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Clean Urban Transport for Europe: A Case Study

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Abstract

This report studies a project being conducted in Europe, called the Clean Urban Transport for Europe (CUTE), in which fuel cell buses are being used in several cities' bus fleet. Using CUTE as a backdrop, a life cycle analysis was done on the emissions of several different types of buses, including diesel, hybrid diesel, ultra low sulfur diesel, and hydrogen fuel cell buses. This data was used to determine what would be the environmental advantage of using fuel cell buses.

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Introduction

The world is coming to a crossroads in its energy needs. In the upcoming century, we will need to choose whether to continue using fossil fuels in combustion engines or switch to electrochemical engines. Our continued combustion of fossil fuels has begun to deplete the earth of its natural stores of oil while creating air pollution, contributing to global warming, and leading to several international conflicts over oil. The fuel cell is an alternate means of energy production that can create electricity from two naturally occurring gases: hydrogen and oxygen. This could potentially remove our dependence on fossil fuels while eliminating the harmful emissions created by the burning of fossil fuels.

This report will focus on the environmental improvements possible from the use of fuel cells both in the short and long terms. Specifically, it will analyze a European Union fuel cell project called the Clean Urban Transport for Europe (CUTE) that is happening in 10 different cities across Europe. Using CUTE as a backdrop, a life cycle analysis will be done on the emissions of fuel cells and diesel engines to see how well, if at all, the replacement of diesel city buses with hydrogen fuel cell (HFC) buses will help the participating cities reach their environmental goals.

Probably the biggest problem with using fossil fuels is that there is a finite reserve of such fuels. One study shows the oil supplies will run out by 2056, barring any major new oil finds and assuming fossil fuel use continues its current trends[1]. While different studies have differing figures, they all agree that the oil supply will run out. It is quite simply impossible to keep burning these fuels at the rate we are for an extended period of time.

The burning of fossil fuels produces several toxic chemicals. Such chemicals include nitrous oxides and sulfur oxides, which are responsible for smog and acid rain. Fossil fuel combustion also produces particulate matter, which is blamed for human respiratory diseases. Finally, burning fossil fuels is a major source of carbon dioxide. Carbon dioxide is the most abundant 'greenhouse gas'. These greenhouse gases gather in

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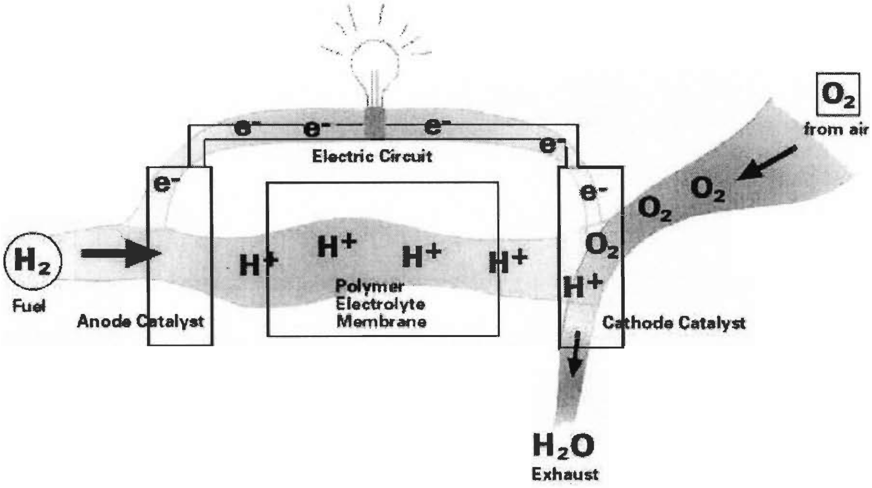
[1] http://www.ncpa.org/pub/bg/bg159/index.html#19 (April 29, 2003)

the upper atmosphere acting as an insulator and raising the temperature of the earth. As the earth's temperature rises, entire ecosystems will not be able to adapt and will be destroyed. If the temperature gets high enough, the Antarctic icecaps could melt raising the level of the oceans and submerging large areas of land.

