Biodiesel Demonstration and Assessment
with the Société de transport de Montréal (STM)

Final Report

May 2003
Foreword

This report was drafted by the BIOBUS project team under the direction of the steering committee. It is the result of cooperative efforts involving representative of the project’s four implementation partners—the Canadian Renewable Fuels Association (CRFA), the Fédération des producteurs de cultures commerciales du Québec (FPCCQ), the Société de transport de Montréal (STM), and Rothsay/Laurenco (Maple Leaf Foods Group)—the Canadian and Quebec governments, which provided funding, and the members of various committees. All participated at different stages in verifying the report’s contents.

The BIOBUS project includes a measurement program carried out under normal operating conditions. The report’s conclusions are thus only prescriptive and in no way commit public transit decision-makers or participating governments and organizations.
BIOBUS Project Committee Members

**Steering Committee**

Bliss Baker  
Canadian Renewable Fuels Association (CRFA)

Claude Barraud  
Natural Resources Canada

Luc Beaudin  
Ministère des Transports du Québec

Claude Bourgault  
Rothsay/Laurenco (Maple Leaf Foods Group)

Daniel Collin  
Société de transport de Montréal (STM)

Michel Goulet  
Ministère de l’Environnement du Québec

Louise Hamel  
Ministère de l’Environnement du Québec, Communications Lead

Pierre Hosatte  
Project Team (CRFA-FPCCQ), Technical Lead

Camil Lagacé  
Project Team (CRFA-FPCCQ), Project Director

Armand Mousseau  
Fédération des producteurs de cultures commerciales du Québec (FPCQ)

Anne-Marie Phan Lan  
Canada Economic Development (CED)

Pierre Sylvestre  
Environnement Canada

Luc Y. Tremblay  
Société de transport de Montréal (STM), Steering Committee Chair

**Technical and Logistical Committee**

Sarah Babès  
Ministère des Transports du Québec

Raynald Archambault  
Ministère des Ressources naturelles du Québec

Luc Beaudin  
Ministère des Transports du Québec

Claude Bourgault  
Rothsay/Laurenco (Maple Leaf Foods Group)

Philippe Coutu  
Société de transport de Montréal (STM)

Pierre Hosatte  
Project Team (CRFA-FPCCQ), Committee Chair

Jacques Jobin  
Ultramar

Douglas Labelle  
Agence de l’efficacité énergétique du Québec (AEÉ)

Camil Lagacé  
Project Team (CRFA-FPCCQ)

Denis Lamothe  
SGS Canada

Georges Lé  
Ministère des Ressources naturelles du Québec

Johnny Mulfati  
Cummins Canada

John Patitsas  
TWD Technologies

René Pigeon  
Natural Resources Canada

Jean-Claude Raymond  
Ministère de l’Environnement du Québec

Martin Roberge  
Ministère de l’Industrie et du Commerce du Québec

Denis Soucy  
Société de transport de Montréal (STM)

Michel Souligny  
Environmental Technology Centre (ETC)

Pierre Sylvestre  
Environnement Canada

**Communications Committee**

Maxime-Pierre Ayotte  
Ministère des Transports du Québec

Claude Bourgault  
Rothsay/Laurenco (Maple Leaf Foods Group)

Sylvie Bussières  
Société de transport de Montréal (STM)

Thérèse Drapeau  
Environnement Canada

Louise Hamel  
Ministère de l’Environnement du Québec, Committee Chair

Camil Lagacé  
Project Team (CRFA-FPCCQ)

Hélène Saint-Pierre  
Canada Economic Development (CED)

Kathleen Smith  
Natural Resources Canada
STM Steering Committee
Pierre Bellemare
Denis Bissonnette
Richard Boyer
Sylvie Bussières
Daniel Collin
Philippe Coutu
Jacques Durocher
Roger Gagnon
Serge Jolin
Gaston Larouche
Jacques Légaré
William Mance
Luc Martin
Serge Savard
Denis Soucy
Robert Stafford
Névine Tadros
Luc Y. Tremblay

Special Thanks
To representatives of
the following organizations:

Marcel Ayoub
Ministère des Transports du Québec

Jean Colpron
Transport Colpron Ltd

Benoît Drolet
Ministère des Ressources naturelles
du Québec

Marc Labelle
Fédération des producteurs de cultures
commerciales du Québec (FPCCO)

Denis Couture
Fédération des producteurs de cultures
commerciales du Québec (FPCCO)

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All bus operations and maintenance
employees, as well as facility
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Claude Beaudry
Robert Collin
Claude Dauphin
Jacques Deslauriers
Yves Devin
Charles Dubois
Miville Dupuis
Jacques Fortin
Alain Fraser
Robert Gagné
Michel Gagnon
Anne-Marie Giuliani
Renée Halley
Michel Lauzier
Michel Lavallée
Daniel Maille
Robert Olivier
Gilline Pageau
Odile Paradis
Pierre Pelletier
Pierre Ruby
Pierre Rocray
Roger Saint-Hilaire
André Therrien
Sylvie Tremblay
Denise Vaillancourt
Marc Vandecastel
Pierre Vandelac

Report Production Team
Coordinator
Camil Lagacé
Writers
Pierre Hosatte
Camil Lagacé
Translator
Andy Lauriston – PluriVox
Graphic Design
Langevin Turcotte
Photographs
Camil Lagacé
Printer
Lithographie G. Monette Inc.
Support Group
Luc Beaudin
Claude Bourgault
Michel Goulet
Michel Souligny
Pierre Sylvestre
Luc Y. Tremblay
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Summary

Solid Partnership

The BIOBUS project was a joint effort by the Canadian Renewable Fuels Association (CRFA), the Fédération des producteurs de cultures commerciales du Québec (FPCCQ), Rothsay/Laurenco and the Société de transport de Montréal (STM). Rothsay/Laurenco produced pure biodiesel for the project and supplied biodiesel blend to STM’s Frontenac terminal, which provided 155 buses and the entire infrastructure used to test the fuel. The Canadian and Quebec governments both made major contributions to project funding.

Three Major Objectives

The BIOBUS project ran for one year, from March 2002 to March 2003, during which the following objectives were pursued:

- test the use of biodiesel as a source of supply for public transit
- assess the viability of the fuel as part of the routine operation of a bus fleet, particularly in cold weather
- measure biodiesel’s environmental and economic impact

Why Biodiesel?

Biodiesel is a methyl ester produced from a chemical reaction between methanol and either vegetable oil or animal fat. It could prove to be a prime alternative fuel for public transit since it:

- promotes sustainable transportation because it is produced from local, renewable resources;
- helps significantly in the reduction of greenhouse gas (GHG) and polluting emissions to achieve goals under the Kyoto protocol; and
- is easy to use, since it requires no change to existing fuel delivery and distribution facilities or diesel engines.

Supplying Biodiesel to the STM

Over the duration of the BIOBUS project, Frontenac terminal buses consumed some 550,000 litres of pure biodiesel (24% based on vegetable oil, 28% on animal fat and 48% on used cooking oil) in 5% (B5) and 20% (B20) blends with petrodiesel. Despite three interruptions in blend delivery during the year, the STM did not encounter any major problems from either a maintenance or customer service standpoint. Quite the contrary, using biodiesel had very positive effects.

Physicochemical Characteristics of Biodiesel Blends

ASTM D 6751-02 is the only biodiesel standard recognized in North America, and applies only to pure biodiesel (B100). To ensure product quality, it was thus necessary to assess the physicochemical properties of biodiesel blends with STM reference petrodiesel.

Accordingly, an independent lab determined the characteristics of biodiesel from the three sources used (vegetable oil, animal fat and used cooking oil) in both 5% and 20% blends. The results confirmed that the pure biodiesel produced by Rothsay/Laurenco complied with ASTM D 6751-02. Key test findings are given below.

Lubricity

- Even at low concentrations, lubricity (the lubricating power of biodiesel blends) is clearly superior to that of petrodiesel. Consequently, engine wear is reduced and engine life increased. Biodiesel could thus be a valuable additive to future very-low-sulphur (<15 ppm) diesel fuels.

Cloud Point and Filterability

- It is safe to use in cold weather biodiesel having a cloud point of -15°C or lower. It is necessary, however, that the petrodiesel is not at a temperature below the biodiesel’s cloud point during blending. In fact, neither the cloud point of B100 nor that of the final blend dictates the solubility of biodiesel in low-temperature petrodiesel.
Cetane Number

- Having a higher cetane number than STM reference petrodiesel, pure biodiesel improves the ignition performance of blends and reduces NOx emissions.

Energy Efficiency

- The energy efficiency of biodiesel blends is comparable to that of petrodiesel. Furthermore, blends have no significant effect on power, maximum torque and fuel consumption of a diesel engine with mechanical fuel injection.

Emission Measurements

The only measurements made were direct tailpipe emissions.

It can be generally concluded from the results that biodiesel both reduces polluting and GHG emissions, be they regulated (PM, CO, THC and NOx) or unregulated (SO4, PAH, CO2 and PM2.5), and helps reduce urban smog.

Direct Carbon Dioxide (CO2) and Greenhouse Gas (GHG) Emissions

For the diesel engines studied, direct CO2 emissions were around 600 g per unit work produced (bhp-h); whereas, N2O and CH4 emissions were in the milligram range. Even if significant variations were found for N2O and CH4 emissions, the impact on the overall GHG balance would have been negligible. Thus CO2 is the only GHG considered in this report.

Biodiesel helps reduce GHG emissions because it comes from animal or plant biomass with a life cycle of a few years. Unlike petrodiesel, it is a renewable energy source. Variations in tailpipe CO2 emissions are negligible. Accordingly, variations in fuel consumed per unit work are not significant and engine energy efficiency is unchanged by adding biodiesel.

Baseline GHG emissions for both engine types are around 2.59 kg of CO2 per litre of STM reference petrodiesel. As a working hypothesis, we can suppose that every litre of pure biodiesel (B100) used to replace a litre of petrodiesel reduces GHGs by 2.33 kg of CO2. This figure is based on the assumption that biodiesel avoids 90% of the emissions from reference petrodiesel because it contains 10% methanol used for esterification and obtained from natural gas (non-renewable fossil energy).

Impact of Biodiesel Use by Urban Transit Authorities on Annual CO2 Emissions

The BIOBUS project demonstrated that it was viable for public transit authorities to use biodiesel. Under the project, a total 550,000 litres of biodiesel in 5% and 20% blends were consumed by Frontenac terminal buses between March 2002 and March 2003, leading to a reduction in CO2 emissions of roughly 1,300 tons. Since the results show that the reduction in polluting and GHG emissions was significant, it can be stated that resorting to biodiesel Quebec- and Canada-wide would help reduce such emissions even further.

The table below gives a rough idea of the impact B20 would have on annual CO2 emissions, assuming that a four-stroke Cummins engine with mechanical fuel injection is representative of bus fleets across Quebec and Canada.

Impact of B20 Use by Urban Transit Authorities on Annual CO2 Emission Reductions

<table>
<thead>
<tr>
<th>Units</th>
<th>Frontenac Terminal</th>
<th>STM</th>
<th>Quebec</th>
<th>Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Fleet</td>
<td>155</td>
<td>1,600</td>
<td>2,850</td>
<td>11,500</td>
</tr>
<tr>
<td>Total Distance Traveled (km)</td>
<td>6.7 million</td>
<td>70.5 million</td>
<td>195.3 million</td>
<td>800 million</td>
</tr>
<tr>
<td>Total Fuel Consumed (litres)</td>
<td>4.5 million</td>
<td>47.2 million</td>
<td>96 million</td>
<td>368 million</td>
</tr>
<tr>
<td>Estimated CO2 Reduction Using B20 (tons)</td>
<td>2,100</td>
<td>22,000</td>
<td>42,000</td>
<td>171,500</td>
</tr>
</tbody>
</table>

Source: Canadian Transit Fact Book (2002 data) and BIOBUS Project
Studies also showed how emissions using biodiesel varied depending on engine type, concentration of biodiesel in the blend, and source of biodiesel. It was found that biodiesel reduced several polluting emissions and did so more noticeably with electronic fuel injection than with mechanical fuel injection (particularly for NOx and PM). It cannot be concluded, however, that emission reductions were proportional to the concentration of biodiesel in the blend, nor can one source of biodiesel be singled out as more beneficial.

From an operational standpoint, using biodiesel did not result in any incident compromising continuity of service. No variation in fuel consumption can be substantiated from the data as a whole. Mechanical maintenance was unproblematic during and after the cutover to biodiesel for most buses, including both older models with 25-µm fuel filters and later models with electronic fuel injection systems. Even the two vehicles having a Cummins engine with electronic fuel injection, used to test the potentially most problematic biodiesel blends (cooking-oil-based B20 and animal-fat-based B20) over the coldest period of winter, ran nearly 10,000 km each without any problems.

Biodiesel thus caused neither bus-related mechanical problems, notably to the fuel injection system, nor any degradation of elastomer components in contact with the fuel. The cleansing period was longer than foreseen for buses with 10-µm filters, longer still because B5 was used for three months before cutting over to B20. Sporadic incidents caused by the finest (10-µm) filters had no real impact on STM operations and resulted in no significant unforeseen costs. Similarly, no specific complications arose from using biodiesel, despite its cloud point, in very cold weather (overnight temperatures dropping to between -20°C and -30°C). The problem that gave rise to incidents would vanish if producers succeed in developing processes to better control pure biodiesel's cloud point.

The **BIOBUS** project demonstrated, under actual operating conditions, that biodiesel is a viable fuel in a region like Montreal where winter temperatures can plummet to -30°C and that it is feasible to continuously supply an urban transit company the size of the STM. It is important, however, to take certain precautions.

Any infrastructure-related problem has a direct impact on process flow; therefore, a consistent multi-step filtering process must be followed to ensure consistent blend quality. It is essential to require that suppliers use filters whose performance has been proven by documented test procedures. Moreover, when cutting over to biodiesel, it is important to use the desired concentration, e.g., B20, from the outset rather than gradually phasing in biodiesel using weaker blends, in order to avoid prolonging the cleansing period. Lastly, adequate training must be planned for technical workers to make them aware of the importance of identifying the source of a problem in order to achieve a correct diagnosis, particularly during the cleansing period.

The project's success is above all due to the unwavering participation of STM employees, particularly those from the Frontenac terminal, who were most closely involved in the great **BIOBUS** adventure. Constant support from various partners was also instrumental.

The innovative nature and global scope of the project were indeed acknowledged. At its April 2003 convention, the Association québécoise du transport et des routes (AQTR) honoured the project team with its environmental award for technical achievement. The project was also a finalist for the Phénix award for sustainable development know-how. The name of the winner was announced only after this report went to press.
Launched in Montreal in March 2002, the BIOBUS project was designed to test the use of biodiesel as a source of supply for public transit, to assess the viability of the fuel as part of the routine operation of a bus fleet, particularly in cold weather, and, to a lesser extent, to measure biodiesel’s environmental and economic impact.

