and three control buses had 280 hp engines, while the three other control buses had 250 hp engines. Note that all buses in the STM's fleet are equipped with 250 hp engines. When the hybrid power systems were ordered for the project, they were offered

buses). The results obtained, see Figure 3-4, show that for the STM's operating conditions, fuel consumption for all the control buses was similar, regardless of engine type.

**Figure 3-4 Fuel consumption of the STM control buses with 250 hp and 280 hp engines (auxiliary heating system consumption is excluded)**



In the light of these results, the performances of the hybrid buses presented in this chapter will be compared with the performances of all the control buses, regardless of the type of engine in the control buses.

The curves below represent the average speeds calculated as illustrated in section "2.4 Instrumentation." Each point on these curves represents the average speed in a stop-and-go cycle, meaning the cycle of acceleration, deceleration and the dwell time between two starts from 0 km/h. This can represent the average speed between two bus stops, or the average speed between two stops in traffic. Therefore, a low average speed (representative of a dense urban environment) indicates that the distance travelled between two stops is short.

Since the most demanding cycle for an internal combustion engine, in terms of fuel consumption, is the acceleration cycle, it is normal that an internal combustion engine consumes more at a low average speed than at a high average speed. In addition, a certain amount of fuel is consumed by the internal combustion engine during stops, since it continues to idle (this time is included in the total time).

The data gathered related to the number of stops per kilometre confirm that the greater the number of stops per kilometre, the higher the fuel consumption. In fact, these are the conditions where a hybrid power system is put to best use, since it recovers energy during

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with 280 hp engines only. The STM therefore decided to acquire 280 hp and 250 hp control buses to be able to do a cross analyses of the results.

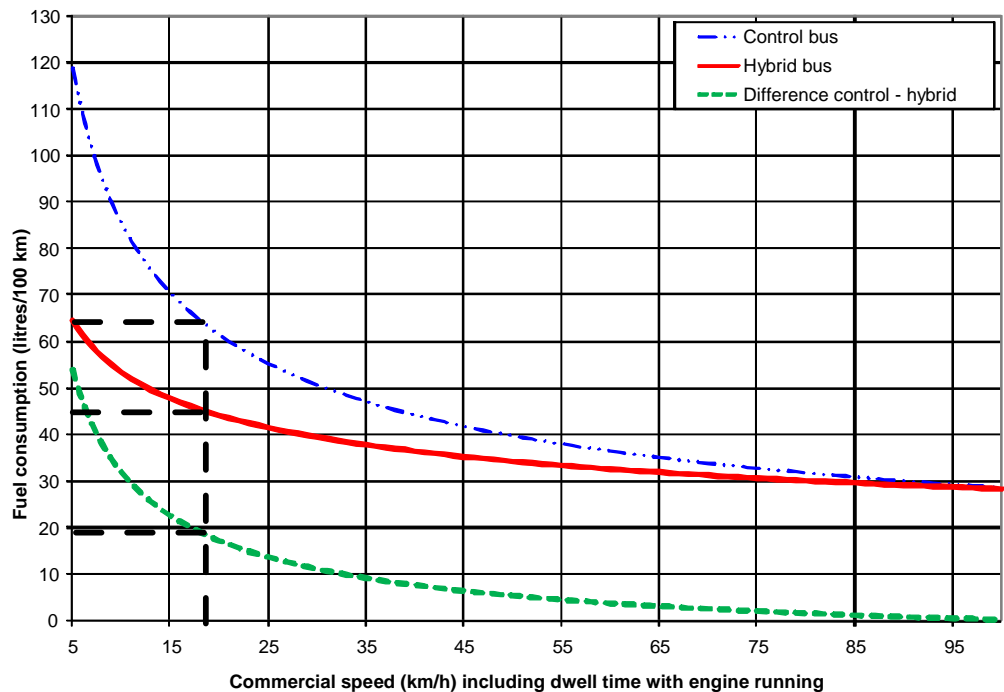
the many decelerations, which is then used in the accelerations. The result is a lower demand on the internal combustion engine, which then uses less fuel.

Figure 3-5 shows fuel consumption depending on average speed for the STM's hybrid and control buses. We can observe that at a speed of **18 km/h**.<sup>9</sup>

- Fuel consumption is 65 litres/100 km for the control bus, while it is 45 litres/100 km for the hybrid bus;
- The reduction in fuel consumption is substantial: 20 litres/100 km, or **30%**;
- However, when the speed tends toward 100 km/h, both types of buses show very similar fuel consumption. This situation represents highway driving conditions where the advantages of a hybrid bus are much less significant than in an urban environment.

Note that fuel consumption includes only the fuel used by the internal combustion engine of the power system. It excludes the fuel consumed by the diesel auxiliary heating system, which is included in Figure 3.6.

**Figure 3-5 Bus fuel consumption depending on average speed – Nova Bus 2008 bus (auxiliary heating system consumption is excluded)**



**Note:** Average of the results gathered over one year, with an average speed of about 18 km/h, a minimum temperature of -28.5°C, a maximum temperature of 33.4°C and an average temperature of 6.6°C, as well as 34% of the time with the engine idling. This curve applies to buses without air-conditioning and with a ZF transmission on the control buses.

Figure 3-6 shows fuel consumption depending on the number of stops per kilometre for the STM's hybrid and standard vehicles. The fuel economy for the hybrid bus compared to the control bus is very low when there are no stops, but increases very rapidly as the number of stops increases. For a number of stops per kilometre varying between two and

<sup>9</sup> Average speed of the 14 STM buses assigned to the UTSP during the year of the project. Note that the values presented are averages and not absolute values.

10, which is what is generally observed for public transit routes in an urban environment, the hybrid bus consumes about 20 litres/100 km less than the control bus.

In general, passenger service usually does not have more than 10 stops per kilometre to allow passengers to get on and off. The graph shows all the stops counted, even when the bus moves only a few metres at a time, as sometimes occurs in congested traffic conditions or in parking lanes.