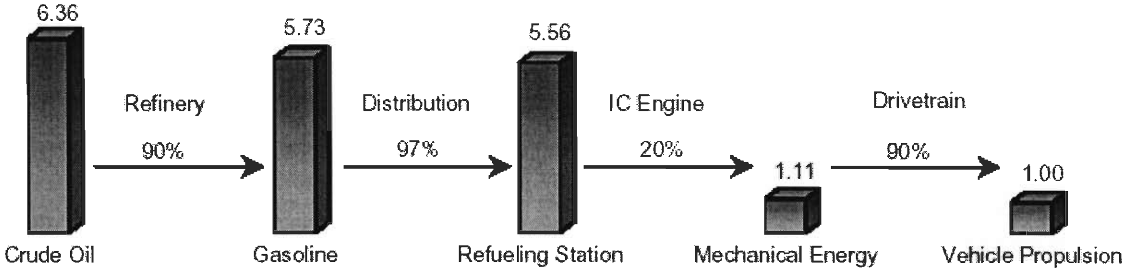
A fuel cell works by combining hydrogen and oxygen to create water and electrical energy. This picture, taken from Fuel Cell 2000's website, shows an overview of the process. The hydrogen enters the fuel cell at the anode. The hydrogen is split into a hydrogen ion and an electron. The ion flows through an electrolyte to the cathode. The electron goes through a wire before meeting back up with the ion at the cathode, thus creating an electrical current. At the Cathode, the ion and cathode combine with oxygen to produce water.



There are six different types of fuel cells: alkaline, molten carbonate, phosphoric acid, proton exchange membrane, solid oxide, and direct methanol. The main differences are the electrolyte and catalysts used. The result is changes in the efficiency, operating temperature, size, and cost of the fuel cell. The type pertinent to this report is the phosphoric acid fuel cell (PAFC) since that is the type used in the fuel cell buses. PAFCs use concentrated phosphoric acid as an electrolyte. They operate around 200 degrees Celsius and have an electrical efficiency of about 40%. The PAFCs are the first commercially available fuel cell. They can used as a small power plant (200 kw) while using their heat for hot water and space heating. They can also be used in buses, the application that is discussed in this report.

Fuel cells have the potential to free us from fossil fuels entirely. Using electricity from renewable power plants to create hydrogen, we could use HFC vehicles exclusively. That vision, however, is far off. In the meantime, HFCs offer the ability to extract energy from fossil fuels electrochemically instead of through combustion. The electrochemical approach can potentially be more efficient than current methods, while reducing emissions. An internal combustion engine (ICE) currently only converts about 20% of the energy in fossil fuel into locomotion[2]. The rest is wasted as heat and noise. PEM fuel cells can double that efficiency[3]. Similar arguments can be made for a coal power plant and SOFC fuel cells.

The main problem with fuel cells is the production and distribution of hydrogen. While an abundant element on earth, hydrogen does not naturally occur by itself – it is always bonded to other elements. The main ways of producing hydrogen is by reforming larger compounds or by electrolyzing water. The following charts[4] show the current transportation pathway along with two fuel cell pathways. They are all normalized to provide 1 mile/kW/h to the end user. Then, working backwards, it is possible to determine how much energy was required at the beginning of the life cycle to give the same amount of end use energy.



Current Transportation Pathway

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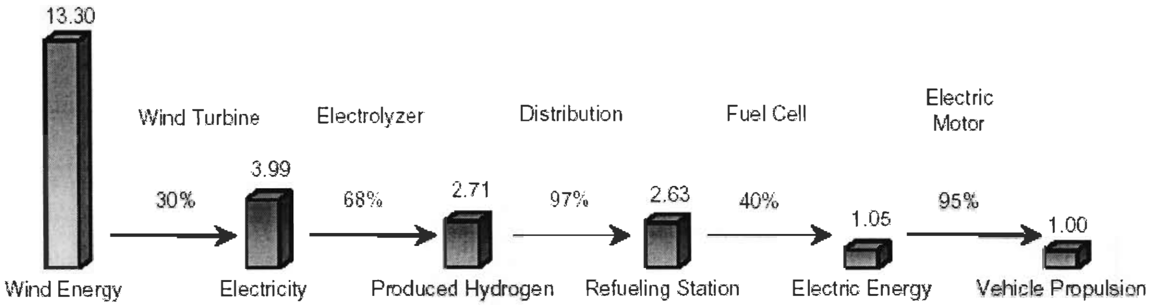
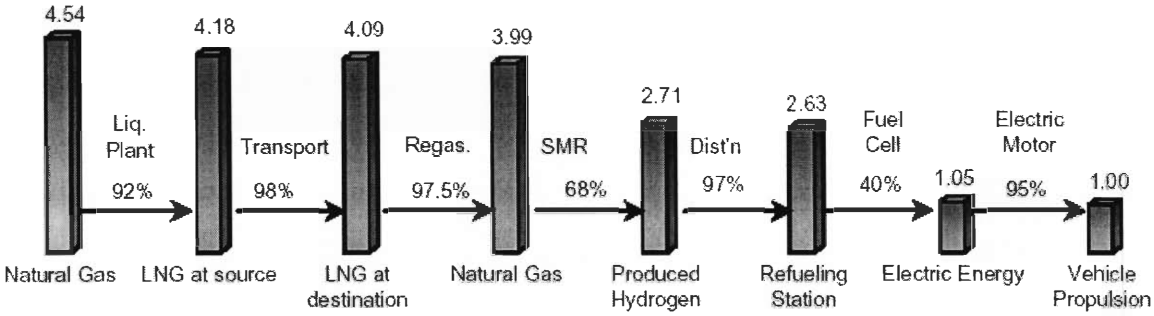
[2] "Nurturing a Clean Energy Future in Hawaii: Assessing the Feasibility of the Large Scale Utilization of Hydrogen and Fuel Cells in Hawaii" (June 2001) pg D-1