The project was an initiative of the Canadian Renewable Fuels Association (CRFA), the Fédération des producteurs de cultures commerciales du Québec (FPCCQ), Rothsay/Laurenco and the Société de transport de Montréal (STM). Rothsay/Laurenco, which produced the pure biodiesel, and the Société de transport de Montréal (STM), which provided 155 buses and the entire infrastructure used to test the fuel, both played key roles throughout the year-long project. It is also important to note support from the project’s outset by both Canadian and Quebec governments.

Urban Transportation and the Environment

The BIOBUS project is part of broader government policies to fight climate change, improve air quality, recover and manage wastes, and promote sustainable development. Following Canada’s ratification of the Kyoto Protocol in December 2002, the federal government adopted an action plan in the fight against climate change and pledged to reduce greenhouse gas (GHG) emissions. On its side, the Quebec government is working to develop a strategy for implementing commitments it made under the Kyoto Protocol.

Quebec’s per capita CO₂ emissions are only half those of the United States and other Canadian provinces. Such a performance, nearly as good as that of Japan and Sweden, is due in part to the development of hydropower, which helped reduce CO₂ emissions by 16% over the last two decades.

Trend in Per-Capita CO₂ Emissions

Source: Hydro-Québec, based on data from the OECD and Quebec’s Department of Natural Resources, 1999
In Québec, the road transportation sector alone accounts for 38% of total GHG emissions compared to 26% for Canada as a whole. Public transit is by far the least polluting means of motorized transportation. Using a biofuel like biodiesel—increasingly commonplace in Germany, France and elsewhere in Europe—could mark an immediate first step toward more environmentally conscious management of transportation. Though its use is not yet widespread in North America, biodiesel is now being envisaged as a potential alternative fuel for road transportation. One city bus can carry as many passengers as 50 cars and produces nitrogen oxide (NOx) and carbon dioxide (CO2) emissions 6 times lower, and hydrocarbon (THC) emissions 18 times lower. It is thus important to promote public awareness of the advantages of public transit. Both promoting greater use of public transit and using a biofuel like biodiesel would magnify the environmental impact.

Transportation-Related GHG Emissions Per Capita
(tons of GHG per capita)

B.C. & Territories
Alberta
Saskatchewan
Manitoba
Ontario
Quebec
Maritimes
Canada

Source: Transportation and Climate Change: Options for Action – Transportation Climate Change Table – November 1999

Biodiesel’s Benefits

Since it helps reduce GHG and other polluting emissions, biodiesel provides both a viable and cost-effective solution for partially reducing the amount of petrodiesel used to operate a city bus fleet. The aim of the BIOBUS project was to assess the impact of using biodiesel under actual operating conditions, especially in cold weather, and to demonstrate that it was feasibility to supply biodiesel to a major transit authority like the STM. Accordingly, nearly 550,000 litres of pure biodiesel, blended at 5% (B5) and 20% (B20) concentrations with petrodiesel, were used to supply the STM’s 155 Frontenac terminal buses from March 2002 to March 2003.

The BIODIESEL project is untypical in that the kind of biodiesel used by the STM came primarily from agro-industry waste: non-food-grade vegetable oil, used cooking oil and animal fat. Typically, projects use biodiesel very largely made up of vegetable oil (soybean, canola, etc.) from cash crops.

Formed from biomass, biodiesel is a renewable energy source that replaces a fossil hydrocarbon fuel. Its production and use involves a cycle generating low GHG emissions. Biodiesel could turn the largely overlooked potential of certain wastes into valuable by-products, reducing amounts buried in landfill sites and thus avoiding significant GHG emissions due to subsequent methane release.
Harsh Quebec Winter

In Quebec, where sub-zero winter weather is common, biodiesel has one major drawback: it starts solidifying at -3°C to 12°C depending on the source of fats or oils it contains. To avoid this problem, biodiesel was blended with petrodiesel, which can stand temperatures of -25°C. A 20% blend of biodiesel in petrodiesel (B20) has a cloud point of -15°C and can be used in very cold weather without problems. No special precautions were required for STM Frontenac terminal buses running on biodiesel during the seven weeks of winter 2002-2003 when temperatures dropped below -25°C. A major advantage was that buses not running were parked in a garage heated to 15°C.

Weekly Temperature Highs and Lows
(March 29, 2002 to March 28, 2003)
Promoters

Recognized as the largest project yet undertaken in North America to demonstrate and use biodiesel for public transit, the BIOBUS project sets itself apart from similar projects carried out in countries with a more temperate climate. It thus provides a baseline for biodiesel use in cold weather (winter 2002-2003). Data on the physicochemical characteristics of blends and emission measurements further support the prospects that this new fuel can successfully supply city bus fleets.

The partners described below promoted the BIOBUS project.

Implementation Partners

Société de transport de Montréal (STM)
To help improve air quality in Montreal, the STM was very keen to assess, in the framework of a demonstration project, how the use of biodiesel would impact its operations. The STM was thus a key partner, providing all facilities required to test biodiesel under actual operating conditions and becoming a technology showcase for other public transit companies across Canada. The STM's contribution amounted to $368,700.

Rothsay/Laurenco (Maple Leaf Foods Group)
Rothsay/Laurenco, which specializes in recycling agro-industry wastes, supplied the STM with pure biodiesel for the duration of the project. It provided 550,000 litres of biodiesel from three different sources: used cooking oil (48%), animal fat (28%) and non-food-grade vegetable oil (24%). Rothsay/Laurenco, whose financial contribution totalled $37,500, tuned its production to meet these requirements following the project schedule.

Canadian Renewable Fuels Association (CRFA) and the Fédération des producteurs de cultures commerciales du Québec (FPCCQ)
The CRFA is a non-profit organization mandated to promote renewable fuels through customer awareness and communications with government. The FPCCQ has the mission of finding markets for Quebec farm produce. In support of sustainable transportation, both organizations promoted the project and together contributed $10,000 in funding.

Financial Partners

Government of Canada
As part of its strategy to promote concrete projects that reduce GHG emissions, the Canadian government decided to support the BIOBUS project in partnership with Natural Resources Canada, Canada Economic Development, Environment Canada and the Technology Early Action Measures (TEAM) component of the Climate Change Action Fund (CCAF). The partnership set out to assess the environmental, economic and social benefits of introducing biodiesel in Canada and to promote the potential marketing of this product as a fuel from renewable resources. Funding from the government of Canada totalled $515,000.

Quebec Government
The BIOBUS project was a perfect fit for the kind of innovation that the Quebec government pledged to support in its 2000-2002 action plan, especially since it helps move from fossil fuels to renewable energy sources. This is why the Quebec government departments responsible for the environment, transportation, industry and commerce, municipal affairs, and natural resources, as well as the Agence de l'efficacité énergétique decided to allocate a total of $375,000 to the project.
STM Participation and Project Credibility

Public transit is a factor shaping Montreal's social and economic development. STM participation thus made such a major undertaking as the BioBus project all the more credible. With its fleet of 1,600 buses operating out of seven terminals, the STM provides for 1.3 million passenger trips over its system every day. The STM's Frontenac terminal was selected to test biodiesel because it serves the Montreal city core with its commercial arteries and many business centres. Very densely populated areas therefore benefited from the positive impact of reduced polluting emissions.

The table below shows the reduction in GHG emissions that would have resulted in 2002 had B20 been used by either all Frontenac terminal buses or by the entire STM fleet.

<table>
<thead>
<tr>
<th>Annual Statistics for 2002</th>
<th>Frontenac Terminal (155 buses)</th>
<th>Entire STM Bus Fleet (1,600 buses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Distance Travelled</td>
<td>6.7 million km</td>
<td>70.5 million km</td>
</tr>
<tr>
<td>Total Fuel Consumed</td>
<td>4.5 million litres</td>
<td>47.2 million litres</td>
</tr>
<tr>
<td>Estimated CO₂ Reduction with B20</td>
<td>2,100 tons</td>
<td>22,000 tons</td>
</tr>
</tbody>
</table>

Results and Perspectives

The demonstration and assessment of this new renewable fuel produced results that are all the more meaningful since they are based on a fleet and fuel supply as vast as that of the STM. The results can thus be more easily adapted to specific operating conditions for other transit authorities.

This report presents the main findings on biodiesel use from the standpoint of the supply, maintenance and operation of a public transit company, highlights results of emission measurements for GHGs and other pollutants, and puts project impacts in a global perspective.
Supplying Biodiesel to the STM

Biodiesel, a methyl ester produced from a chemical reaction between methanol and either vegetable oil (e.g., non-food-grade or recycled cooking oil) or animal fat, is a prime fuel for urban transportation.

- **It helps develop sustainable transportation** because it is produced from local, renewable resources, whether agricultural products or agro-industry by-products. This project called for the use of biodiesel produced from animal fat and vegetable oil that were recycled agro-industry waste (slaughterhouse waste, recycled cooking oil, non-food-grade virgin oil or agricultural surplus) and that would otherwise have been dumped or discarded into the environment with a potential risk of later release as methane, one of the greenhouse gases.

- **Biodiesel is easy to use**, since unlike other alternative fuels, no changes are needed either to the existing infrastructure for fuel distribution and delivery or to the diesel engines of today's buses when used in a 5% to 20% blend. Use under cold-weather conditions is the only aspect that required close scrutiny and special checks.

- **It helps significantly in the reduction of greenhouse gas (GHG) and polluting emissions.** Biodiesel is a renewable energy source that replaces a fossil hydrocarbon fuel. Its production and use involves a cycle generating low GHG emissions.

### Blending and Fuel Delivery

To ensure quality of source products and blends, processes were implemented both for fuel procurement and delivery and for quality control of pure biodiesel and the B5 and B20 blends.

Rothsay/Laurenco supplied biodiesel for the 155 Frontenac terminal buses from March 2002 to March 2003, making three deliveries a week following the procedure below.

- At the Montreal East Ultramar terminal, a tanker truck was loaded with petrodiesel to the 80% or 95% level depending on the desired biodiesel blend. Early morning loading was avoided so the petrodiesel would be as warm as possible.

- The Colpron-operated tanker truck then travelled about 30 km from the Ultramar terminal to Rothsay/Laurenco's Sainte-Catherine plant on Montreal's South Shore to be topped up with biodiesel. The volume of biodiesel was based on that of petrodiesel to achieve the desired blend (B5 or B20, depending on the phase of the project). When necessary, the pure biodiesel was heated during the hours preceding delivery to a temperature high enough for the final blend to be above 0°C, if possible.

- The trip to the Frontenac terminal further mixed the blend before it was unloaded into the STM's underground storage tank.

### Quantity of Biodiesel Used

A total of 550,000 litres of pure biodiesel—24% from vegetable oil, 28% from animal fat and 48% from used cooking oil—were consumed during the BIOBUS project.

![Diagram showing biodiesel blend composition](image_url)

- **Animal Fat: 28%**
- **Used Cooking Oil: 48%**
- **Vegetable Oil: 24%**
The three sources of biodiesel were used over the periods specified below.

1. Vegetable Oil:
   - B5: March 29 to July 14, 2002
   - B20: July 15 to August 18, 2002

2. Animal Fat:
   - B20: August 19 to August 23, 2002
   - September 2 to November 3, 2002
   - January 20 to January 31, 2003
   - February 10 to February 16, 2003

3. Used Cooking Oil:
   - B20: November 4, 2002 to January 19, 2003
   - February 17 to March 28, 2003

This chart shows weekly fuel deliveries to the Frontenac bus terminal from March 2002 to March 2003.

The red bars show that deliveries had to be stopped on the three occasions discussed below:

1. **Last week of August (Week 22): Animal-fat-based B20**
   Shipment were halted because of prolonged filter clogging on vehicles with a Cummins engine whose fuel system had a 10-µm filter at the fuel tank outlet. Buses with 25-µm filters were unaffected. At that time, the phenomenon was unexplained and believed possibly to be normal. Since the start of the school year is one of the busiest periods for the STM, it was thought best to be prudent and avoid risking disrupted service.

   It was confirmed that the problem stemmed from the ongoing release of deposits on tank walls. Finding the origin of the problem made the team aware of the need to comply with the finest level of filtering from supplier to engine. Checks showed that biochemical degradation of biodiesel was not an issue. B20 was sampled at different points in the supply chain (between delivery and bus fuel filter deposits) and tested for mould and bacteria. Lab results showed the presence of mould only, which is common in conventional petrodiesel.
2. First week of February 2003 (Week 45): Animal-fat-based B20
The challenge was to use animal-fat-based B20 during the coldest period in winter. The limiting factor was not running buses in cold weather but achieving a quality blend when petrodiesel temperature dropped below -10°C (see graph below). Certain fatty acid esters formed crystals, plugging garage pump filters.

3. Third week of February 2003 (Week 47): Animal-fat-based B10
In response to the problem encountered during Week 45, the concentration of biodiesel in the blend was reduced to 10% but this brought no noticeable improvement. It was thus decided to revert to cooking-oil-based biodiesel. Deliveries were interrupted for the time needed to produce a new batch of biodiesel.

Weekly Temperature Highs and Lows vs. Cloud Point
(March 29, 2002 to March 28, 2003)

Findings
- Even though products are filtered individually before blending, since certain animal-fat-based esters can cause flocculation problems during low-temperature blending, the blend should be refiltered before delivery to the user.
- These incidents caused problems with refuelling pump filters and reduced flow but had no impact on buses. By following a multi-step filtering process, potential fuel quality issues are easily resolved.
ASTM D 6751-02 is the only standard specification recognized in North America for biodiesel, and applies only to pure biodiesel (B100). It was necessary to make sure that Rothsay/Laurenco products complied with that standard.

The designations applied to sources of biodiesel (vegetable oil, animal fat or cooking oil) have no standard definitions. The biodiesel used in the BIOBUS project came from the following three sources:

- vegetable (soybean) oil
- animal fat with equal portions of pork lard and beef tallow
- used cooking oil collected from restaurants and agro-industry plants in Greater Montreal and for which the proportion of vegetable oil to animal fat varied from 75%-25% to 90%-10% depending on the group of customers from whom it was collected

One goal of the BIOBUS project was to assess the physicochemical properties of biodiesel blended with STM reference petrodiesel and compare them to the properties of conventional petrodiesel. This characterization would serve to better understand the products (biodiesel and petrodiesel) used in the project and to help interpret test results from Environment Canada’s Environmental Technology Centre (ETC) in Ottawa.

Compliance of Biodiesel Blends to Conventional Petrodiesel Standards

The pure biodiesel supplied by Rothsay/Laurenco complied with the applicable standard (ASTM D 6751-02). Currently, there are no standards for biodiesel blends. For information purposes, the characteristics of blends were compared with Quebec standards for petrodiesel. Disregarding low-temperature behaviour, whose impact needed to be assessed, biodiesel blends met all criteria except acidity. Petrodiesel acidity is specified to prevent excessive build-up of petroleum gums and varnishes in engines. For pure biodiesel, acidity measurements help ascertain that esterification is complete and no free fatty acids remain. The pertinence of taking this factor into account for biodiesel blends is an open question.

The physicochemical characteristics of blends were checked against biodiesel performance. Analyses performed by an independent lab helped gain a better understanding of the characteristics of 5% (B5) and 20% (B20) blends of biodiesel derived from different sources (vegetable oil, used cooking oil and animal fat) and how they stood up to petrodiesel standards. The analyses were also designed to check the quality of the STM supply, specifically against ASTM D 6751-02, the only existing standard for pure biodiesel (B100).