**Figure 3-6 Fuel consumption depending on the number of stops per kilometre – Nova Bus 2008 (auxiliary heating system consumption is excluded)**

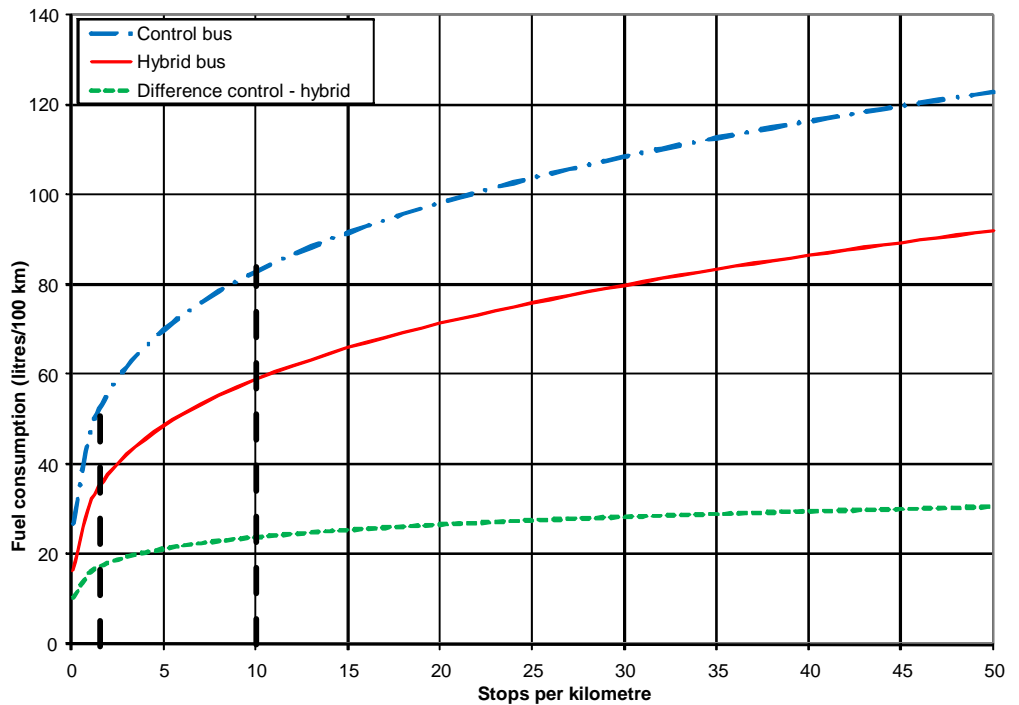


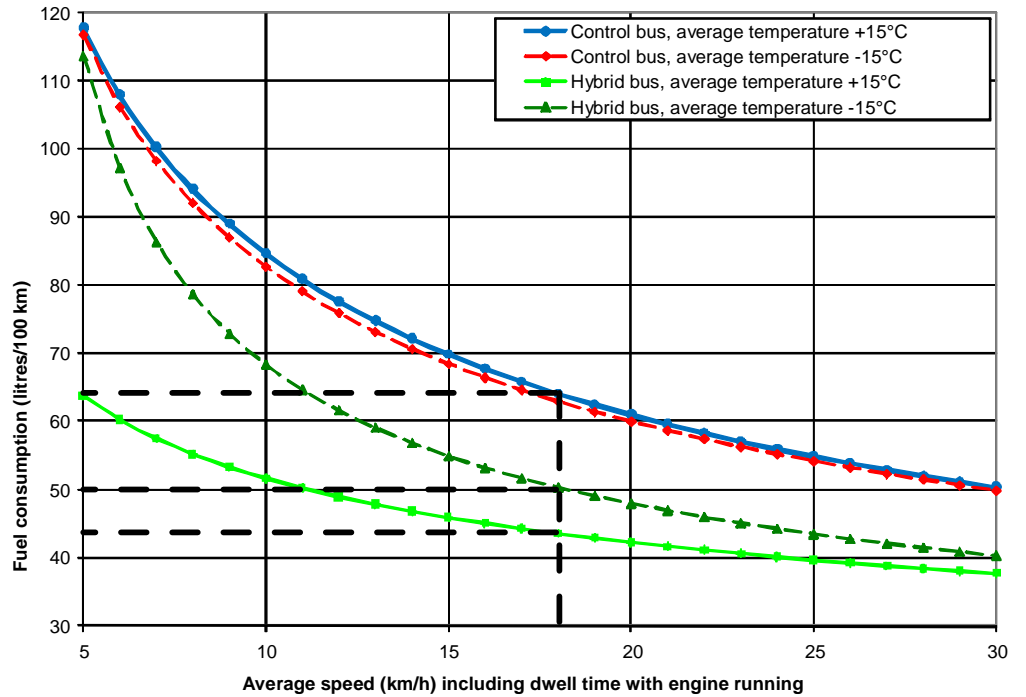
Figure 3-7 shows fuel consumption depending on average speed at temperatures of +15°C and -15°C for the STM's hybrid and control buses.

It can be seen that the variation in fuel consumption depending on outdoor temperature is greater for the hybrid bus than for the control bus. For example, at a speed of 18 km/h, the hybrid bus consumes 43 litres/100 km at +15°C whereas it consumes 50 litres/100 km at -15°C, or an increase of 7 litres/100 km. In the case of the control buses, fuel consumption is practically identical at both temperatures, or 64 litres/100 km.

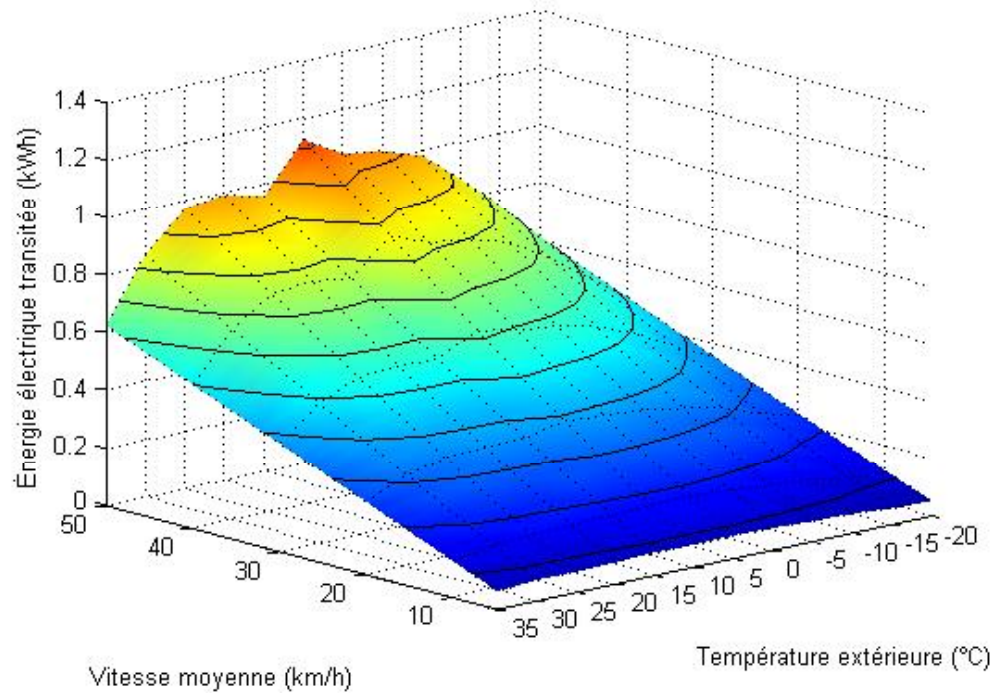
In this difference of 7 litres/100 km observed for the hybrid buses, fuel consumption of the auxiliary heating alone accounted for about 3 litres/100 km. This can be explained by the fact that the thermal engine in the hybrid bus does not have to work as hard at low speeds as the engine in a standard bus, thereby generating less heat and using the auxiliary heating more. In addition, low temperatures reduce the efficiency of hybrid batteries, which means that at -15°C, the thermal engine in the hybrid works harder than at +15°C. It therefore compensates for the drop in performance of the hybrid system at colder temperatures. This aspect explains the remaining total increase in consumption.