[3] "Nurturing a Clean Energy Future in Hawaii: Assessing the Feasibility of the Large Scale Utilization of Hydrogen and Fuel Cells in Hawaii" (June 2001) pg D-2

[4] "Nurturing a Clean Energy Future in Hawaii: Assessing the Feasibility of the Large Scale Utilization of Hydrogen and Fuel Cells in Hawaii" (June 2001) pg D1 – D5



Pathway Using Electricity from Wind Turbines



Pathway Using a Steam Methane Reformer

Electrolysis is the process of breaking water into its elementary compounds, hydrogen and oxygen. Electricity is the catalyst that drives the reaction. The electricity for electrolysis should, logically, come from a renewable source. Using electricity generated by burning fossil fuels defeats the purpose of using a fuel cell in many ways. Electrolysis is currently one of the most expensive options for creating hydrogen because of the cost of electricity. On the upside, the process can be completely emission free if the electricity comes from a renewable energy source.

Steam methane reforming (SMR) involves breaking the hydrogen off a methane molecule. In the process, the fuel and steam are combined at high temperature and the hydrogen is separated out through membranes. Steam reforming works well with light hydrocarbons, like methane, but doesn't work well with heavier hydrocarbons. SMR is one of the cheapest ways to produce hydrogen, and nearly half the world's hydrogen supply comes from SMR. One problem, however, is that large amounts of CO_2 are produced during the process and some methane is released as well[5]. These are both greenhouse gases. Partial oxidation (POX) is a technique of stripping the hydrogen off of heavier hydrocarbons, such as gasoline. Other techniques include biomass reforming, fermentative and photosynthetic biological production, and nuclear production. Only SMR and electrolysis are part of the CUTE project.

In the context of HFC vehicles, hydrogen can either be produced on site (at the refueling station) or at a central location. One advantage of on site production is that there is no need for the transportation of hydrogen. Hydrogen is lighter than air and highly flammable. In order to transport it, it is either compressed or cryogenically liquefied. Both processes consume energy and add a level of complication to the process of refueling a vehicle. One advantage of central production is that SMR facilities require a large capital investment. One plant with a high capacity can be cheaper than several smaller capacity plants. A single plant would also give more options as to what to do with the emissions from the hydrogen production process. It would be possible to sequester the CO_2 underground or secure it for use in other industrial processes.

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[5] "Life Cycle Assessment of Hydrogen Production via Methane Steam Reforming" (NREL 2001) pg. 10

Clean Urban Transportation for Europe

On November 24, 2001, nine European cities signed a contract in Bruxelles formalizing their inclusion in the Clean Urban Transportation for Europe (CUTE) project. These cities were London, Luxemburg, Hamburg, Barcelona, Amsterdam, Madrid, Porto, Stockholm, and Stuttgart. Each city agreed to incorporate three fuel cell buses in their regular bus routes as well as to implement the hydrogen infrastructure necessary to keep these buses in the road. Since that meeting, Perth has also joined the project, though they are receiving no funding from the European Union (EU) and their timetable is about one year behind the other cities. The buses are to run for two years in order to gather data on how to best institute larger scale hydrogen infrastructure. The performance of the buses themselves will also be analyzed to determine possible improvement to be made to the fuel cell technology.