Methodology

The blends analyzed are the same as those used for emission measurements made on the ETC engine test facility. The reference petrodiesel for the BIOBUS project was low-sulphur (500 ppm) #2 petrodiesel (type B), delivered to the STM between February and May 2002. The biodiesel blends were made from this fuel. Characterization covered over 20 criteria found in various fuel standards. For details, see the table in the Appendix entitled Characterization of Fuels Used in the BIOBUS Project.

As far as possible, the same methods were used to analyze petrodiesel, biodiesel and blends. The results confirm the usefulness of biodiesel while highlighting a few important precautions to consider for ensuring reliability.

Lubricity

Even at low concentrations, biodiesel blends have clearly superior lubricity (lubricating power) compared to petrodiesel. That means that certain mechanical parts in contact with fuel, notably the injection pump, are less prone to wear. Biodiesel could thus be a valuable additive to future very-low-sulphur (<15 ppm) diesel fuels.
With B5, wear scars were already reduced by 90% compared to pure petrodiesel. B20 has the same lubricity as B100.

**Cloud Point and Low-Temperature Filterability**

Wanting to use animal-fat-based biodiesel during the winter, the project team took a close look at the operating conditions of STM buses. It was then able to implement a fuel-use procedure that took into account the minimum temperature the fuel could reach under extreme conditions. This lower threshold temperature is above the coldest winter temperature, given the operating conditions for buses.

Measurements showed that the temperature of the fuel supply on the road for all types of STM buses, including those having engines with electronic fuel injection, tended to stabilize around 30°C above the outdoor temperature. Once vehicles stop, it takes around an hour for the temperature of fuel lines and primary filter to drop by about 20°C. Based on these observations and knowing that Frontenac terminal buses park in a garage heated to roughly 15°C, the STM was not concerned about using a fuel with a cloud point as high as -15°C, even though the #2 petrodiesel it usually buys has a -24°C cloud point. It even agreed to test animal-fat-based B20 with a -10°C cloud point.

The project team also verified that it was possible to blend biodiesel at -5°C (the lowest temperature of delivered petrodiesel allowed by the STM supply contract, specified to avoid problems associated with the frosting of pump nozzle sensors). Blending at -5°C is not a problem provided the biodiesel is warm enough (e.g., 30°C for cooking-oil-based biodiesel). It was not known at that point in the project that the petrodiesel supplier was unable to comply with the minimum-temperature specification, particularly because of cold snaps during winter 2002-2003. Blends thus had to be made sometimes using petrodiesel colder than -10°C. Experience showed that neither the B100 cloud point nor that of the final blend dictated the solubility of biodiesel in low-temperature petrodiesel. When blending animal-fat-based biodiesel with cold petrodiesel, it was not enough to heat the B100 to a high enough temperature for the resulting blend to be above its cloud point (-10°C for animal-fat-based B20). The waxy crystals that form clump and then cannot completely dissolve again, even at 20°C. The problem could be solved by modifying the characteristics of fatty acid esters in animal-fat-based biodiesel so that the cloud point is closer to that of vegetable-oil-based biodiesel.

The graph at the bottom of this page and top of the next show that the use of animal-fat-based biodiesel will be a greater challenge in cold weather, particularly at concentrations of more than 5%.
Energy Efficiency

The energy efficiency of biodiesel blends used in the BIOBUS project was entirely comparable to that of petrodiesel. Results from ETC lab tests show that the use of biodiesel blends had no significant impact on the performance of diesel engines with mechanical fuel injection regarding power, maximum torque and fuel consumption. For details, see the Appendix under Impact of Biodiesel on Diesel Engine Efficiency.

The three variables below combine in determining energy efficiency.

1. Energy Content
   - Pure biodiesel typically contains 8% less energy than the same mass of petrodiesel.

2. Density
   - Biodiesel is 5% heavier than petrodiesel. Since the energy efficiency of engines is based on the volume of fuel consumed, energy content must be compared by unit volume and not by unit mass. Taking this into account, the energy content of pure biodiesel is just 4% below that of petrodiesel. The impact is in the order of 0.5% for B20 and not significant for B5.

3. Cetane Number
   - Lab measurements on a benchmark engine show that pure animal-fat-based biodiesel has a cetane number ranging from 52 to over 56 compared to 42 for STM reference petrodiesel. The higher number improves ignition performance and lowers NOx as confirmed by the U.S. Environmental Protection Agency report Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions (Draft Technical Report EPA 420-P-02-001, October 2002).

A higher cetane number normally results in better combustion and reduced NOx emissions.
Water Content
The hygroscopic properties of biodiesel can lead to high levels of chemically bound water, without blends containing free or suspended water. Water content can exceed 1,000 mg of water per kg of pure biodiesel. Tests at normal temperatures have detected no free water, only sediment. A test method remains to be found, however, to check whether this finding remains valid for blends at lower temperatures. Water content can have advantages for diesel engines, reducing emissions (particularly NOx) and increasing engine efficiency. The development of blends of emulsified water in petrodiesel is proof of this. Biodiesel's tendency to increase the fuel's water content, at least in warm weather, is thus an asset worth exploiting.

Thermal Stability
An assessment was made of the risk that the fuel degrades when heated in the diesel engine’s fuel line. Biodiesel blends have shown no significant change in thermal stability, even when exposed to humidity and temperatures above 70°C, the temperature fuel can reach in bus fuel tanks during summer. Furthermore, fuel samples showed no sign of bacteria, only traces of mould, which is quite common in petroleum products.

Flash Point
Even though the flash point of pure biodiesel (from 150°C to 190°C) is higher than for conventional diesel (50°C), this does not affect the flammability of blends, since the vapour pressure of a blend’s most volatile component determines the flash point.

Recommendations
Based on the findings, we can make the recommendations below.

- Once biodiesel and petrodiesel have been blended, the fuel must be filtered again before delivery, despite prior filtering of each product individually. The second filtering avoids problems associated with the flocculation of certain fatty acid esters when petrodiesel temperature is below the cloud point during blending.

- It is essential to ensure that the fuel supply process includes consistent multi-step filtering by requiring suppliers to use filters whose performance has been proven by documented test procedures. Specifically, checks must:
  - determine the micron rating (pore size) of the finest filters equipping the bus fleet (e.g., 10 µm based on a specific standard);
  - ensure that refuelling pumps have filters that are at least as fine, based on the same standard; and
  - ensure that the biodiesel blend delivered has first been filtered just as finely.

Cost of Biodiesel
Though beyond the scope of this project, it is interesting to take a brief look at biodiesel from a cost standpoint, given that its price is higher than that of petrodiesel. There appears to be a developing trend in North America to offset the difference by removing taxes from this emerging renewable fuel. The Ontario government introduced fiscal measures to this effect in its June 2002 budget, followed by the Canadian government in November 2002. The Quebec government showed that it intended to do likewise in March 2003 through a road tax rebate, which has yet to be confirmed.
Public transit will play a leading role in the fight against climate change. Urban transit authorities studying biodiesel’s potential as an alternative fuel must not focus, however, uniquely on greenhouse gas (GHG) emissions. Since buses influence urban air quality, one goal of the BIBOBUS project was to provide data to help assess the impact of biodiesel on pollutants in vehicle tailpipe emissions. The project involved assessing biodiesel use and did not study the fuel’s life cycle. The project team had the further role of ensuring that biodiesel had no significant impact on the total fuel consumption of buses.

Tests were carried out using a dynamometer bench at Environment Canada’s Environmental Technology Centre (ETC) in Ottawa using biodiesel from three sources (vegetable oil, animal fat and used cooking oil) in 5% and 20% blends fuelling two four-stroke Cummins diesel engines, one with mechanical fuel injection and the other with electronic fuel injection. In all instances, measurements were of tailpipe emissions taken after engine exhaust passed through the same type of catalytic converter as those equipping STM buses.

Fact sheets in the Appendix give the data for each emission type and are followed by methodological details.

### Emission Measurement

**Results**

Overall, biodiesel either had no effect or reduced polluting and GHG emissions whether regulated (PM, CO, THC and NOx) or unregulated (SO4, PAH, CO2 and PM2.5).

<table>
<thead>
<tr>
<th>Emission Type</th>
<th>Mechanical Fuel Injection System</th>
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<th>Electronic Fuel Injection System</th>
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<tr>
<td>Total Mass of Emitted</td>
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<td>Particulate Matter – PM</td>
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<td>Carbon Monoxide – CO</td>
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<td>Total Hydrocarbons – THC</td>
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<tr>
<td>Nitrogen Oxides – NOx</td>
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<tr>
<td>Fine Particulate Matter – PM2.5</td>
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<tr>
<td>Sulphates – SO4</td>
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<tr>
<td>Polycyclic Aromatic Hydrocarbon – PAH</td>
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**Percent Emission Reduction with B20 vs. STM Reference Petrodiesel**

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<tr>
<th>Emission Type</th>
<th>Mechanical Fuel Injection System</th>
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<td>Sulphates – SO4</td>
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<tr>
<td>Polycyclic Aromatic Hydrocarbon – PAH</td>
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Regulated Emissions

Total Mass of Particulate Matter (PM)
• Among emissions produced by a diesel engine, particulates are those that must be most closely scrutinized. Biodiesel has the greatest impact in engines with mechanical fuel injection, which, before adding biodiesel, emit 2.5 times more particulate matter than engines with electronic fuel injection. The most noticeable reductions, 25% to 30% depending on engine type, are achieved with vegetable-oil-based B20. Animal-fat-based B20 only reduces emissions 20% with mechanical fuel injection and 8% with electronic fuel injection.

Carbon Monoxide (CO)
• Diesel engine CO emissions, already 15 times lower than the Canadian standard, are reduced a further 20% to 30% with B20, regardless of engine type.

Total Hydrocarbons (THC)
• Diesel engine THC emissions are already far below the standard. Without biodiesel, engines with electronic fuel injection produce THC emissions 15% lower than those with mechanical fuel injection. Biodiesel used in an engine with electronic fuel injection results in a further 20% reduction for vegetable-oil-based B20 and 30% for animal-fat-based B20. For the engine with mechanical fuel injection, the reduction was only 10%, half that with electronic fuel injection.

Nitrogen Oxides (NOx)
• Generally speaking, biodiesel has a neutral effect on NOx emissions. A biodiesel fuel with a higher cetane number (animal-fat-based biodiesel and cooking-oil-based biodiesel containing animal fat) apparently tends to reduce NOx emissions. This is particularly true for an engine with electronic fuel injection, whose NOx emissions are about 3% to 5% lower. This tendency is confirmed by the U.S. Environmental Protection Agency report Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions (Draft Technical Report EPA 420-P-02-001, October 2002).

Unregulated Emissions

Sulphates (SO4)
• SO4 in particulate emissions are very low for both types of diesel engine studied.
• B20 results in a 15% reduction in SO4 emissions from an engine with electronic fuel injection.

Polycyclic Aromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs) and Carbonyl Compounds
• PAHs include highly carcinogenic substances. Compared to emissions produced by both diesel engines running on conventional petrodiesel, biodiesel results in no significant amount of new PAHs and does not upset the proportions of these complex, carcinogenic organic compounds (COVs and carbonyls).
• B20 from all three sources results in substantially lower PAH emissions, around 10% to 30% with electronic fuel injection.

Fine Particulates Below 2.5 µm (PM2.5)
• Biodiesel has a greater impact on total fine particulate emissions for engines with mechanical fuel injection, whose fine particulate emissions without biodiesel are 2.5 times higher than those of engines with electronic fuel injection.
• Biodiesel’s contribution to reducing the total mass of fine particulate matter stems primarily from reduced elemental carbon (apparent as sooty exhaust fumes). This can be explained by the fact that biodiesel, low in sulphur, reduces total sulphur in the blend and that sulphur has a determining effect on the formation of elemental carbon particles.
• It cannot be concluded that there was a reduction in soluble organic fraction (SOF) or in particulates below 1.5 µm, both thought to be higher health risks. It can be stated, however, that there was no significant increase in such particulate emissions from the engine with electronic fuel injection.
The following GHG emissions targeted by the Kyoto Protocol are likely to be found in internal-combustion engine emissions: carbon dioxide (CO2) and both nitrous oxide (N2O) and methane (CH4), the latter two gases having a global warming potential respectively 310 times and 21 times that of an equivalent mass of CO2. For the diesel engines studied, direct CO2 emissions were 600 g per unit work produced (bhp-h). Test measurements put N2O and CH4 emissions in the milligram range. It was thus decided to ignore detailed data for these two types of emissions despite their global warming potential. Even if significant variations were found for N2O and CH4, the impact on the overall GHG balance would have been negligible.

Thus CO2 is the only GHG considered in this report and CO2 emissions are the only GHG emissions dealt with in the Appendix. The appended fact sheet supports two findings.

1. Baseline GHG emissions for both engine types are roughly 2.59 kg of CO2 per litre of STM reference petrodiesel.
2. Biodiesel can be considered to have a negligible effect on direct CO2 emissions, only animal-fat-based B20 resulting in 2% lower direct (tailpipe) CO2 emissions from engines with mechanical fuel injection.

Despite this, using biodiesel does help reduce GHG emissions. Project data does not contradict this statement since it only applies to direct tailpipe emissions. When an engine burns one litre of biodiesel, whose physicochemical properties are very similar to those of petrodiesel, it makes no distinction between the sources of the two fuels. Reduction in GHG emissions arises from the fact that biodiesel comes from animal or plant biomass with a life cycle of a few years; whereas, petrodiesel is a fossil fuel that releases into the atmosphere carbon that has been tied up for hundreds of millions of years. Biodiesel, unlike petrodiesel, is thus a renewable energy source.

That tailpipe CO2 emissions do not significantly change is a point in favour of biodiesel since the engine’s fuel combustion energy balance is based on these emissions. This proves that variations in fuel consumed per unit work are negligible and that engine energy efficiency is unchanged by adding biodiesel.

As a working hypothesis, we can state that:
Every litre of pure biodiesel (B100) used to replace a litre of petrodiesel reduces GHGs by 2.33 kg of CO2.

This figure is based on the assumption that biodiesel avoids 90% of the emissions from reference petrodiesel because it contains 10% methanol used for esterification and obtained from natural gas (non-renewable fossil energy). Since the biodiesel manufacturing process requires about 10% methanol (from natural gas), the potential reduction in GHG emissions for B20 has been estimated at about 17% (about 4.5% for B5). Although this hypothesis simplifies matters, it does set an order of magnitude. It would have to be confirmed, however, by thorough life-cycle studies, which were not the goal of the BIOBUS project.

The BIOBUS project demonstrated the viability of biodiesel use by public transit authorities. Under the project, a total 550,000 litres of biodiesel in 5% and 20% blends were consumed by Frontenac terminal buses between March 2002 and March 2003, leading to a reduction in CO2 emissions of roughly 1,300 tons. Since the results show that the reduction in polluting and GHG emissions was significant, it can be stated that Quebec- and Canada-wide use of biodiesel would help reduce such emissions even further.