Figure 3-8 shows the variation in electric energy supplied by the hybrid system depending on the outdoor temperature. A lower hybrid contribution can be observed at low temperatures.

**Figure 3-7 Fuel consumption of the bus and auxiliary heating depending on average speed and outdoor temperature – Hybrid bus without air-conditioning and Nova 2008 control bus**



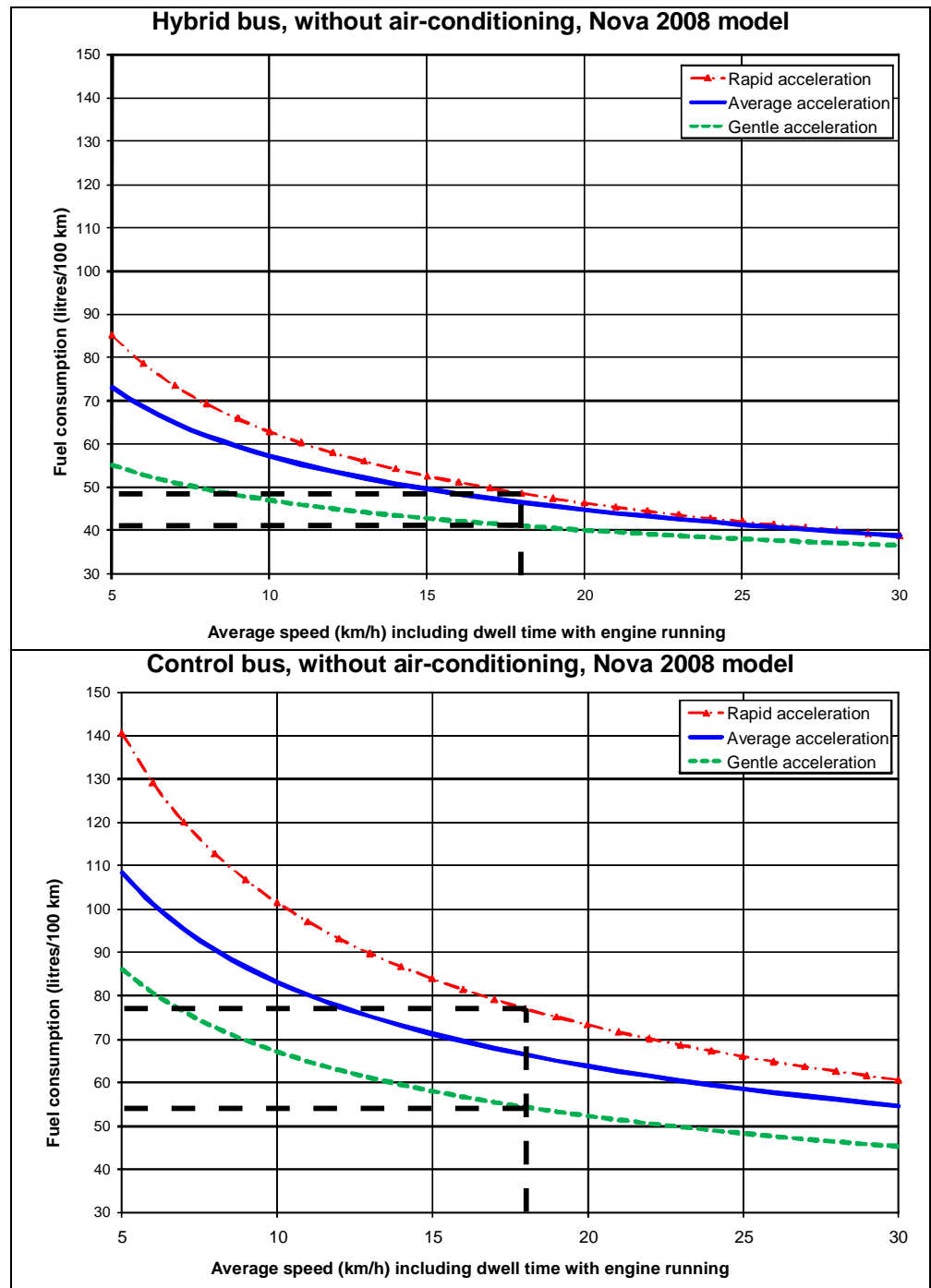
**Figure 3-8 Electric energy transited by the hybrid system depending on outdoor temperature – Nova 2008 hybrid bus (auxiliary heating system consumption is excluded)**



Énergie électrique transitée = Electric energy transited  
Vitesse moyenne (km/h) = Average speed (km/h)  
Température extérieure (°C) = Outdoor temperature (°C)

Figure 3-9 shows fuel consumption depending on the average speed and average acceleration for the STM's hybrid and control buses. These curves show that the acceleration rate has an impact on fuel consumption for both hybrid and control buses. Aggressive acceleration by drivers generates greater fuel consumption.

**Figure 3-9 Fuel consumption depending on average speed and average acceleration rate – Hybrid and control bus (auxiliary heating system consumption is excluded)**



Note: Average of results gathered over one year, with an average speed of about 18 km/h

For example, at a speed of 18 km/h, rapid acceleration generates fuel consumption that is about 18% higher than gentle acceleration, in the case of hybrid buses. This variation is about 42% higher for the control bus. The impact is much less pronounced in the case of hybrid vehicles because a large amount of the energy required to accelerate comes from the energy recovered during the preceding deceleration. Furthermore, the demand for

power and the rotations of the diesel engine are controlled by the computer of the hybrid system to optimize fuel consumption.

To summarize:

- The acceleration rate has much less influence on the fuel consumption of the hybrid bus than that of the control vehicle;
- When acceleration is rapid, the hybrid bus's reduction in consumption compared with the control vehicle is at its best;
- All buses have reduced consumption when acceleration is gentle, which reduces the gap between the hybrid bus and the control bus, but the hybrid vehicle still maintains the advantage.

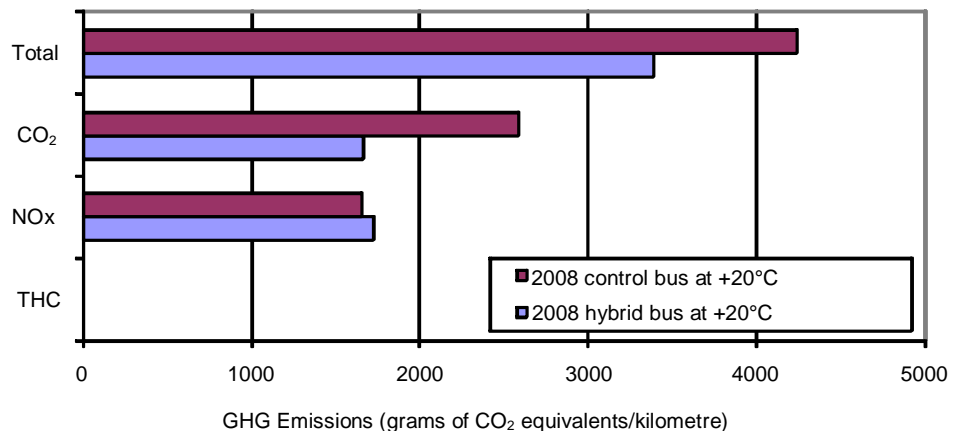
Numerous results of the analysis are presented in Appendix D.

### 3.4 GHG balance

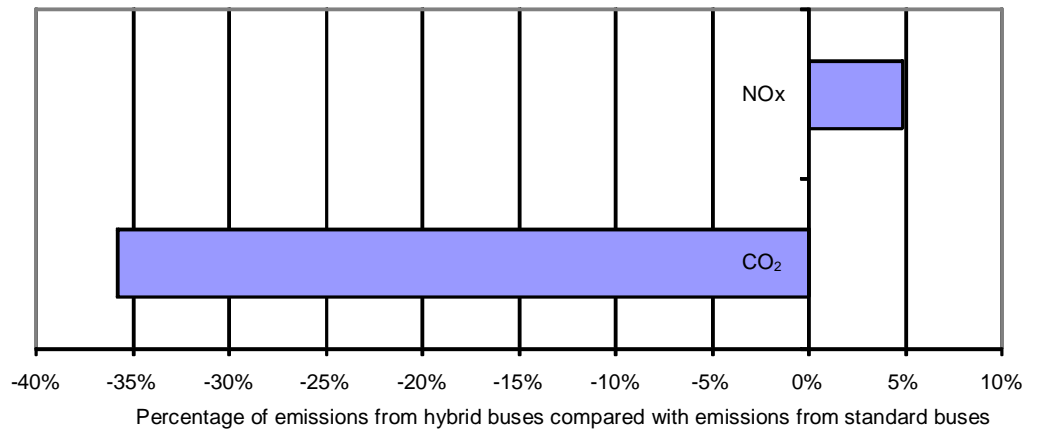
The tests at the Environment Canada laboratory made it possible to characterize the GHG emissions of the two power systems being compared. Figure 3-10 presents the values in grams per kilometres of GHGs measured for power systems with engines that meet the EPA 2007 standard, while Figure 3-11 shows the data as a percentage. These results show that:

- EPA 2007 compliant engines do not emit a significant amount of particles or total hydrocarbons (THC);
- The hybrid power system emits 5% more nitrogen oxides (NO<sub>x</sub>) than the standard power system and 36% less carbon dioxide (CO<sub>2</sub>).

**Figure 3-10 GHG emissions of EPA 2007 compliant hybrid and standard power systems obtained at the Environment Canada laboratory at +20°C (grams/kilometre)**



**Figure 3-11 Comparison of GHG emissions of EPA 2007 compliant hybrid buses and standard buses obtained at the Environment Canada laboratory at +20°C**



The results of the tests conducted at the Environment Canada laboratory were obtained in ideal, controlled conditions; they cannot be compared directly to the results obtained by vehicles in service with passengers. In fact, the difference between the fuel consumption results shows this. (See figures 3-1 and 3-4)

In order to be consistent with other studies in this field, the conventionally accepted conversion factor of 2.7 kg of GHGs per litre of diesel is used. This calculation method implies that the amounts of GHGs emitted during diesel consumption are directly proportional to the amount consumed.

**2.7 kg of GHGs per litre of diesel consumed by the STM's buses**

Analysis of the results obtained by buses in service with passengers makes it possible to observe that the relationship between fuel consumption and average speed, for hybrid and standard vehicles could be represented mathematically. Thus, when the average speed is known, it is possible to calculate the theoretical fuel consumption and consequently the corresponding GHG emissions.

Bus fleet managers who would like to have an idea of the potential reduction in GHG emissions can use the formula below to determine whether hybrid power is viable. Only the average speed is required to use the formula. The result is expressed in kilograms of GHGs avoided per 100 kilometres travelled. Note that this equation was formulated from data obtained at an average air temperature of 6.6°C.<sup>10</sup>

$$GHG = ((255.331 \times V^{-0.4753}) - (101.031 \times V^{-0.2761})) \times 2.7$$

Where: GHG = Reduction in GHGs in kg/100 km  
 V = Average speed in km/h

<sup>10</sup> Nova bus without air-conditioning and ZF transmission on the standard bus.

For STM buses whose average speed is **18 km/h**, the fuel economy offered by a hybrid bus is about **20 litres/100 km**. Assuming that each bus travels 70,000 km annually, there is a reduction of **36 tonnes of GHGs per hybrid bus annually**.