The table below gives an order of magnitude for the impact B20 would have on annual CO2 emissions, assuming that a four-stroke Cummins engine with mechanical fuel injection is representative of bus fleets across Quebec and Canada.
Smog is a toxic mixture of air pollutants that often appears as a haze hovering over cities. Individuals exposed to smog may become more vulnerable to cardiopulmonary diseases. The two main components of smog that impact health are ground-level ozone and fine airborne particulates. Ground-level ozone is a colourless, extremely irritant gas that forms just above the earth’s surface. It is called a “secondary pollutant” because it is produced when two “primary pollutants” react to sunlight in stagnant air. The two primary pollutants are nitrogen oxides (NOx) and volatile organic compounds (VOCs).

Other noteworthy pollutants found in smog include nitrogen dioxide (NO2), one of the foremost nitrogen oxides (NOx), sulphur dioxide (SO2), which can be chemically transformed into acid pollutants like sulphuric acid, and sulphates (SO4), primary components of fine particulates.

Regardless of concentration or source, biodiesel can help reduce urban smog formation. Using biodiesel does not increase NOx emissions, and can even reduce them. It also substantially lowers the mass of particulate emissions and, depending on the measures taken, reduces sulphur dioxide (SO2) emissions. This is in part because biodiesel, not containing sulphur, dilutes the proportion of sulphur in the blend the engine burns.

Another family of emissions that act as ozone (O3) precursors in smog formation are non-methane organic compounds, a major component of smog and a powerful irritant to the respiratory tract.

The chart below shows ozone precursor emissions from an engine with electronic fuel injection for the six biodiesel blends and STM reference petrodiesel. The emissions are non-methane organic gases (NMOGs) quantified by their total ozone-forming potential (in mg of O3) per unit work by the engine (in brake horsepower-hours). The ozone-forming potential of a compound corresponds to the compound’s ozone emissions (in mg) multiplied by a reactivity factor, which expresses the effect of sunlight on the compound. NMOGs are comprised of all hydrocarbons (THC), volatile organic compounds (VOCs) and aldehydes from the carbonyl group.

The chart shows that all biodiesel blends result in a very significant reduction in ozone-forming potential. B5 blends result in a reduction of at least 25% (up to 50% for animal-fat-based B5); whereas, B20 blends result in reductions of about 30%. Neither the source of B20 nor the concentration of biodiesel in the blend had a significant effect. It is noteworthy, however, that ozone-forming potential was lowered the most with animal-fat-based B5 and cooking-oil-based B20, the two blends for which the most significant NOx reductions were observed. One nitrogen oxide, NO2, is also known to contribute to ozone formation though not an organic compound.

In conclusion, biodiesel has the overall effect of reducing polluting and GHG emissions, be they regulated (PM, CO, THC and NOx) or unregulated (SO4, PAH, CO2 and PM2.5), and helps reduce urban smog.
The issue of emissions was also studied from another standpoint: how biodiesel’s effect varies depending on engine type, concentration of biodiesel in the blend, and source of biodiesel.

**Impact of Engine Type**
- Biodiesel had the overall effect of reducing polluting emissions both for the engine with mechanical fuel injection and for the one with electronic fuel injection.
- Phasing in engines with electronic fuel injection to replace those with mechanical fuel injection will generally result in substantially lower emissions, particularly for NO\textsubscript{x} and PM\textsubscript{i}. Biodiesel nevertheless has a bright future since it reduces several polluting emissions and does so more noticeably with electronic fuel injection than with mechanical fuel injection.

**Impact of Concentration of Biodiesel in the Blend**
- Test data does not establish that emission reductions are proportional to the concentration of biodiesel in the blend.
- With B20, significant reductions were generally noted.

**Impact of Source of Biodiesel**
- Each source of biodiesel has its advantages and limitations, depending on the type of emission considered. In short, all sources were on a par from the emissions standpoint. Emission tests alone do not provide sufficient basis for selecting any given source of biodiesel over another.
Ce véhicule roule au biodiesel!
STM Fleet Operations and Maintenance

Operations covers all activities associated with delivering service to the system of STM buses on the road every day throughout Montreal. Maintenance includes scheduled bus inspection and repair, while infrastructure relates to the management of STM facilities.

Breakdown of Frontenac Terminal Bus Fleet by Engine Type

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Start of Project</th>
<th>End of Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Stroke Detroit Diesel Engine with Mechanical or Electronic Fuel Injection</td>
<td>85</td>
<td>75</td>
</tr>
<tr>
<td>Four-Stroke Cummins Diesel Engine with Mechanical Fuel Injection</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Four-Stroke Cummins Diesel Engine with Electronic Fuel Injection</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Total Number of Vehicles</td>
<td>155</td>
<td>157</td>
</tr>
</tbody>
</table>

The BIOBUS project included a series of tests prior to using biodiesel and subsequent assessment of the impact of blends on STM operations, maintenance and infrastructure.

Before bringing biodiesel on stream for general use across the entire STM Frontenac terminal fleet (over 155 buses), several preliminary tests were carried out to reassure decision-makers. These tests began in summer 2001, when the demonstration and impact assessment project was still being planned and financing arranged. Testing was designed to:

- prove that STM buses could tank up on biodiesel without creating engine problems;
- check that this was true even for old buses with two-stroke diesel engines having run over 500,000 km, since it was feared that, because of its “cleansing” properties, biodiesel might attack accumulated deposits on piston rings or gaskets between mechanical parts and lead to compression loss or leaks; and
- show that buses could use biodiesel in cold weather.

The tests below reassured the STM on all of these points.

- During a first one-week test in July 2001, a half dozen buses ran on soybean-oil-based biodiesel in blends of up to 30% with manual fill-ups.
- Similar tests were then carried over more than two weeks with a 20% blend using a dozen buses, including some older buses with higher kilometrage. No filter-clogging problems were encountered during this period.
- Buses with high kilometrage were tested by STM staff on the company’s dynamometer bench to measure exhaust opacity before and after using B20. Results did not indicate any loss of engine efficiency but did show a substantial reduction (50%) in exhaust opacity. Furthermore, particulate emissions were at a much more constant level from one acceleration test to the next. With STM reference petrodiesel, particulate emission peaks are very irregular and sometimes vary by a factor of five from one acceleration test to the next.
- A four-stroke Cummins engine with mechanical fuel injection was tested at -20°C in an ETC cold chamber. It was discovered that significant temperature increases in the fuel system made it possible to use a fuel with a cloud point higher than the ambient temperature.
- The tendency for fuel to be heated to up to 30°C above the ambient temperature (including in buses with electronic fuel injection) was confirmed by sampling tank temperatures for the various types of buses on a cold March 2002 morning following an overnight low of -20°C.
### Impact of Biodiesel on Bus Fleet Operations

One goal of the **BIOBUS** project was to assess the impact of using biodiesel on bus fleet reliability. To do so, the STM database of on-road service calls was used. Statistics can be retrieved from the database on driver calls to report technical problems, coded by type, then the mechanic’s follow-up diagnostic recorded with another code, and work performed by bus maintenance staff. For instance, if a driver reported “loss of power” a check can be made to see whether or not it was related to the vehicle’s fuel system and to which terminal the bus belonged.

It was found that Frontenac terminal bus availability was maintained and that biodiesel resulted in no recorded incident affecting customer service.

The **BIOBUS** project was well received by bus drivers because of the positive impact on the environment. The satisfaction expressed stemmed especially from the fact that no trouble arose from using biodiesel. From the drivers’ standpoint, the power of their buses remained the same and, on the whole, exhaust smelled less. Their perception entirely agrees with results from the test facility, which showed that variations in engine power and torque were around 3% and probably not significant (see Appendix under *Impact of Biodiesel on Diesel Engine Efficiency*).

### Impact of Biodiesel on Bus Fleet Maintenance

Another **BIOBUS** project objective was to assess statistically the impact of using biodiesel on mechanical maintenance and fuel consumption per distance travelled. To reveal and confirm any patterns, a cross-analysis was made using data from different STM terminals. The analysis was not limited to comparing data for the year preceding biodiesel use with data obtained during the **BIOBUS** project. To account for natural trends in the data, first and foremost ageing of the fleet, the same comparisons were run using 2001 and 2002 data for two other STM terminals, the Saint-Denis and Mont-Royal terminals. The fleets at these two terminals have about the same breakdown and the area they cover has similar characteristics, some lines in the city core even being shared.

**Fuel Consumption**

A global assessment was made of fuel consumption but the data revealed no conclusive variation. Note that bus kilometrage is not recorded on an odometer but calculated based on the lines run and the number of runs along those lines in the course of the day. The loan or exchange of buses between terminals and other such circumstances means that one terminal could make up for a shortage of buses every day with ones from other terminals. The absence of any variation in bus fuel consumption is supported by test facility data (see Appendix under *Impact of Biodiesel on Diesel Engine Efficiency*). It can be noted that STM buses on city core routes consume an average 65 litres/100 km.
Mechanical Maintenance
Comparisons for mechanical maintenance were based on data for mechanical work that is normally archived as either corrective action or preventive maintenance. No corrective action to fuel injection pumps or nozzles arose from the use of biodiesel.

To probe the issue of repeated filter clogging on one bus model, certain elastomer components in contact with the fuel were analyzed (thickness, appearance, possible cracking, colour changes, flexibility, etc.). No component degradation was found.

There was no problem with most buses, particularly older models with 25-µm fuel filters and the latest models with electronic fuel injection systems, even during the first weeks following the cutover to biodiesel. The behaviour of these buses was better than those that had already been subjected to biodiesel tests, for which there was a risk of filter plugging due to deposits loosened by the first fill-ups. In general, filters on the latter buses are located above the engine compartment or against the engine block, i.e., in the coolest part of the fuel system.

The only real problem to report (backed up by an explanation and solution) was the repeated, then sporadic, clogging of one model of 10-µm filter, the Fleetguard FS-1000, installed as the primary filter only in Cummins engines with mechanical fuel injection. Unlike others, this filter is located directly at the fuel tank outlet and thus in an area of the engine compartment that is not as warm.

The two first waves of filter clogging resulted from the cutover first to B5, then to B20. They were caused by the formation of a jelly laden with fine black particles that completely plugged the cartridge. The fine particles came from the release of black deposits that had built up on the inner walls of bus fuel tanks. A third wave of clogging occurred three months later during the Christmas season when refuelling pumps with older 25-µm filters were used by mistake instead of 10-µm ones.

In response to sporadic 10-µm filter clogging, electron microscope scans were carried out at the Fleetguard labs and infrared reflectance spectroscopy tests conducted by an independent lab. The clogging was caused by a thin film of light-coloured wax from a group of fatty acid esters. Once suppliers can better control the cloud point of their biodiesel products, they will probably be able to eliminate the fatty acid esters that are at the root of this problem.

Note on Buses with Electronic Fuel Injection
One issue was whether Cummins engines with electronic fuel injection, known to be the most prone to fuel quality problems, would work well with biodiesel. To check this out, four buses, one brand new having an engine with electronic fuel injection, were loaned to the Frontenac terminal from January to April 2003. They were used to test, during the coldest season, the potentially most problematic biodiesel blends: cooking-oil-based B20 and animal-fat-based B20. The result was that these buses travelled nearly 10,000 km each during this period without a single problem.

Although the number of buses was too limited to establish statistics, it is noteworthy that no incidents occurred. These buses were equipped with Fleetguard FS-1022 filters having the same filter cartridge as FS-1000s but located in a warmer area of the engine compartment.

Impact of Biodiesel on Terminal Infrastructure Maintenance
The project team was also mandated to assess biodiesel’s impact on Frontenac terminal infrastructure. Build-ups on refuelling pump filters in the second week of September lead to reduced flow and slower bus fuelling. Any infrastructure-related problem has a direct impact on process flow. It is thus worth reiterating the importance of a consistent multi-step filtering process.

Another matter was air quality, monitored inside the garage by the STM before and after biodiesel was introduced, as required by the CSST, the workers’ compensation, health and safety board in Quebec. The results were positive, the STM finding a significant reduction in emissions and in the quantity of sooty fumes.
Findings

- Biodiesel caused no bus-related mechanical problems, notably with the fuel injection system. It was even verified that no degradation of elastomer components in contact with the fuel had occurred.
- Most buses, particularly those with 25-µm filters (and Detroit Diesel engines), went through the cleansing period without any problems.
- The cleansing period was longer than predicted for buses with 10-µm filters, longer still because B5 was used for three months before cutting over to B20.
- When a rigorous multi-step filtering process is followed, potential blend quality issues do not affect buses.
- The sporadic incidents caused by the finest (10-µm) filters located farthest from sources of heat in the engine compartment of buses had no real impact and resulted in no significant costs for the STM. Once producers use processes allowing better control of the cloud point of pure biodiesel, this problem will be solved at the source.
- In certain bus models, some mechanical failures can result in symptoms similar to those associated with plugged fuel filters. For a correct diagnosis, it is thus important to single out the source of the problem.
- No significant change in engine efficiency was noted.
- On the whole, drivers said they were satisfied with how the project went.
- Cold caused no operating problems for buses on the road despite three cold spells three to five days long when daytime temperatures remained below -20°C and overnight temperatures dropped to -30°C.
- The two buses having engines with electronic fuel injection used during the winter months were each driven over 10,000 km on B20. They did not prove any more prone to problems on biodiesel than did other vehicles, even during very cold weather.

Recommendations

- Analysis of the cause of incidents arising with 10-µm filters highlights the importance of a consistent multi-step filtering process (see section Supplying Biodiesel to the STM). The determining value is the pore size of the finest filters equipping buses.
- When cutting over to biodiesel, it is better to shift to the desired concentration, e.g., B20, from the outset rather than gradually phasing in biodiesel using weaker blends, in order to avoid prolonging the cleansing period.
- Transit authorities with vehicles not parked in a heated garage should probably limit the concentration of biodiesel in the blend to 5% or less, making any impact on cloud point negligible. It is preferable, however, not to return to pure petrodiesel in order to avoid a new transition period the following spring. Minimal biodiesel in a blend prevents build-ups on fuel tank walls that have been cleansed by earlier use of B20.
- During the first year after cutover, a stock of spare filters adequate for the entire fleet should be kept on hand, particularly filters located in cooler areas of the engine compartment. The cleansing period will also entail one or two additional filter changes at an estimated cost of $100 per bus.
- To avoid filter problems and potentially to increase kilometrage between two preventive fuel filter changes, it is worth discussing matters with the supplier. For a few extra dollars, some filter models housed in the same engine-adapted cartridge have a larger surface area than the standard model. Changing models could avoid more frequent filter changes and, with time, bring savings by making filter changes less frequent.
- A training program should be implemented to instruct technical staff on the transition from petrodiesel to biodiesel. Its content should emphasize the importance of identifying the true source of a problem, particularly during the cleansing period, in order to achieve a correct diagnosis.
L’autobus qui arrive roule au biodiesel !

Pendant un an, 155 autobus de la STM rouleront au biodiesel dans le centre-ville de Montréal.

Le biodiesel est produit à partir de matières grasses végétales ou animales recyclées.

L’utilisation de biodiesel entraîne une réduction des émissions polluantes et des gaz à effet de serre.

Voyagez dans un BIBUS et participez à la lutte contre les changements climatiques !

Pour en savoir plus, consultez le site www.stm.info
Communications

The **BIOBUS** project had the entirely legitimate goal of heightening public awareness of the issue of greenhouse gas (GHG) emissions and climate change and of the importance of taking action through the combined use of biodiesel and public transit. Communications efforts played a leading role in achieving this awareness both within the STM and other project partners, and among STM customers. All surveys point to the same finding: the project was very warmly received and satisfaction with it was high.

### Internal Communications

Partners promoted the project both on their web sites and through a variety of means including special T- and polo shirts, buttons and even a cardboard **BIOBUS** piggybank for schoolchildren. Employees were kept abreast of objectives, action taken, progress and results as the project unfolded.

The STM informed all its personnel of project highlights. Frontenac terminal employees were those most directly involved in the great **BIOBUS** adventure. It was thus important to remain attentive to their concerns and keep spirits high. Nothing could have been easier. Drivers of biodiesel-fuelled buses encountered no major problems, and infrastructure and vehicle maintenance workers were not flustered by the few sporadic incidents that arose during the project. Quite the contrary, satisfaction with the project remained high and Frontenac terminal engineers, maintenance workers and other staff showed unwavering support. Words of support rang loud and clear in the STM’s internal newsletters (*en Commun* and *Nouvelles STM*) and during the various meetings held. Staff felt closely concerned by the **BIOBUS** project. This gave rise to genuine team spirit and helped everyone work well together.

### External Communications

Opportunities to promote the project were not in short supply. Invitations were received by the project team, which participated in some forty public and industry activities, including symposia and fairs attended by specialists in the environment, transportation and agriculture (e.g., Americana 2003, the AQTR’s road and transportation show, and Excellence 2003), popular events (e.g., Montreal’s Fête des neiges, Children’s Festival and Clean Air Day), news stories broadcast by the CBC, by Télé-Québec, and even by a Japanese network specialized in sustainable development with five million viewers. It is fair to claim that the **BIOBUS** project had favourable and repeated exposure in a range of contexts both nationally and internationally.

The project was also applauded in the print media. The widely circulated **BIOBUS** Newsletters first gave an initial description of the project, and then overviewed its progress. News coverage and feature articles on the project appeared in *Métro*, in major newspapers (e.g., *the Gazette*, *Globe and Mail*, *La Presse*, *Le Soleil*, and *Le Devoir*), and in trade magazines (e.g., *Forum*, *Canadian Technology and Business*, *La maîtrise de l’énergie*, and *Le bulletin des agriculteurs*). The April 2003 issue of *Québec Science*, for instance, contained a feature article describing the project’s objectives and scope.

High project visibility was certainly achieved by such means as decking out a **BIOBUS** running throughout the area covered by the STM, identifying buses running on biodiesel with the **BIOBUS** logo on their sides and banners on the back bumper, displaying posters inside buses, distributing leaflets to passengers and visitors, and posting publicity on bus shelters.

Users were also asked to provide feedback. Many individuals shared their impressions either in person or by sending e-mail. Behind all feedback was growing public concern regarding polluting emissions and the importance of reducing them. The STM was widely praised for making the environment a priority.

### Summary of Communication Activities

<table>
<thead>
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<th>External</th>
<th>Total</th>
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</table>
On several occasions, the **BIOBUS** project was held up as an example because of the social and environmental importance of its mission. During its annual convention held in Sherbrooke on April 8, 2003, with Quebec Minister of Transport Serge Ménard in attendance, the Association québécoise du transport et des routes (AQTR) honoured the project team with its environmental award for technical achievement. The media at large then had an opportunity to tour a **BIOBUS** that was driven down to Sherbrooke for the event.

The project is also a finalist for the Phénix award for sustainable development know-how given to a primary or secondary industry having applied processes or technology to improve its environmental performance. The name of the winner was announced only after this report went to press.

The scale of the **BIOBUS** project earned it mention as the most important initiative of its kind in North America. It has opened the way to a more environmentally conscious view of public transit and now serves as a showcase for transit authorities and users alike.
This section contains all project findings and recommendations regarding fuel supply, emission measurements, operations and maintenance. Each finding or recommendation identifies the issue and individuals addressed.

**Recommendations Regarding Fuel Supply**

- **Refilter fuel to prevent clogging of refuelling pump filters**
  - Once biodiesel and petrodiesel have been blended, the fuel must be filtered again before delivery, despite prior filtering of each product individually. The second filtering avoids problems associated with the flocculation of certain fatty acid esters should the petrodiesel be too cold during blending.

- **Follow strict multi-step filtering to prevent clogging of refuelling pump filters and bus fuel system filters**
  - It is essential to ensure that the fuel supply process include consistent multi-step filtering by requiring suppliers to use filters whose performance has been proven by documented test procedures. Specifically, checks must:
    1. determine the micron rating (pore size) of the finest filters equipping the bus fleet (e.g., 10 µm based on a specific standard);
    2. ensure that refuelling pumps have filters that are at least as fine, based on the same standard; and
    3. ensure that the biodiesel blend delivered has first been filtered just as finely.

**Findings Regarding Emission Measurements**

- **Reduced polluting emissions, GHGs and urban smog**
  - Biodiesel has the overall effect of reducing polluting and GHG emissions, be they regulated (PM, CO, THC and NOₓ) or unregulated (SOₓ, PAH, CO₂ and PM₂.₅), and helps reduce urban smog.

- **Direct tailpipe CO₂ emission produced with petrodiesel – Engines with mechanical and electronic fuel injection**
  - Baseline GHG emissions for both engine types are roughly 2.59 kg of CO₂ per litre of STM reference petrodiesel. Direct GHG emissions are, for all intents and purposes, only comprised of CO₂ since despite their high global warming potential, direct N₂O and CH₄ emissions were negligible and completely overshadowed by CO₂.

- **Direct CO₂ emissions produced with biodiesel**
  - As a working hypothesis, we can state that:
    Every litre of pure biodiesel (B100) used to replace a litre of petrodiesel reduces GHGs by 2.33 kg of CO₂.
    Based on this hypothesis, it is possible to calculate by how much GHGs are reduced for each litre of B100 used to replace a litre of petrodiesel. The figure above is based on the assumption that biodiesel avoids 90% of the emissions from reference petrodiesel because it contains 10% methanol used for esterification and obtained from natural gas (non-renewable fossil energy). Although this hypothesis simplifies matters, it does set an order of magnitude. It would have to be confirmed, however, by thorough life-cycle studies, which were not the goal of the BIOBUS project.
Impact of biodiesel on urban smog

- Regardless of concentration or source, biodiesel can help reduce urban smog formation. Using biodiesel does not increase NOx emissions, and can even reduce them. It also substantially lowers the mass of particulate emissions and, depending on the measures taken, reduces sulphur dioxide (SO2) emissions. This is in part because biodiesel, not containing sulphur, dilutes the proportion of sulphur in the blend the engine burns.

- Another family of emissions that act as ozone (O3) precursors in smog formation are non-methane organic compounds, a major component of smog. Ozone-forming potential was lowered the most with animal-fat-based B5 and cooking-oil-based B20, the two blends for which the most significant NOx reductions were observed. One nitrogen oxide, NO2, is also known to contribute to ozone formation though not an organic compound.

Impact of engine type

- Biodiesel had the overall effect of reducing polluting emissions both for the engine with mechanical fuel injection and for the one with electronic fuel injection.

- Phasing in engines with electronic fuel injection to replace those with mechanical fuel injection will generally result in substantially lower emissions, particularly for NOx and PM. Biodiesel nevertheless has a bright future since it reduces several polluting emissions and does so more noticeably with electronic fuel injection than with mechanical fuel injection. However, it was noted for mechanical fuel injection alone that biodiesel could significantly increase the proportion of certain very fine particulates.

Impact of the concentration of biodiesel in the blend

- Test data does not establish that emission reductions are proportional to the concentration of biodiesel in the blend.

- With B20, significant reductions were generally noted.

Impact of the source of biodiesel

- Each source of biodiesel has its advantages and limitations, depending on the type of emission considered. In other words, all sources were on a par from the emissions standpoint. Emission tests alone do not provide sufficient basis for selecting any given source of biodiesel over another.

Findings Regarding Maintenance

Take into account a cleansing period

- Biodiesel caused no bus-related mechanical problems, notably with the fuel injection system. It was even verified that no degradation of elastomer components in contact with the fuel had occurred.

- Most buses, particularly those with 25-µm filters (and Detroit Diesel engines), went through the cleansing period without any problems.

- The cleansing period was longer than predicted for buses with 10-µm filters, longer still because B5 was used for three months before cutting over to B20.

Follow a multi-step filtering process

- When a rigorous multi-step filtering process is followed, potential blend quality issues do not affect buses.

- The sporadic incidents caused by the finest (10-µm) filters located farthest from sources of heat in the engine compartment of buses had no real impact and resulted in no significant costs for the STM. Once producers use processes allowing better control of the cloud point of pure biodiesel, this problem will be solved at the source.

Know how to pinpoint the problem

- In certain bus models, some mechanical failures can result in symptoms similar to those associated with plugged fuel filters. For a correct diagnosis, it is thus important to single out the source of the problem.
Dependability of biodiesel as a winter fuel

- No significant change in engine efficiency was noted.
- Cold caused no operating problems for buses on the road despite three cold spells three to five days long when daytime temperatures remained below -20°C and overnight temperatures dropped to -30°C.
- The two buses having engines with electronic fuel injection used during the winter months were each driven over 10,000 km on B20. They did not prove any more prone to problems on biodiesel than did other vehicles, even during very cold weather.

Follow a multi-step filtering process

- Analysis of the cause of incidents arising with 10-µm filters highlights the importance of a consistent multi-step filtering process (see section Supplying Biodiesel to the STM). The determining value is the pore size of the finest filters equipping buses.

Make effective plans for the cutover to B20

- When cutting over to biodiesel, it is better to shift to the desired concentration, e.g., B20, from the outset rather than gradually phasing in biodiesel using weaker blends, in order to avoid prolonging the cleansing period.
- Transit authorities with vehicles not parked in a garage heated during the winter should probably limit the concentration of biodiesel in the blend to 5% or less, making any impact on cloud point negligible. It is preferable, however, not to return to pure petrodiesel in order to avoid a new transition period the following spring. Minimal biodiesel in a blend prevents build-ups on fuel tank walls that have been cleansed by earlier use of B20.
- During the first year after cutover, a stock of spare filters adequate for the entire fleet should be kept on hand, particularly filters located in cooler areas of the engine compartment. The cleansing period will also entail one or two additional filter changes at an estimated cost of $100 per bus.
- To avoid filter problems and potentially to increase kilometrage between two preventive fuel filter changes, it is worth discussing matters with the supplier. For a few extra dollars, some filter models housed in the same engine-adapted cartridge have a larger surface area than the standard model. Changing models could avoid more frequent filter changes and, with time, bring savings by making filter changes less frequent.

Implement an adequate training program

- A training program should be implemented to instruct technical staff on the transition from petrodiesel to biodiesel. Its content should emphasize the importance of identifying the true source of a problem, particularly during the cleansing period, in order to achieve a correct diagnosis.
Results of Emission Measurements

A measurement program was implemented to ensure a reliable fuel supply and reliable testing. Regulated and unregulated emissions were measured for the various biodiesel blends (based on source and concentration) using both types of engine and related to emissions for the reference petrodiesel used by the STM. This appendix comprises a series of fact sheets to help interpret the test results. Further tests were carried out for carbon dioxide, polycyclic aromatic hydrocarbons, and fine \(< 2.5 \mu m\) particulates. Details regarding the methodology used follow the fact sheets.

Greenhouse Gas (GHG) Emissions

Measurements were carried out using a test facility at Environment Canada’s Environmental Technology Centre (ETC) in Ottawa. This appendix contains emission test results for the following:

### Regulated emissions
- **CO** carbon monoxide
- **THC** total hydrocarbons
- **NOx** nitrogen oxides
- **PM** particulate matter (total mass)

### Unregulated emissions
- **PM_{2.5}** fine particulates below 2.5 µm
- **SO_{4}** sulphates
- **PAH** polycyclic aromatic hydrocarbons
- **CO_{2}** carbon dioxide

Greenhouse gas (GHG) emissions
The following greenhouse gas (GHG) emissions targeted by the Kyoto Protocol are likely to be found in internal-combustion engine emissions: carbon dioxide (CO₂), and both nitrous oxide (N₂O) and methane (CH₄). The latter two gases have a global warming potential of respectively 310 times and 21 times that of an equivalent mass of CO₂. For the diesel engines studied, direct CO₂ emission measurements were around 600 g per unit work produced (bhp-h). Test measurements put N₂O and CH₄ emissions in the milligram range. It was thus decided to ignore detailed data for these two types of emissions despite their high global warming potential. Even if significant variations were found for N₂O and CH₄, the impact on the overall GHG balance would have been negligible. Thus CO₂ is the only GHG reported here.

Each type of emission is described in a fact sheet comprising:

- a table summarizing the mean result for each test
- a comparative analysis of the test results
- bar charts showing:
  - total emissions in g/bhp-h
  - reduction in emissions vs. STM reference petrodiesel in g/litre
  - percent reduction in emissions vs. STM reference petrodiesel, based on the results in g/bhp-h
- key findings from the tests:
  - the impact of engine type, and of concentration and source of biodiesel
  - other specific findings, particularly regarding emission tests for CO₂, PAHs and fine \(< 2.5 \mu m\) particulates

The data is presented in such a way that emissions from biodiesel blends can be compared to those for STM reference petrodiesel. The comparisons highlight the impact of the concentration of biodiesel in the blend (B5 or B20) and of the source of biodiesel (vegetable oil, animal fat or used cooking oil) for both types of engines (with mechanical fuel injection or with electronic fuel injection).

To correctly interpret the data, it is important to determine whether any variation noted between two test measurements is statistically significant or not. Anova analysis was used to achieve this. With this method, it is possible to state whether or not the difference between two sets of values is the result of chance and to determine the likelihood that the same tests, carried out again, would still show a difference. Differences with a probability of 95% or higher have been declared significant.

Notes

bhp-h
The unit bhp-h (brake horsepower-hour) designates one brake horsepower applied for one hour. Brake horsepower is used to measure the power of the drive shaft before transmission losses.

tons/year
This unit shows the impact over one year of using a biodiesel blend for the entire STM bus fleet. It was calculated by multiplying test results in g/bhp-h by the total number of brake horsepower-hours used by the STM over one year. The calculation gave 203 million bhp-h by assuming that the STM fleet’s overall energy efficiency equalled that of an engine with mechanical fuel injection running on reference petrodiesel (0.2314 l/bhp-h) and based on an annual fuel consumption of 47.2 million litres. The simplifying assumption is thus that two-stroke diesel engines are offset by higher efficiency engines with electronic fuel injection.

tons/year Quebec; tons/year Canada
These two values are obtained using annual fuel consumption data for 2002 published by the Canadian Urban Transit Association (CUTA). It is assumed that the four-stroke Cummins engine with mechanical fuel injection is representative of bus fleets in Quebec and Canada.

g/km
This value is based on a typical consumption by a city bus of 65 l/100 km.