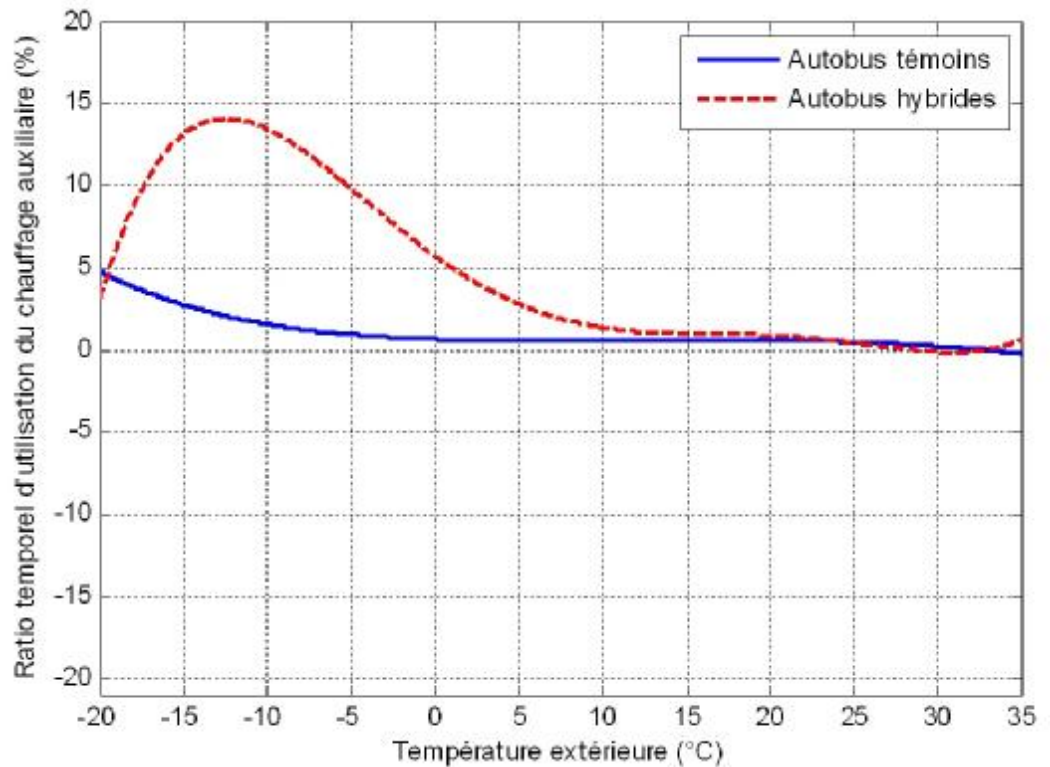
### 3.5 Service life

Besides the difference in purchase price between a hybrid bus and a standard bus, the maintenance and operating costs are also different for these two types of vehicles. The main differences are explained below, and the service life details are provided in Appendix F.

- The **maintenance costs for an internal combustion engine** should be lower for a hybrid bus than a standard bus, since the engine is not used as much in a hybrid configuration.
- The **maintenance costs for the brakes** on standard STM and STO buses should be very similar to the maintenance costs for hybrid buses, contrary to what several hybrid bus operators noted after putting such buses into service. This can be explained by the way the retarder operates on the standard bus transmissions on the STM and STO buses.
  - Standard buses have an internal mechanical retarder system in the transmission. They are configured to use this retarder as soon as the accelerator is released. Consequently, the brakes are seldom applied.
  - Hybrid buses are configured to slow the bus significantly as soon as the accelerator is released in order to recover as much kinetic energy as possible. The design of the hybrid system allows electric motors built into the transmission to turn into generators as soon as the accelerator is released. By doing this, these motors create a slowing force on the drive wheels. This force slows the bus.
- The cost of using an **auxiliary heating system**. A notable difference was observed in the operation of hybrid and control buses: the rate of use of auxiliary heating between 0°C and -15°C on hybrid buses is higher than the control buses.

Figure 3-12 illustrates the time in service ratio for which diesel auxiliary heating is used by STM buses, depending on the outdoor temperature. For the control bus, the curve increases gradually from about -10°C, whereas the increase starts at +10°C for the hybrid bus. This behaviour is due to the fact that the internal combustion engine, when used in a hybrid power system, is applied much less than when it is used in a standard power configuration; therefore, as soon as the outdoor temperature drops below -10°C, it does not generate enough heat to warm the passenger cab. Note that the hybrid power system is calibrated to ensure that the internal combustion engine runs at the most efficient speed possible. Its operation is controlled by the computer that controls the hybrid system.

**Figure 3-12 Use of auxiliary heating depending on outdoor temperature – Nova 2008 bus**



Ratio temporel d'utilisation du chauffage auxiliaire = Time ratio of the use of auxiliary heating

Température extérieure (°C) = Outdoor temperature (°C)

Autobus témoins = Control buses

Autobus hybrides = Hybrid buses

### 3.6 Driver and passenger satisfaction

Customer satisfaction is an important factor that can promote the use of public transit. In this case, the reduced noise and gentle ride of the hybrid buses are two aspects that can promote the modal transfer from cars to public transit, resulting in a significant reduction in GHGs. The main results of the surveys conducted among passengers on the STM's hybrid buses and among STM employees are presented below, and the detailed results are given in Appendix G.

The reactions of STM bus drivers to the hybrid technology are positive. Almost all (94%) of the drivers surveyed believe that the hybrid buses contribute to protecting the environment. They are comfortable driving the buses (92% of drivers) and 86% would like to have more of them in the STM's fleet. The advantage that drivers appreciate the most is the reduction in noise level, followed by the gentle ride. The results are shown in Table 3-1.

**Table 3-1 Results of the survey among STM bus drivers**

Question	% Agree	Response Details
<b>Hybrid buses help to protect the environment</b>	94%	Agree completely 73% Agree somewhat 21%
<b>Feel comfortable driving a hybrid bus</b>	92%	Agree completely 71% Agree somewhat 21%
<b>Would like to have more hybrid buses in the STM's fleet</b>	86%	Excellent 67% Good 19%

Among the passengers surveyed, a very large majority (94%) believes that the hybrid buses help to protect the environment and most of the respondents (88%) would like to see more of the buses in the STM's fleet. Among those who rode a hybrid bus, 63% found it more quiet than standard buses and 54% found that the ride was more gentle. The results are shown in Table 3-2.

**Table 3-2 Results of the survey among STM passengers**

	Question	% Agree	Response Details
Among people who had heard about the hybrid buses	<b>Help to protect the environment</b>	94%	Agree completely 78% Agree somewhat 16% Don't know 6%
	<b>Appreciate that the STM acquired the buses</b>	90%	Agree completely 81% Agree somewhat 9% Disagree somewhat 1% Disagree completely 2% Don't know 6%
	<b>Would like to have more hybrid buses in the STM's fleet</b>	88%	Agree completely 79% Agree somewhat 9% Disagree somewhat 2% Disagree completely 3% Don't know 6%
Among people who rode one of the STM's hybrid buses	<b>Are quieter than standard buses</b>	63%	Agree completely 56% Agree somewhat 7% Disagree somewhat 7% Disagree completely 0% Don't know 29%
	<b>Have a more gentle ride than standard buses</b>	54%	Agree completely 44% Agree somewhat 10% Disagree somewhat 5% Disagree completely 0% Don't know 41%

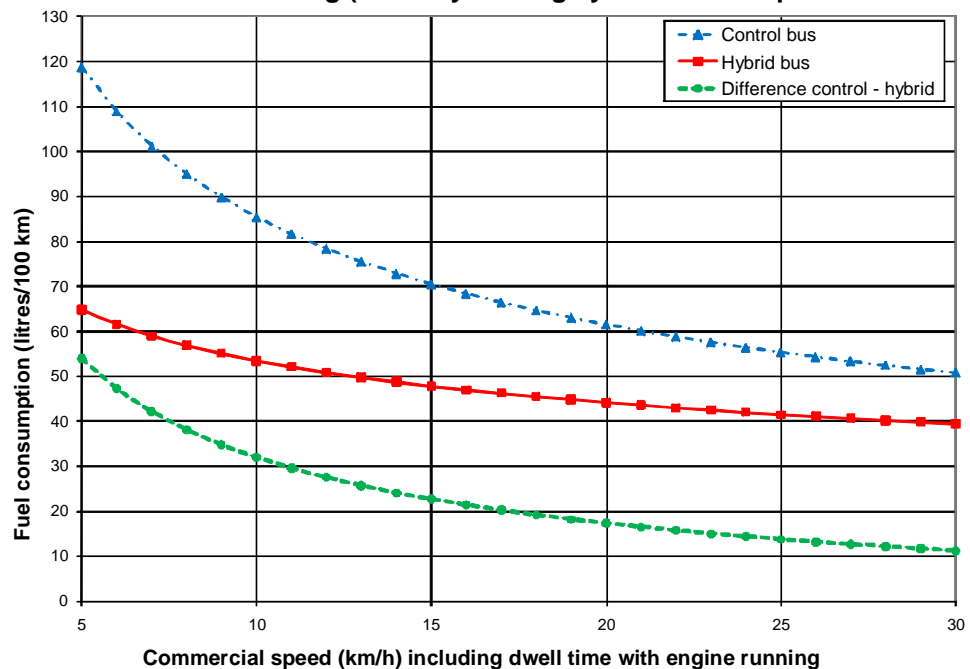
## 4 Decision-making tool

Public transit corporation managers who would like to reduce the GHG emissions produced by the vehicles in their bus fleet can use the graphs in this section to estimate the potential offered by hybrid power systems. All they need to know is the average speed and total average fuel consumption for the buses in their fleet.

The graphs below represent the averages of operational results, compiled throughout the year of the study. Over the year, the outdoor temperature varied between -28°C and +33°C; the average temperature was 6.6°C. The buses maintained an average speed of 18 km/h, made an average of 3.8 stops/km and their engines idled<sup>11</sup> 34% of the time.

Figure 4-1 shows the fuel consumption for Nova 2008 hybrid and control vehicles depending on average speed. In a very congested environment, or at an average speed of 10 km/h, the hybrid bus consumes about 32 litres/100 km less than the standard bus. At an average speed of 30 km/h, or at the average speed in moderately dense cities or in suburbs, the hybrid bus consumes about 11 litres/100 km less than the standard bus.

**Figure 4-1 Fuel consumption depending on average speed for speeds ranging from 5 to 30 km/h – NOVA 2008 hybrid and control bus, without air-conditioning (auxiliary heating system consumption is excluded)**

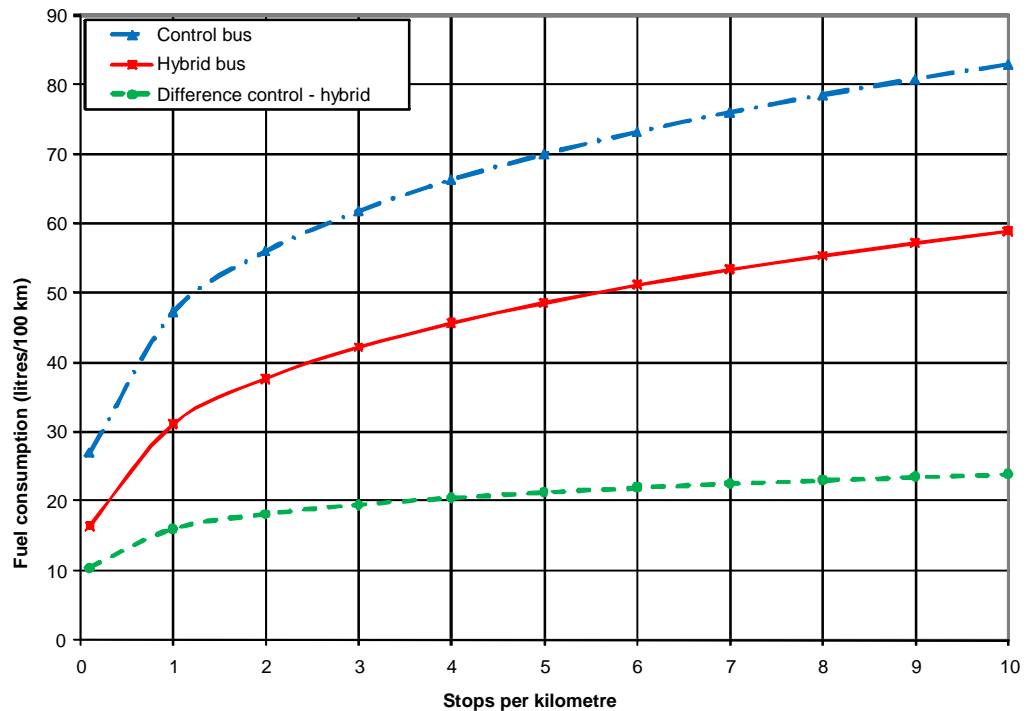


**Note:** Average of the results gathered over one year, with an average speed of about 18 km/h, a minimum temperature of -28.5°C, a maximum temperature of 33.4°C and an average temperature of 6.6°C, as well as 34% of the time with the engine idling. This curve applies to buses without air-conditioning and with a ZF transmission on the control buses and an Allison Electric Drive EP-40 on the hybrid buses.

<sup>11</sup> Idling occurred primarily when the buses were stopped at bus stops for passengers to board or get off, or when buses were stopped in traffic.

Figure 4-2 shows the fuel consumption for Nova 2008 hybrid and control vehicles depending on the number of stops per kilometre.<sup>12</sup> When the buses make one stop per kilometre, the hybrid vehicle consumes an average of 16 litres less per 100 km than the standard vehicle. The benefits of a hybrid bus become more pronounced as the number of stops per kilometre increases. At 10 stops per kilometre, the hybrid vehicle consumes an average of 24 litres/100 km less than the standard vehicle.

**Figure 4-2 Fuel consumption depending on number of stops per kilometre for a number of stops ranging from 0 to 10 – NOVA 2008 hybrid and control bus, without air-conditioning (auxiliary heating system consumption is excluded)**



In the previous chapter, it was demonstrated that the hybrid power system has a lower performance at very low temperatures; therefore, the results obtained in more temperate climates can only be more beneficial. Finally, the results are based on the hybrid technology in use at the time of the study. Developments in hybrid technology will likely make it more efficient in the coming years.

Public transit operators can validate the relevance of these curves in relation to their own operations. They can obtain precise fuel consumption data for their diesel engines, running time, by connecting to the data ports of the engine control computer. Once the average speed and average consumption are calculated, they can transpose these data to the "control consumption" curve to validate whether the curve applies to their operations.