N.B.
All emission measurements were made at the output of the vehicle’s exhaust system after the exhaust passed through the catalytic converter, the same converter being used for both engine types on the test facility.
**Impact of engine type**
- Electronic fuel injection alone reduced CO emissions by around 40% before any use of biodiesel.
- The impact of using B20 on CO emissions, depending on the source of the blend, resulted in:
  - a 17% to 25% reduction for the engine with mechanical fuel injection
  - a 25% to 31% reduction for the engine with electronic fuel injection
- Whether expressed in grams per litre of blend or tons per year, the impact of B20 is of the same order of magnitude for both engine types.

**Impact of concentration of biodiesel in the blend**
- Though B20 contains 4 times more biodiesel than B5, it only resulted in emission reductions 2 to 3 times greater than those using B5.
- Thus it cannot be concluded that the impact on CO emissions is proportional to the concentration of biodiesel in the blend.

**Impact of source of biodiesel**
- Testing revealed that the source of biodiesel had a minor effect on CO emissions. The impact of animal-fat-based biodiesel was significantly lower than that of vegetable-oil-based biodiesel.

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### Raw Test Compared with STM Reference Petrodiesel Compared with Vegetable-Oil-Based Biodiesel

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<td>B20 – Vegetable Oil</td>
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<td>-0.1330</td>
<td>-31.4%</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>0.4420</td>
<td>-0.1730</td>
<td>-31.1%</td>
</tr>
</tbody>
</table>

### Combined Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Combined Results</th>
<th>Compared with STM Reference Petrodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/(bhp-h)</td>
<td>g/(bhp-h)</td>
</tr>
<tr>
<td>STM Quebec Canada</td>
<td>47.2</td>
<td>90.0</td>
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<tr>
<td>Annual Fuel Consumption</td>
<td>million/year</td>
<td>47.2</td>
</tr>
<tr>
<td>Estimated Annual Mechanical Energy</td>
<td>million (bhp-h)/year</td>
<td>203.9</td>
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</tbody>
</table>

---

### Impact of engine type

- Electronic fuel injection alone reduced CO emissions by around 40% before any use of biodiesel.
- The impact of using B20 on CO emissions, depending on the source of the blend, resulted in:
  - a 17% to 25% reduction for the engine with mechanical fuel injection
  - a 25% to 31% reduction for the engine with electronic fuel injection
- Whether expressed in grams per litre of blend or tons per year, the impact of B20 is of the same order of magnitude for both engine types.

---

**Impact of concentration of biodiesel in the blend**
- Though B20 contains 4 times more biodiesel than B5, it only resulted in emission reductions 2 to 3 times greater than those using B5.
- Thus it cannot be concluded that the impact on CO emissions is proportional to the concentration of biodiesel in the blend.

**Impact of source of biodiesel**
- Testing revealed that the source of biodiesel had a minor effect on CO emissions. The impact of animal-fat-based biodiesel was significantly lower than that of vegetable-oil-based biodiesel.
Other findings

- Even without biodiesel, CO emissions produced by both diesel engines studied were very low. Tests with reference fuel gave figures 15 to 20 times lower than the limit of 15.5 g/(bhp-h) set by 1998 Canadian standards.
- In short, B20 reduced CO emissions by 17% to 32%, depending on the source of biodiesel and engine type.

- For CO emissions from the engine with electronic fuel injection, there was no benefit in using #1 petrodiesel rather than STM reference petrodiesel (#2).
- By switching to B20, the STM could reduce its current 200 tons of annual CO emissions by roughly 40 tons. Once all vehicles in its fleet are equipped with electronic fuel injection, the impact of B20 would remain of similar magnitude.
### Impact of engine type
- Electronic fuel injection alone reduced THC emissions by around 15% (0.30 g/l) before any use of biodiesel.
- The impact of using B20 on THC emissions, depending on the source of the blend, resulted in:
  - a reduction of around 10% (0.10 g/l of blend) for the engine with mechanical fuel injection
  - a reduction of 22% to 31% (0.17 g/l to 0.23 g/l) for the engine with electronic fuel injection
- For B20, the engine with electronic fuel injection yielded twice the reduction in THC emissions as did the engine with mechanical fuel injection.

### Impact of concentration of biodiesel in the blend
- It cannot be concluded from the tests that the impact on THC emissions is proportional to the concentration of biodiesel in the blend.

### Impact of source of biodiesel
- The source of biodiesel had no significant effect on THC emissions.
Other findings

- Even without biodiesel, total hydrocarbon (THC) emissions by both diesel engines studied were very low, tests with reference fuel giving figures 6 to 7 times lower than the limit set by 1998 Canadian standards.

- In short, B20 reduced THC emissions by 10% to 30%, depending on source of biodiesel and engine type.

- For THC emissions from the engine with electronic fuel injection, there was no benefit in using #1 petrodiesel rather than STM reference petrodiesel (#2).

- By switching to B20, the STM could reduce its current 40 tons of annual THC emissions by between 2 and 3 tons. Once all vehicles in its fleet are equipped with electronic fuel injection, there would be an additional 7-ton to 10-ton annual reduction.

Percent reduction in total hydrocarbon (THC) emissions vs. STM reference petrodiesel

(grams per litre of total fuel consumed)
Impact of engine type
- Electronic fuel injection alone reduced NOx emissions by around 35% (10.8 g/l) before any use of biodiesel.
- Only with electronic fuel injection did the use of biodiesel have a significant impact on NOx emissions.
- For biodiesels not based on pure vegetable oil, for instance, the effect was to lower emissions by up to 1 g/l of blend (3% to 5%). With mechanical fuel injection, biodiesel had no significant effect on NOx emissions.

Impact of concentration of biodiesel in the blend
- No conclusion can be drawn from the tests regarding the effect of B20 on NOx emissions.

Impact of source of biodiesel
- Data from various tests seems to point to the presence of animal-fat-based esters as a factor contributing to reduced NOx emissions.
Other findings

- Diesel engine NOx emissions are closely monitored to check how well they stand up to pollution standards.
- Using #1 petrodiesel with electronic fuel injection lowered NOx emissions by 6% compared to STM reference petrodiesel (#2).
- By switching to a B20 blend not based on vegetable oil, the STM could reduce its current 1,500 tons of annual NOx emissions by up to 40 tons once all vehicles in its fleet are equipped with electronic fuel injection systems.

- The correlation between lower NOx and animal fat is probably related to the fact that animal-fat-based biodiesel has a higher cetane number. This would corroborate a recent report by the U.S. Environmental Protection Agency [Draft Technical Report EPA 420-P-02-001, October 2002].
Impact of engine type

- Electronic fuel injection alone reduced total particulate matter emissions by around 60%, lowering the total mass of particulate matter from 0.42 g/l to 0.18 g/l before any use of biodiesel.
- The impact of using B20 on total particulate matter emissions, depending on the source of the blend, resulted in:
  - a reduction of 19% to 31% (0.08 g/l to 0.13 g/l of blend) for the engine with mechanical fuel injection
  - a reduction of 8% to 17% (0.01 g/l to 0.05 g/l) for the engine with electronic fuel injection
- Biodiesel had a much greater impact on total particulate matter emissions for engines with mechanical fuel injection, whose particulate matter emissions when not running on a biodiesel blend were 2.5 times higher than for engines with electronic fuel injection.

Impact of concentration of biodiesel in the blend

- No conclusion can be drawn from the tests regarding the effect of B5 on total particulate matter emissions from engines with electronic fuel injection.

Impact de l’origine du biodiesel

- Vegetable-oil-based B20 resulted in the greatest reduction in total particulate matter emissions: 17% (0.03 g/l) with electronic fuel injection and 31% (0.13 g/l) with mechanical fuel injection.

### Data

<table>
<thead>
<tr>
<th>Test</th>
<th>Raw Test Data</th>
<th>Compared with STM Reference Petrodiesel</th>
<th>Compared with Vegetable-Oil-Based Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/(bhp-h)</td>
<td>g/(bhp-h)</td>
<td>%</td>
</tr>
<tr>
<td>1998 Canadian Standard</td>
<td>0.10009</td>
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</tr>
<tr>
<td>STM Reference Petrodiesel</td>
<td>0.09679</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1 Petrodiesel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>0.08884</td>
<td>-0.00994</td>
<td>-10.3%</td>
</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>0.07527</td>
<td>-0.02152</td>
<td>-22.2%</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>0.07786</td>
<td>-0.01993</td>
<td>-19.6%</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>0.06700</td>
<td>-0.02979</td>
<td>-30.8%</td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td>0.05016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>0.03900</td>
<td>-0.00116</td>
<td>-2.9%</td>
</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>0.03956</td>
<td>-0.00059</td>
<td>-1.5%</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>0.03900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td>0.03349</td>
<td>-0.00607</td>
<td>-16.6%</td>
</tr>
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</table>

### Consumption Combined Compared with STM Reference Petrodiesel

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<thead>
<tr>
<th>Test</th>
<th>g/l</th>
<th>g/l</th>
<th>%</th>
<th>Quebec</th>
<th>Canada</th>
<th>g/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM Reference Petrodiesel</td>
<td>0.2314</td>
<td>0.483</td>
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<td>47.2</td>
<td>90.0</td>
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</tr>
<tr>
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<td>153.9</td>
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<tr>
<td>B5 – Animal Fat</td>
<td>0.2312</td>
<td>0.375</td>
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<td>-10.2%</td>
<td>-2.004</td>
<td>-15.691</td>
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<tr>
<td>B5 – Vegetable Oil</td>
<td>0.2310</td>
<td>0.329</td>
<td>-0.0934</td>
<td>-22.1%</td>
<td>-4.344</td>
<td>-34.016</td>
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<tr>
<td>B20 – Animal Fat</td>
<td>0.2298</td>
<td>0.291</td>
<td>-0.1267</td>
<td>-30.3%</td>
<td>-5.956</td>
<td>-46.835</td>
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<tr>
<td>B20 – Vegetable Oil</td>
<td>0.2297</td>
<td>0.150</td>
<td>-0.0252</td>
<td>-14.3%</td>
<td>-2.264</td>
<td>-25.838</td>
</tr>
</tbody>
</table>

### Impact of engine type

- Electronic fuel injection alone reduced total particulate matter emissions by around 60%, lowering the total mass of particulate matter from 0.42 g/l to 0.18 g/l before any use of biodiesel.
- The impact of using B20 on total particulate matter emissions, depending on the source of the blend, resulted in:
  - a reduction of 19% to 31% (0.08 g/l to 0.13 g/l of blend) for the engine with mechanical fuel injection
  - a reduction of 8% to 17% (0.01 g/l to 0.05 g/l) for the engine with electronic fuel injection
- Biodiesel had a much greater impact on total particulate matter emissions for engines with mechanical fuel injection, whose particulate matter emissions when not running on a biodiesel blend were 2.5 times higher than for engines with electronic fuel injection.

### Impact of concentration of biodiesel in the blend

- No conclusion can be drawn from the tests regarding the effect of B5 on total particulate matter emissions from engines with electronic fuel injection.

### Impact de l’origine du biodiesel

- Vegetable-oil-based B20 resulted in the greatest reduction in total particulate matter emissions: 17% (0.03 g/l) with electronic fuel injection and 31% (0.13 g/l) with mechanical fuel injection.
Other findings

- Total mass of particulate matter (PM) is closely monitored for diesel engine emissions to check how well they stand up to pollution standards.
- For particulate emissions from the engine with electronic fuel injection, there was no benefit in using #1 petrodiesel rather than STM reference petrodiesel (#2).
- By switching to B20, the STM could reduce its current 20 tons of annual particulate emissions by nearly 5 tons. Once all vehicles in its fleet are equipped with electronic fuel injection, the STM could limit its emissions to about 1 ton of particulate matter per year.
Impact of engine type

- Electronic fuel injection alone reduced the mass of fine (<2.5 µm) particulate matter emissions by around 60%, lowering the total mass of such emissions from 0.37 g/l to 0.15 g/l before any use of biodiesel.
- With electronic fuel injection, using biodiesel had no significant effect on fine particulate emissions, except for using cooking-oil-based B20, which lead to a 15% reduction (0.02 g/l of blend).
- There was a significant impact for engines with mechanical fuel injection. With B20, fine particulate emissions were reduced by about 23% (0.08 g/l of blend).

Biodiesel had a greater impact on total fine particulate emissions for engines with mechanical fuel injection, whose particulate matter emissions when not running on a biodiesel blend were 2.5 times higher than for engines with electronic fuel injection.

Impact of concentration of biodiesel in the blend

- Except in the case of cooking-oil-based blends, a higher concentration of biodiesel in the blend lead to an increase in the ratio of the mass of fine (<2.5 µm) particulates to the mass of total particulates. This means that biodiesel first helped reduce the mass of larger particulates. Biodiesel did not increase, however, the mass of fine particulates. Any statistically significant data pointed to a reduction in fine particulates as well.
The tests showed no significant effect for B5 on particulate emissions from the engine with electronic fuel injection.

Since only a single point was measured for B5 using the engine with mechanical fuel injection, no conclusion can be drawn regarding the effect of blend concentration on fine particulate emissions.

Impact of source of biodiesel

- Unlike vegetable- and cooking-oil-based biodiesel blends for which reduced emissions were recorded, animal-fat-based biodiesel had no significant effect on fine particulate emissions from the engine with electronic fuel injection. It was not possible from the tests performed to say whether this pattern holds true with mechanical fuel injection.

Other findings

- By switching to B20, the STM could reduce its current 17 tons of annual fine particulate emissions by over 3 tons. Once all vehicles in its fleet are equipped with electronic fuel injection, the reduction due to biodiesel would drop to only 1 ton of fine particulates per year.
- Fine particulates below 2.5 µm are closely monitored since they are more likely to reach the respiratory tract than larger particulates.
Analysis of Particulates below 2.5 µm (PM$_{2.5}$)

### Organic Carbon Emissions

<table>
<thead>
<tr>
<th></th>
<th>mg/(bhp-h)</th>
<th>mg/(bhp-h)</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electronic Fuel Injection System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>STM Reference Petrodiesel</td>
<td>7.656</td>
<td>25.488</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>#1 Petrodiesel</td>
<td>7.656</td>
<td>25.488</td>
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<tr>
<td>B5 – Animal Fat</td>
<td>6.505</td>
<td>6.505</td>
<td>-0.7%</td>
<td>6.4%</td>
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</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>8.518</td>
<td>8.518</td>
<td>17.3%</td>
<td>76%</td>
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<tr>
<td>B5 – Vegetable Oil</td>
<td>8.269</td>
<td>8.269</td>
<td>8.9%</td>
<td>41.7%</td>
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</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>7.751</td>
<td>7.751</td>
<td>1.2%</td>
<td>12.8%</td>
<td>no</td>
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<tr>
<td>B20 – Used Cooking Oil</td>
<td>8.586</td>
<td>8.586</td>
<td>12.1%</td>
<td>74.1%</td>
<td>no</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>8.103</td>
<td>8.103</td>
<td>5.8%</td>
<td>48.8%</td>
<td>no</td>
</tr>
</tbody>
</table>

### Elemental Carbon Emissions

<table>
<thead>
<tr>
<th></th>
<th>mg/(bhp-h)</th>
<th>mg/(bhp-h)</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electronic Fuel Injection System</strong></td>
<td></td>
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<tr>
<td>STM Reference Petrodiesel</td>
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<td>25.488</td>
<td></td>
<td></td>
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</tr>
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<td>#1 Petrodiesel</td>
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<td>25.488</td>
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</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>24.343</td>
<td>24.343</td>
<td>-4.5%</td>
<td>93.8%</td>
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<tr>
<td>B5 – Used Cooking Oil</td>
<td>26.679</td>
<td>26.679</td>
<td>4.7%</td>
<td>81.6%</td>
<td>no</td>
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<tr>
<td>B5 – Vegetable Oil</td>
<td>21.140</td>
<td>21.140</td>
<td>17.1%</td>
<td>98.9%</td>
<td>yes</td>
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<tr>
<td>B20 – Animal Fat</td>
<td>19.641</td>
<td>19.641</td>
<td>-17.1%</td>
<td>99.9%</td>
<td>yes</td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td>20.634</td>
<td>20.634</td>
<td>-19.0%</td>
<td>99.7%</td>
<td>yes</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>21.256</td>
<td>21.256</td>
<td>-16.6%</td>
<td>81.4%</td>
<td>no</td>
</tr>
</tbody>
</table>

### SOF Emissions (soluble organic fraction of particulate emissions)

<table>
<thead>
<tr>
<th></th>
<th>mg/(bhp-h)</th>
<th>mg/(bhp-h)</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Fuel Injection System</strong></td>
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<td></td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
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<td></td>
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</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The fact that biodiesel first reduced the mass of larger particulates warrants discussion of the results of particle counts based on size.
- The analysis of particle size distribution gives the results below.
  - The engine with mechanical fuel injection mainly produced particles around 0.102 µm for the reference fuel and for cooking-oil-based B5; whereas, with cooking- and vegetable-oil-based B20, particles ranged primarily from 0.059 µm to 0.029 µm. Furthermore, for the engine with mechanical fuel injection, the number of particles no larger than 1.5 µm increased 80%, rising from 2.5 to 4.0 standard measurement units.
  - For the engine with electronic fuel injection, particle size distribution remained the same for all fuels, most being close to 0.059 µm. There was no noticeable increase in the number of particles 1.5 µm or below, which remained at 1.4 standard measurement units. Studies were also conducted on the characteristics of particles emitted, including their soluble organic fraction (SOF), and their breakdown into pure carbon (elementary carbon) and organic molecules (organic carbon). It is the soluble or organic fraction of the particles that are most likely to interact with the body and that are thus the most carcinogenic.
  - An analysis of SOF in particulate emissions from the engine with mechanical fuel injection showed that adding biodiesel increases SOF.
  - For mechanical fuel injection testing, it was decided to analyze the breakdown of particulate matter into elemental and organic carbon. The tables above summarize data for elemental vs. organic carbon in particulates from the engine with electronic fuel injection. The Anova analysis of the data clearly shows that the apparent increase in mass of the more dangerous organic carbon is not significant. The reduction in mass of elemental carbon, however, is significant with values of up to 20% for B20.
  - In conclusion, biodiesel’s contribution to reducing the total mass of particulate matter stems from reduced elemental carbon (apparent as sooty exhaust fumes). This finding agrees with the fact that biodiesel, low in sulphur, reduces total sulphur in the blend and that sulphur is a determining factor in the formation of elemental carbon particles.
  - It cannot be concluded that there is a reduction in soluble organic fraction or particulates below 1.5 µm, both thought to be more serious health risks. It can be stated, however, that there was no significant increase in such particulate emissions from the engine with electronic fuel injection.
**Sulphate (SO\textsubscript{4}) Emissions**

<table>
<thead>
<tr>
<th>Test</th>
<th>Raw Test Data</th>
<th>Compared with STM Reference Petrodiesel</th>
<th>Compared with Vegetable-Oil-Based Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/(bhp-h)</td>
<td>% Anova</td>
<td>Significant Difference</td>
</tr>
<tr>
<td>1986 Canadian Standard</td>
<td>n/a</td>
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</tr>
<tr>
<td>STM Reference Petrodiesel</td>
<td>128.80</td>
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</tr>
<tr>
<td>#1 Petrodiesel</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>134.90</td>
<td>6.10</td>
<td>4.7%</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>112.90</td>
<td>-15.90</td>
<td>-12.3%</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>108.80</td>
<td>-20.00</td>
<td>-15.5%</td>
</tr>
<tr>
<td>Electronic Fuel Injection System</td>
<td>134.35</td>
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<td></td>
</tr>
<tr>
<td>STM Reference Petrodiesel</td>
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</tr>
<tr>
<td>#1 Petrodiesel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>122.31</td>
<td>-12.04</td>
<td>-9.0%</td>
</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>135.26</td>
<td>0.91</td>
<td>0.7%</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>131.57</td>
<td>-2.79</td>
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</tr>
<tr>
<td>B20 – Animal Fat</td>
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</tr>
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<td>B20 – Used Cooking Oil</td>
<td>114.51</td>
<td>-19.85</td>
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<tr>
<td>B20 – Vegetable Oil</td>
<td>111.29</td>
<td>-23.07</td>
<td>-17.2%</td>
</tr>
</tbody>
</table>

**Impact of engine type**

- Without biodiesel, the fuel injection system had little impact on SO\textsubscript{4} emissions from the reference fuel.
- Tests on the engine with mechanical fuel injection did not show that biodiesel had any significant effect on SO\textsubscript{4} emissions.
- Tests on the engine with electronic fuel injection did show that biodiesel had a significant effect on SO\textsubscript{4} emissions. The effect was as follows:
  - a 9% (0.05 g/l) reduction using B5 (animal-fat-based only)
  - a 15% reduction using B20, with no significant difference between sources

**Impact of concentration of biodiesel in the blend**

- Except for animal-fat-based biodiesel in the engine with electronic fuel injection, B5 had no significant impact on SO\textsubscript{4} emissions.
- Based only on the engine with electronic fuel injection running on animal-fat-based biodiesel, SO\textsubscript{4} emissions were not found to be proportional to concentration of biodiesel in the blend.

**Impact of source of biodiesel**

- Tests using B20 showed a minor difference in the effect that the source of biodiesel had on SO\textsubscript{4} emissions. Animal-fat-based biodiesel alone had a significant effect with a 5% blend.
Other findings

- Even without biodiesel, SO₄ emissions produced by both types of diesel engine studied were very low: 130 mg (0.013 g/bhp-h).
- In short, B20 reduced SO₄ emissions by 12% to 17%, depending on source of biodiesel and engine type.
- By switching to B20, the STM could reduce its current 25 tons of annual SO₄ emissions by about 4 tons and even more once all vehicles in its fleet are equipped with electronic fuel injection systems.
Polycyclic Aromatic Hydrocarbon (PAH) Emissions

Impact of engine type
- Electronic fuel injection alone reduced PAH emissions by around 20% (0.02 g/l) before any use of biodiesel.
- Only with electronic fuel injection using B20 was it possible to establish that using biodiesel had any effect.

Impact of concentration of biodiesel in the blend
- No conclusion can be drawn from the tests regarding the effect of B5 on PAH emissions.
- A 20% blend of biodiesel from the three sources lead to substantially lower PAH emissions using electronic fuel injection.

Impact of source of biodiesel
- No conclusion can be drawn regarding the effect of cooking-oil-based biodiesel on PAH emissions since data for both engine types and blends gave conflicting results.
- The data for B20 from the three sources in the engine with electronic fuel injection suggests that PAH emission reductions are higher in the presence of animal fat. The data for B5 did not support this possible tendency.

Impact of concentration of biodiesel in the blend
- No conclusion can be drawn from the tests regarding the effect of B5 on PAH emissions.
- A 20% blend of biodiesel from the three sources lead to substantially lower PAH emissions using electronic fuel injection.

Impact of engine type
- Electronic fuel injection alone reduced PAH emissions by around 20% (0.02 g/l) before any use of biodiesel.
- Only with electronic fuel injection using B20 was it possible to establish that using biodiesel had any effect.

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Impact of concentration of biodiesel in the blend
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- A 20% blend of biodiesel from the three sources lead to substantially lower PAH emissions using electronic fuel injection.
Other findings

- At 0.1 mg per bhp-h, PAH emissions are very low, total annual STM emissions only amounting to about 20 kg.
Polycyclic aromatic hydrocarbons (PAHs) include highly carcinogenic substances. Before drawing conclusions, it is important to analyze and compare PAH emissions with other test data for such compounds as volatile organic compounds (VOCs), carbonyl compounds, and particularly BETX (benzene, ethyl benzene, toluene, xylenes and 1,3-butadiene). Among carbonyl compounds, certain aldehydes and other substances that are particularly carcinogenic, e.g., acrolein, are monitored by urban transportation officials.

With electronic fuel injection, B20 substantially reduced all major PAHs. Given the uncertainty associated with this kind of measurement and the low PAH levels measured, it can be stated that:

- Using biodiesel does not significantly increase any PAH and does not upset the proportions of these complex, carcinogenic organic compounds in emissions from the diesel engines studied.

The main carbonyls—whose combined emissions are shown in the chart above left—consist of six compounds as volatile organic compounds (VOCs), carbonyl compounds, and particularly BETX (benzene, ethyl benzene, toluene, xylenes and 1,3-butadiene). Among carbonyl compounds, certain aldehydes and other substances that are particularly carcinogenic, e.g., acrolein, are monitored by urban transportation officials.

For the engine with electronic fuel injection, the other chart upper right shows BETX emissions, to which public health officials are paying increasing attention.
Impact of engine type

- No conclusions can be drawn regarding the effect of engine type on direct (tailpipe) CO₂ emissions.

Impact of concentration of biodiesel in the blend

- No conclusions can be drawn regarding the effect of concentration of biodiesel in the blend on direct (tailpipe) CO₂ emissions.

Impact of source of biodiesel

- Only cooking-oil-based B20 with mechanical fuel injection lead to slightly (2%) but significantly lower direct (tailpipe) CO₂ emissions.

Other findings

- The standard emission level for both engine types is 2.59 kg of CO₂ per litre for STM reference petrodiesel.
- Biodiesel can be considered to have a negligible effect on direct (tailpipe) CO₂ emissions.
- Variations in direct CO₂ emissions are minimal. This is a favourable factor for biodiesel since the engine’s fuel combustion energy balance is based on these emissions. This shows that variations in fuel consumed per unit work were also negligible and that engine energy efficiency was undiminished by introducing biodiesel.

### Raw Test Compared with STM Reference Petrodiesel

<table>
<thead>
<tr>
<th>Test</th>
<th>Raw Test Data</th>
<th>Compared with STM Reference Petrodiesel</th>
<th>Compared with Vegetable-Oil-Based Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/(bhp-h)</td>
<td>% Anova Significant Difference tons/year</td>
<td>g/(bhp-h) % Anova Significant Difference</td>
</tr>
<tr>
<td>1998 Canadian Standard</td>
<td>n/a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### STM Reference Petrodiesel

<table>
<thead>
<tr>
<th>Test</th>
<th>g/(bhp-h)</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
<th>tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Petrodiesel</td>
<td>590.530</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>600.694</td>
<td>1.164</td>
<td>0.2%</td>
<td>46.5%</td>
<td>no</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>593.915</td>
<td>-5.715</td>
<td>-1.0%</td>
<td>76.9%</td>
<td>no</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>588.157</td>
<td>-11.373</td>
<td>-1.3%</td>
<td>97.5%</td>
<td>yes</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>594.313</td>
<td>-5.217</td>
<td>-0.9%</td>
<td>85.3%</td>
<td>no</td>
</tr>
</tbody>
</table>

### Electronic Fuel Injection System

<table>
<thead>
<tr>
<th>Test</th>
<th>g/(bhp-h)</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
<th>tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Petrodiesel</td>
<td>592.614</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>589.928</td>
<td>-2.687</td>
<td>-0.5%</td>
<td>no</td>
<td>-557.3</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>590.070</td>
<td>-2.544</td>
<td>-0.4%</td>
<td>75.3%</td>
<td>no</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>597.110</td>
<td>4.496</td>
<td>0.8%</td>
<td>97.9%</td>
<td>yes</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>598.990</td>
<td>6.338</td>
<td>1.1%</td>
<td>43.4%</td>
<td>no</td>
</tr>
</tbody>
</table>

### STM Quebec Canada

| Annual Fuel Consumption | million l/year | 47.2 | 90.0 | 368.0 |
| Total Annual CO₂ Emissions | million | 122,290 | 233,180 | 953,450 |

### Estimated Annual Mechanical Energy

| million (bhp-h)/year | 203.9 |

### Combined Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Combined Results</th>
<th>g/l</th>
<th>g/l</th>
<th>%</th>
<th>Anova</th>
<th>Significant Difference</th>
<th>tons/year</th>
<th>tons/year</th>
<th>tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM Reference Petrodiesel</td>
<td>0.2314</td>
<td>2,590.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1 Petrodiesel</td>
<td>0.2312</td>
<td>2,598.2</td>
<td>7.275</td>
<td>0.3%</td>
<td>349.2</td>
<td>654.8</td>
<td>2,677.4</td>
<td>4.729</td>
<td></td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>0.2310</td>
<td>2,570.8</td>
<td>-20.253</td>
<td>-0.8%</td>
<td>-972.1</td>
<td>-1,822.8</td>
<td>-7,453.1</td>
<td>-13.164</td>
<td></td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>0.2291</td>
<td>2,567.3</td>
<td>-23.630</td>
<td>-0.9%</td>
<td>-1,134.3</td>
<td>-2,126.7</td>
<td>-8,696.0</td>
<td>-15.360</td>
<td></td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>0.2298</td>
<td>2,586.2</td>
<td>-4.662</td>
<td>-0.2%</td>
<td>-223.8</td>
<td>-419.6</td>
<td>-1,715.7</td>
<td>-3.030</td>
<td></td>
</tr>
</tbody>
</table>

### Other findings

- The standard emission level for both engine types is 2.59 kg of CO₂ per litre for STM reference petrodiesel.
- Biodiesel can be considered to have a negligible effect on direct (tailpipe) CO₂ emissions.
- Variations in direct CO₂ emissions are minimal. This is a favourable factor for biodiesel since the engine’s fuel combustion energy balance is based on these emissions. This shows that variations in fuel consumed per unit work were also negligible and that engine energy efficiency was undiminished by introducing biodiesel.
Note on biodiesel and greenhouse gas (GHG) reduction

- Using biodiesel reduces GHG emissions. The data does not contradict this statement since it only applies to direct tailpipe emissions. When the engine burns 1 litre of biodiesel, whose physicochemical properties are very similar to those of petrodiesel, it makes no distinction between the source of the two fuels. Reduction in GHG emissions arises from the fact that biodiesel comes from animal or plant biomass with a life cycle of a few years; whereas, petrodiesel is a fossil fuel that releases into the atmosphere carbon that has been tied up for hundreds of millions of years. Biodiesel, unlike petrodiesel, is thus considered a renewable fuel.