The average speed "V" resulting from the operating conditions of the bus is determined using the information saved in the ECM of the Cummins engines of buses with an EPA

<sup>12</sup> The term "stop" includes not only when the bus comes to a halt to let passengers on or off, but also when it stops in traffic.

2007 compliant ISL engine and a ZF transmission. The following information should be gathered:

- Total number of kilometres travelled;
- Total number of hours the engine is operating;
- Total number of litres consumed.

The average speed, V in km/h, can then be calculated using the following equation:

$$V = \frac{\text{total number of kilometres travelled}}{\text{total number of hours in operation}}$$

Total average consumption, in litres/100 km, is obtained using the following equation:

$$\text{Average total consumption} = \frac{\text{total number of litres consumed}}{\text{total number of kilometres travelled}/100}$$

An algebraic representation was developed to estimate the fuel economy of the hybrid bus compared with a standard bus depending on the average speed for an average temperature of 6.6°C.

The equation is:

$$FE = (255.331 \times V^{-0.4753}) - (101.031 \times V^{-0.2761})$$

Where: FE = Fuel economy in litres/100 km  
V = average speed in km/h

It is therefore possible to calculate the possible fuel economy of a hybrid bus compared with a standard diesel bus. If the annual distance travelled by the buses is known, it is possible to transpose this fuel economy into an annual reduction in GHGs using the following equation:

$$RG = \frac{E_{GHG} \times FE \times AD}{100,000}$$

Where: RG = Reduction in GHGs in tonnes per year  
E<sub>GHG</sub> = Emission factor for GHGs in kg per litre of fuel  
= 2.7 kg/litre for diesel buses  
FE = Fuel economy in litres/100 km  
AD = Average annual distance of the bus in kilometres

## 5 Beyond hybrid technology

Although the primary objective of the STM's component of the UTSP was to evaluate the environmental impact of the hybrid power system, this project created opportunities to go a bit further. The instrumentation for the hybrid and control buses with the ISAAC data acquisition system made it possible to assess and quantify the environmental impact of two other technology solutions that are frequently mentioned in industry documentation:

- The use of low-voltage (24 volts) electric ventilation rather than hydraulic ventilation to cool the engine;
- Optimization of the standard transmission program according to the specific conditions of public transit bus users. The programming software is called "Topodyn."

Documentation about power systems for road vehicles promotes the potential of these technologies in reducing fuel consumption and thereby also reducing GHG emissions.

### 5.1 Low-voltage electric ventilation

Most low-floor urban buses have a radiator fan system powered by a hydraulic motor that in turn gets its power from a diesel engine driven hydraulic pump. The main disadvantages of such systems are:

- Relatively low energy efficiency: putting the hydraulic fluid into motion under pressure results in significant heat loss and therefore loss in performance;
- Difficulty in optimizing control of the power: many areas of the system have different cooling needs. A single fan covers all areas at the same time; power is therefore occasionally wasted cooling part of a system that does not need to be cooled.

These two aspects can be improved easily by installing an electric ventilation system composed of several small fans that cool the areas separately. The system improves energy efficiency because less heat is lost in the electric transfer between the diesel engine and the fans using a high-performance 24-volt alternator. It is important to note that this modification can be done on hybrid and standard buses.



The low-voltage electric fan system is installed on the outside of the radiator of the STM buses, shown here with the outside grill open. Because of the lack of space near the engine's radiator and the limited time to carry out this test, a section of additional cooling for the hybrid transmission was added to the roof. It is made of unpainted aluminum. In an optimized version, it would be better to integrate the configuration of this oil cooler into the body.

## 5.2 Optimized standard transmission programming (Topodyn software)

Modifying the standard transmission programming does not require any physical modifications to the buses, because this is done through ZF's control module. Two days of on-road testing with an STM bus were required to calibrate and optimize the programming. Then the optimized programming was implemented on the buses in service. This was done simply by replacing the original electronic module with a reprogrammed module. Only the diesel control buses were equipped with a standard transmission.

The Topodyn programming had the following effects:

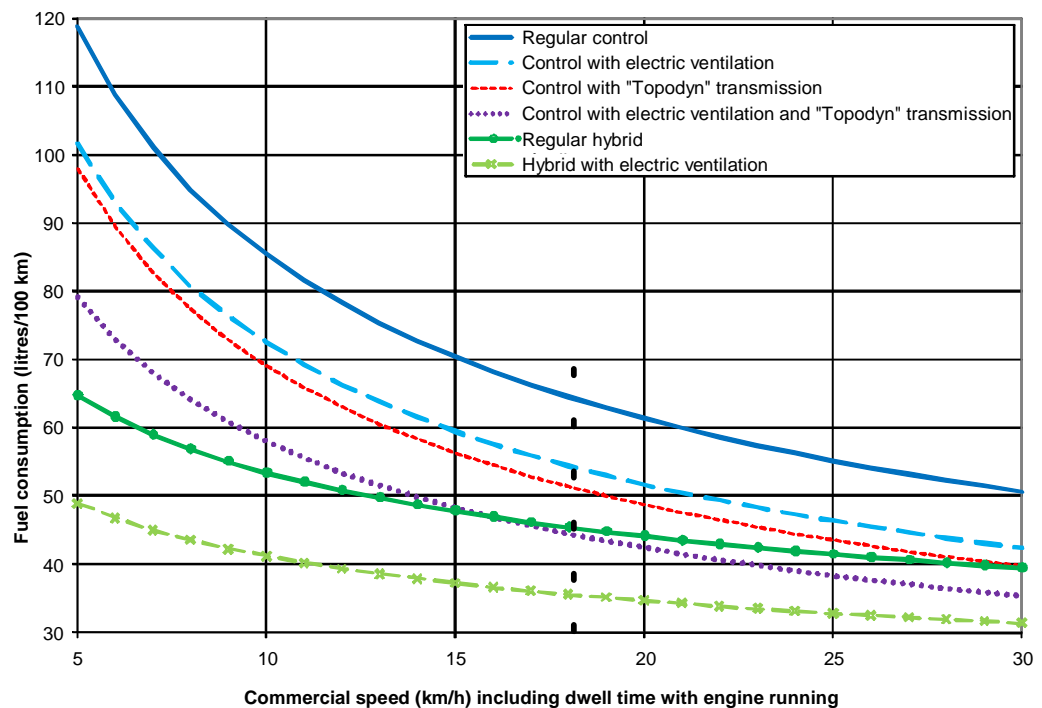
- It created conditions similar to the conditions inherent in green driving. Overall, it ensures gentle acceleration:
  - It tempers the acceleration demanded when bus speed is under 40 km/h;
  - It maintains the acceleration rate when the bus is on a slope or is carrying a full load.
- It optimizes the fuel consumption conditions by reducing engine rotation speed when shifting gears. This increases the torque produced, and causes an increase in the combustion temperature and pressure that translates into a reduction in fuel consumption for the same power produced.