- The reduction in GHG emissions arising from the use of biodiesel as a replacement for petrodiesel depends on a comparison of the life cycle of both fuels, a subject beyond the scope of this project. We would nevertheless suggest the following working hypothesis:
  - Every litre of pure biodiesel (B100) used to replace a litre of petrodiesel reduces GHGs by 2.33 kg of CO₂.
  - This figure is based on the hypothesis that biodiesel avoids 90% of the emissions from reference petrodiesel because it contains 10% methanol used for esterification and obtained from natural gas (non-renewable fossil energy). Although this hypothesis simplifies matters and would need to be confirmed by thorough life-cycle studies, it does set an order of magnitude.
Comparative Emission Measurements for Different Biodiesel Blends

Methodology

So emission data could be compared from test to test, and particularly with data for reference petrodiesel, the decision was made to use the dynamometer bench at Environment Canada’s Environmental Technology Centre (ETC) in Ottawa. Besides ensuring reproducibility, this decision is in line with urban bus emission regulations under which an emissions certificate is required only for engines equipping such buses.

Test procedure

The ETC dynamometer bench is certified and recognized in North America for the testing of heavy-duty engines. The load is controlled electronically and simulated by a 500-HP (375-kW) electric generator that develops engine torque and speed to reproduce the same load cycle from test to test. The cycle used is that prescribed by the U.S. Environmental Protection Agency (EPA) for heavy-duty diesel engines. [U.S. EPA Heavy Duty Engine Transient Test, Code of U.S. Federal Regulations (CFR) 40, Part 86 – Protection of Environment, Section 86.1332-90].

Summary of EPA transient cycle test for heavy-duty diesel engines

<table>
<thead>
<tr>
<th>Test Duration (s)</th>
<th>1,199</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Speed (% of rated speed)</td>
<td>111.9</td>
</tr>
<tr>
<td>Maximum Torque (% of rated torque)</td>
<td>100.0</td>
</tr>
<tr>
<td>Mean Speed (% of rated speed)</td>
<td>47.5</td>
</tr>
<tr>
<td>Mean Torque (% of rated torque)</td>
<td>28.3</td>
</tr>
</tbody>
</table>

Tests were conducted using the following two engines: 1998 and 2000 four-stroke, 250-HP, 2200-rpm Cummins diesel engines equipped with either a mechanical fuel injection pump or a computer-controlled electronic fuel injection system. These six-cylinder in-line engines have a total displacement of 8.3L, with a turbocharger and charge air cooler at the intake. So data would be representative of actual STM operating conditions, emission measurements for both engines were taken at the output of the same (broken-in) catalytic converter, the one equipping the STM’s Novabus low-floor buses.

Exhaust gas sampling and testing methods

The test facility was designed not only to certify engines under the regulatory requirements of several countries, but also to carry out engine and fuel research projects. Exhaust gases were sampled after dilution in order to assess the mass of a large number of emission components during the test. Emissions were measured either directly by instant-reading analyzers (infrared sensors, chemiluminescence or flame ionization), whose results were averaged over the test, or indirectly using filters or indicators, which were subsequently analyzed in the lab to obtain a cumulative value for the test. Gas samples were also bagged and later analyzed by chromatography. A detailed description of the facilities can be found on the ETC web site at: http://www.etc-cte.ec.gc.ca.

The test methods follow the recommendations below:

<table>
<thead>
<tr>
<th>Emissions Measured</th>
<th>Data Kept?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonyl Compounds</td>
<td>Yes</td>
</tr>
<tr>
<td>Light Hydrocarbons and Methane</td>
<td>Yes</td>
</tr>
<tr>
<td>Volatile and Semi-Volatile Hydrocarbons</td>
<td>Yes</td>
</tr>
<tr>
<td>Soluble Organic Fraction (SOF)</td>
<td>Yes</td>
</tr>
<tr>
<td>Polycyclic Aromatic Hydrocarbons (PAHs)</td>
<td>Yes</td>
</tr>
<tr>
<td>Sulphates</td>
<td>Yes</td>
</tr>
<tr>
<td>Elemental and Organic Carbon</td>
<td>Yes</td>
</tr>
</tbody>
</table>


Test operations

Each fuel was tested as follows:
1. Before testing any given type of fuel, the fuel feed was emptied and fuel filter changed.
2. The new fuel was then supplied to the engine fuel feed system.
3. The engine was started and warmed up following standard procedures.
4. Once the engine reached a stable temperature, the torque curve was measured.
5. Tests were then conducted in the following order:
   a. FTP heavy-duty transient cold start (engine not running for at least 12 hours)
   b. 20-minute halt of engine
   c. FTP heavy-duty transient hot start, followed by another 20-minute halt
   d. three or five more FTP hot Starts at 20-minute intervals, depending on the test

The process was repeated for each fuel. Each test was repeated from three to five times to determine test repeatability and to run an Anova analysis of the variance between the test results for pairs of fuels. Some tests were rerun due to abnormal deviations. The reference fuel was tested first, between test runs for each biodiesel blend, and last. Each time, at least two tests were rerun to check for instrument drift or gradual changes in engine behaviour.

The table below gives the order of testing using the engine with mechanical fuel injection. Data from the first three tests was ignored. Apparently the break-in period for the factory-remanufactured engine used was too short despite running the engine for 35 hours on the dynamometric bench prior to beginning the tests.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emissions Measured</th>
<th>Data Kept?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>All</td>
<td>No</td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>All</td>
<td>No</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>All</td>
<td>No</td>
</tr>
<tr>
<td>Reference</td>
<td>All</td>
<td>Yes</td>
</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>All</td>
<td>Yes</td>
</tr>
<tr>
<td>Reference</td>
<td>C0, CO2, NOx, PM, THC</td>
<td>Yes</td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td>All</td>
<td>Yes</td>
</tr>
<tr>
<td>Reference</td>
<td>C0, CO2, NOx, PM, THC</td>
<td>Yes</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>All</td>
<td>Yes</td>
</tr>
<tr>
<td>Reference</td>
<td>C0, CO2, NOx, PM, THC</td>
<td>Yes</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>C0, CO2, NOx, PM, THC</td>
<td>Yes</td>
</tr>
<tr>
<td>Reference</td>
<td>C0, CO2, NOx, PM, THC</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Characterization of Fuels Used in the BIOBUS Project

### Biofuels from Three Sources

<table>
<thead>
<tr>
<th>Test</th>
<th>Pure Petrodiesel</th>
<th>5% Biodiesel Blend (B5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vegetable Oil</td>
<td>Used Cooking Oil</td>
</tr>
<tr>
<td></td>
<td>Type A</td>
<td>Type B-LSC</td>
</tr>
<tr>
<td>#1</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

#### Tables

<table>
<thead>
<tr>
<th>Test</th>
<th>Pure Petrodiesel</th>
<th>5% Biodiesel Blend (B5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vegetable Oil</td>
<td>Used Cooking Oil</td>
</tr>
<tr>
<td></td>
<td>Type A</td>
<td>Type B-LSC</td>
</tr>
<tr>
<td>#1</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

1. Pure biodiesel (B100) based on vegetable oil, cooking oil and animal fat was taken from the Rothsay/Laurenco tanks in May 2002.
### Impact of Biodiesel on Diesel Engine Efficiency

Does using biodiesel affect engine performance and energy efficiency, given that pure biodiesel typically contains 8% less energy per unit mass than conventional petrodiesel? The question can be answered by performing the analyses below.

- **Fuel energy content**
  
  This table takes into account that biodiesel was used in 5% or 20% blends and also that it is denser (heavier) than petrodiesel. Energy content is measured per litre since fuel is sold by the litre.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Gross Energy Content</th>
<th>Energy Density</th>
<th>Energy Content Variation per Unit Mass</th>
<th>Energy Content Variation per Unit Volume</th>
<th>Gross Energy Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D 240 BTU/lb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STM Reference Petrodiesel</td>
<td>18.710</td>
<td>10.118</td>
<td></td>
<td></td>
<td>837.1</td>
</tr>
<tr>
<td>#1 Petrodiesel</td>
<td>18.554</td>
<td>9.900</td>
<td>-0.8%</td>
<td>-2.1%</td>
<td>826.0</td>
</tr>
<tr>
<td>B5 – Animal Fat</td>
<td>18.634</td>
<td>10.101</td>
<td>-0.4%</td>
<td>0.2%</td>
<td>839.1</td>
</tr>
<tr>
<td>B5 – Used Cooking Oil</td>
<td>18.632</td>
<td>10.102</td>
<td>-0.4%</td>
<td>-0.2%</td>
<td>839.3</td>
</tr>
<tr>
<td>B5 – Vegetable Oil</td>
<td>18.630</td>
<td>10.141</td>
<td>-0.4%</td>
<td>-0.2%</td>
<td>842.6</td>
</tr>
<tr>
<td>B20 – Animal Fat</td>
<td>18.406</td>
<td>9.948</td>
<td>-1.6%</td>
<td>-0.7%</td>
<td>845.0</td>
</tr>
<tr>
<td>B20 – Used Cooking Oil</td>
<td>18.398</td>
<td>10.005</td>
<td>-1.7%</td>
<td>-0.6%</td>
<td>846.0</td>
</tr>
<tr>
<td>B20 – Vegetable Oil</td>
<td>18.392</td>
<td>10.087</td>
<td>-1.7%</td>
<td>-0.3%</td>
<td>849.0</td>
</tr>
<tr>
<td>B100 – Animal Fat</td>
<td>17.192</td>
<td>9.742</td>
<td>-1.8%</td>
<td>-3.7%</td>
<td>877.0</td>
</tr>
<tr>
<td>B100 – Used Cooking Oil</td>
<td>17.149</td>
<td>9.771</td>
<td>-8.3%</td>
<td>-3.4%</td>
<td>882.0</td>
</tr>
<tr>
<td>B100 – Vegetable Oil</td>
<td>17.119</td>
<td>9.831</td>
<td>-8.5%</td>
<td>-2.8%</td>
<td>889.0</td>
</tr>
</tbody>
</table>

- **Consumption during testing**
  
  The thermodynamic efficiency of engines, a gauge of their energy efficiency, can be calculated from the fuel’s energy content per litre. A fuel’s specific fuel consumption is calculated from its stoichiometric rate of emissions, particularly that for CO₂.

- **Maximum power and torque of engines for each fuel (mechanical efficiency)**
  
  This data checks whether bus drivers will have the impression of driving the same vehicle regardless of a change in fuel (ability to accelerate, climb a hill, etc.).

### Fuel energy content

This table shows that the variation in energy content per litre of fuel is negligible for B5 and around 0.5% for B20.

### Engine fuel consumption and thermodynamic and mechanical efficiency vs. fuel type

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>(l/(bhp-h))</td>
<td>(l/(bhp-h))</td>
<td>(l/kWh)</td>
<td>HP</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Mechanical Fuel Injection System

| STM Reference Petrodiesel  | 0.2314 | 0.3144 | 10.118 | 31.4% | 249.94 | 691.0 |
| #1 Petrodiesel             |        |        |        |       |        |       |
| B5 – Animal Fat            | 0.2312 | -0.0002 | -0.1% | 0.3141 | 10.102 | 31.5% | 252.30 | 2.3650 | 0.9% | 694.8 | 3.8 | 0.6% |
| B5 – Vegetable Oil         | 0.2310 | -0.0004 | -0.2% | 0.3139 | 10.048 | 31.7% | 239.20 | -10.7350 | -4.3% | 665.9 | -25.1 | -3.6% |
| B20 – Animal Fat           | 0.2291 | -0.0023 | -1.0% | 0.3113 | 10.050 | 32.0% | 252.30 | 2.3650 | 0.9% | 705.5 | 14.4 | 2.1% |
| B20 – Used Cooking Oil     | 0.2298 | -0.0016 | -0.7% | 0.3122 | 10.048 | 31.9% | 249.34 | -0.5950 | -0.2% | 686.4 | -4.8 | -0.7% |
| B20 – Vegetable Oil        |        |        |        |       |        |       |                                        |                                       |                                       |                                       |

| Electronic Fuel Injection System

| STM Reference Petrodiesel  | 0.2285 | 0.3195 | 10.118 | 31.8% | 241.04 | 691.2 |
| #1 Petrodiesel             |        |        |        |       |        |       |
| B5 – Animal Fat            | 0.2279 | -0.0006 | -0.3% | 0.3097 | 10.100 | 32.0% | 243.73 | 2.6900 | 1.1% | 678.5 | -12.7 | -1.8% |
| B5 – Used Cooking Oil      | 0.2278 | -0.0006 | -0.3% | 0.3096 | 10.102 | 32.0% | 238.68 | -2.3500 | -1.0% | 680.0 | -3.2 | -0.5% |
| B5 – Vegetable Oil         | 0.2206 | 0.0021 | 0.9%  | 0.3133 | 10.141 | 31.5% | 236.01 | -5.0400 | -2.1% | 674.2 | -17.0 | -2.5% |
| B20 – Animal Fat           | 0.2320 | 0.0035 | 1.5%  | 0.3152 | 10.048 | 31.9% | 236.21 | 1.1700 | 0.7%  | 679.7 | -11.5 | -1.7% |
| B20 – Used Cooking Oil     | 0.2297 | 0.0012 | 0.5%  | 0.3137 | 10.050 | 31.9% | 236.21 | 1.1700 | 0.7%  | 679.7 | -11.5 | -1.7% |
| B20 – Vegetable Oil        | 0.2314 | 0.0029 | 1.3%  | 0.3144 | 10.048 | 31.7% | 238.56 | -2.4800 | -1.0% | 665.3 | -25.9 | -2.7% |
Thermodynamic efficiency of engines vs. fuel type

**Mechanical Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

**Electronic Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

Percent variation of specific fuel consumption vs. STM reference petrodiesel

**Mechanical Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

**Electronic Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

Maximum power at 2000 rpm vs. fuel type

**Mechanical Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

**Electronic Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

Percent variation of maximum engine power vs. STM reference petrodiesel

**Mechanical Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil

**Electronic Fuel Injection System**

- STM Reference Petrodiesel
- #1 Petrodiesel
- B5 – Animal Fat
- B5 – Used Cooking Oil
- B5 – Vegetable Oil
- B20 – Animal Fat
- B20 – Used Cooking Oil
- B20 – Vegetable Oil
Findings

- Using biodiesel has no overall impact on the thermodynamic efficiency of engines.
- Engines with mechanical fuel injection tend to consume less fuel when biodiesel is added.
- The slightly higher efficiency without biodiesel noted for electronic fuel injection over mechanical fuel injection does not seem to hold for B20. This could mean that certain electronic fuel injection parameters could be better tuned to B20 characteristics (e.g., a higher cetane number), and that the specific fuel consumption of the engine with electronic fuel injection would then achieve its initial level of efficiency.
- It can be concluded that the variations noted are negligible since 1% variations are not significant. The very fact that animal-fat-based B5 reduced and animal-fat-based B20 increased consumption shows that uncertainty in the measurements is around 0.5% and that variations are not significant. This is in line with the non-significant variations noted for direct CO₂ emissions.
Ce rapport est également publié en français.