## 5.3 Impact on fuel consumption and reduction in GHGs

Figure 5-1 shows fuel consumption depending on the technology tested for speeds ranging from 5 to 30 km/h on the STM's hybrid and control buses. At an average speed of about 18 km/h including stops, the following can be observed:

- Installing electric ventilation helped to reduce fuel consumption by about 16% (from 65 to 54 litres/100 km) on a standard bus and by 22% (from 46 to 36 litres/100 km) on a hybrid bus;
- The ZF transmission programming (Topodyn) helped to reduce fuel consumption by about 21% (from 65 to 51 litres/100 km) on a standard bus;
- Therefore, the combined effect of installing electric ventilation and the Topodyn programming helped to reduce fuel consumption by 31% (from 65 to 45 litres/100 km) on a standard bus.
- The hybrid bus equipped with electric ventilation showed a reduction in fuel consumption of about 20% (from 45 to 36 litres/100 km) compared with the control bus that combined the electric ventilation and the transmission programming. Note that without these changes, the hybrid bus showed a fuel economy of 30% (from 65 to 46 km/h) compared with the control bus.

**Figure 5-1 Effect of electric ventilation and transmission programming (Topodyn) on fuel consumption (auxiliary heating system consumption is excluded)**



**Note: The STM's average speed is about 18 km/h**

The comparison in fuel consumption for the various scenarios is shown in Table 5-1 for a speed of 18 km/h. More information about the analysis of these two technologies is given in Appendix H.

**Table 5-1 Fuel consumption (in litres/100 km) for various scenarios and comparison of reductions in fuel consumption – For an average speed of 18 km/h**

	Unit	Regular control	Control with electric ventilation	Control with "Topodyn" transmission	Regular hybrid	Control with electric ventilation and "Topodyn" transmission	Hybrid with electric ventilation
<b>Average consumption</b>	<b>Litres per 100 km</b>	<b>64.6</b>	<b>54.4</b>	<b>51.4</b>	<b>45.5</b>	<b>44.5</b>	<b>35.6</b>
<b>Reduction compared with</b>							
<b>Regular control</b>	litre		10.2	13.3	19.1	20.1	29.0
	%		16%	21%	30%	31%	45%
<b>Control with electric ventilation</b>	litre			3.1	8.9	9.9	18.8
	%			6%	16%	18%	35%
<b>Control with "Topodyn" transmission</b>	litre				5.9	6.9	15.8
	%				11%	13%	31%
<b>Regular hybrid</b>	litre					1.0	9.9
	%					2%	22%
<b>Control with electric ventilation and "Topodyn" transmission</b>	litre						8.9
	%						20%

## 6 Summary and recommendations

### 6.1 Summary

The primary objective of this study was to measure the environmental impact of hybrid buses by comparing them with standard diesel buses. The results of the analysis, which covered one year, made it possible to compose a detailed, conclusive portrait of the environmental benefits of hybrid technology.

The hybrid technology (Nova 2008) made it possible to reduce fuel consumption by an average of **30%** compared with standard power technology. The average speed of the buses monitored during the project was about **18 km/h**, while the average number of stops was 3.8 per kilometre. The average temperature during the year of the project was 6.6°C (from -28.5°C to +33.4°C).

The percentage that fuel consumption was reduced with hybrid buses also translates into a **reduction in GHG emissions of almost 36 tonnes annually** for a bus that travels about 70,000 km per year. This represents seven fewer individual vehicles on the road, assuming an average production of 5 tonnes of GHGs per year and a distance of 20,000 km/year.

In particular, it should be pointed out that:

- EPA 2007 compliant engines do not emit a significant amount of particles or total hydrocarbons (THC);
- The hybrid power system emits 5% more nitrogen oxides (NO<sub>x</sub>) than the standard power system and 36% less carbon dioxide (CO<sub>2</sub>).

Analysis of the results showed that hybrid technology is particularly advantageous when the average operating speed is relatively low and the distance between stops is short. The main results obtained after one year of testing in service with passengers, based on the conditions prevailing at the STM, are:

- The hybrid bus consumes about 20 litres/100 km less than the control bus when the number of stops per kilometre varies between two and 10;
- In cold weather, fuel consumption by the hybrid bus is greater. At 18 km/h, fuel consumption of the hybrid bus increases by 16% when the outdoor temperature goes from +15°C to -15°C. This variation is 2% for the control bus;
- Acceleration rate has a more pronounced impact on the fuel consumption of the control bus. At 18 km/h, aggressive acceleration generates 42% higher fuel consumption than gentle acceleration in the case of the control bus. This variation is 18% for the hybrid bus.

**The analysis tools** developed during the study enable public transit corporation managers to evaluate the anticipated benefits of hybrid technology based on easily measured factors such as total average speed and total fuel consumption. In addition, the data gathered make it possible to determine the circumstances in which hybrid technology is optimal, among others, in terms of outdoor temperature or acceleration rate.

Irrespective of the cost, hybrid electric technology combined with an optimized thermal engine is for the moment still the **most effective way** to reduce fuel consumption and therefore GHG emissions for transit corporations where the average speed is low and the distance between stops is short. Furthermore, the analysis of service life costs and evaluation of implementation costs must be completed in order to quantify all the financial

impacts involved if hybrid power is incorporated into a bus fleet. Finally, passenger expectations and the impact that introducing such technology can have on the public transit corporation's image must also be taken into account. A positive impact could result in increased ridership and a modal transfer that would benefit public transit.

Note that this study made it possible to test **other technologies** that proved promising. Replacing the hydraulic ventilation system with a low-voltage electric system made it possible to reduce GHG emissions on both the hybrid and standard buses, at an advantageous implementation cost. Optimizing the standard transmission programming helped to reduce the GHG emissions of the regular buses and required only a minimal investment.

## 6.2 Recommendations

Urban bus fleet operators and managers who would like to acquire hybrid vehicles can refer to the decision-making tool developed in this study and presented in this document. The tool enables them to make an informed choice with respect to potential fuel economies and reductions in GHGs using data that are easily measured.

Furthermore, reducing GHG emissions is not just about a single solution. The curves presented in this report illustrate that the effectiveness of the different technologies studied varies depending on the operating and weather conditions. The results gathered also show that the human factor can play a significant role in fuel consumption. It is therefore recommended that operators wishing to reduce their fuel consumption and thereby also their GHG emissions should acquire a multi-disciplinary strategy with a variety of technologies.

## Reference documentation

070216 AED, Student workbook, Allison Transmission, February 2007

N8884393-L350, Parts Manual, Nova Bus, March 2009

SRME No 08-34, Environment Canada, March 2009