The main purpose of the CUTE project is to demonstrate a no emission, low noise transportation system. To do this fuel cell buses that are competitive with their diesel counterparts must be manufactured. Also, a viable hydrogen infrastructure system must be constructed to keep the buses on the road. The project will also strengthen the competitiveness of European industry in areas such as hydrogen production, transportation, and storage. The European Union lists the main objectives as follows [6]:

→ Demonstration of 30 fuel cell powered regular service buses over a period of two years in 9 European inner city areas to illustrate the different operating conditions to be found in Europe
→ Design, construction and operation of the necessary infrastructure for hydrogen production, including the required refueling stations.
→ Collection of findings concerning safety, standardization, and operating behavior of hydrogen production for mobile and static use, and exchange of experiences including bus operation under differing conditions among the numerous participating companies.
→ Ecological, technical and economical analysis of the entire life cycle and comparison with conventional alternatives. Accompanying social study to analyze and increase

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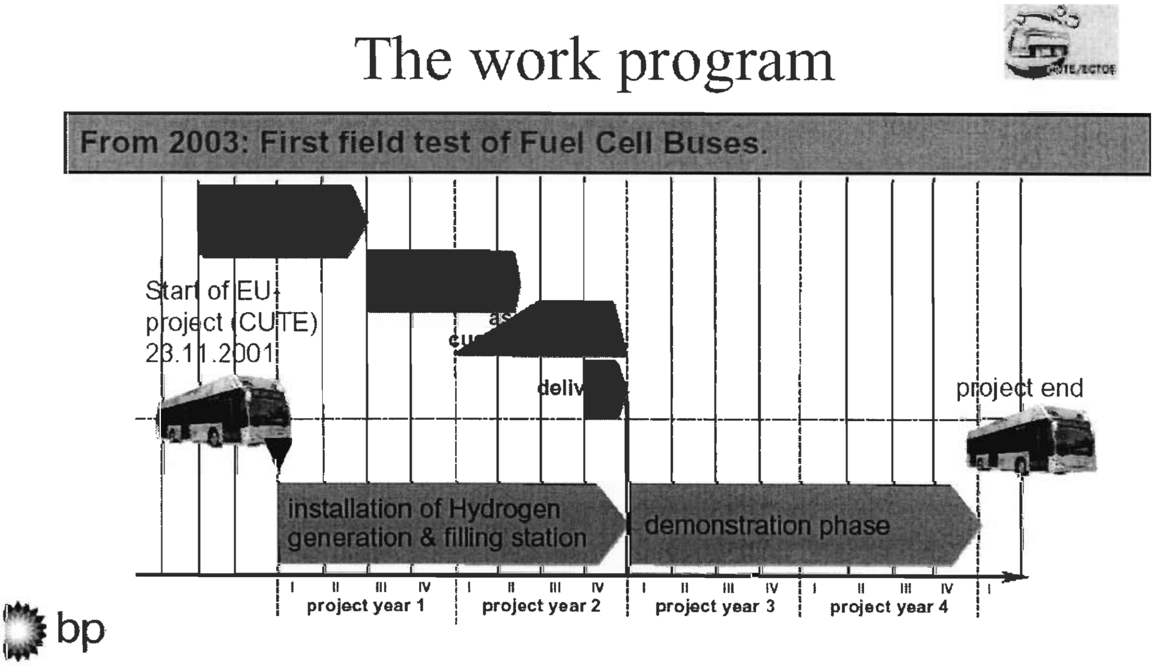
[6] Clean Urban Transport for Europe: General Information Brochure (European Union, 2002) pg. 2

awareness of these new technologies. Quantification of the abatement of CO2 at European level and contribution to commitments of Kyoto.

→ Registration of the socio-economic effects such as the impact on employment and relations between individual industrial sectors as a result of the changes to energy and transport systems.

The project is to last from 2001 'till 2005 (except in Perth). The first 2 years will be spent installing the hydrogen generation and filling stations on the infrastructure side, and assembling and testing the buses on the technology side. The delivery of the buses is to begin in 2003 the demonstration phase will continue for two years after the bus delivery.



Timetable of CUTE project [7]

The buses used will be Mercedes-Benz Citaro buses. The fuel cell engine can provide a maximum power of 205kW. The performance is similar to that of the conventional diesel buses with a maximum speed of about 50 mph while seating 70 passengers[8]. The engine runs on pure hydrogen, meaning that any reforming must take place before the bus is fueled.

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[7] Jones, Mike. Providing Cleaner Fuels: Hydrogen (Global Hydrogen 2002) pg. 12

[8] http://www.daimlerchrysler.co.jp/index_e.html?/news/2002/021008_1_e.html

	Amsterdam	**Barcelona**	**Hamburg**	**London**	**Luxembourg**
Motivation	Environment Policy Plan (noise, CO2, odor, emissions)	Technological Innovation	Traffic Development Policy and national hydrogen focus	Air Quality	Combat potential traffic problems
Participating Companies	GVB Amsterdam, Shell Hydrogen, Nuon, Hoek Loos, Milieudienst Amsterdam	Transports Metropolitans de Barcelona, BP	Hamburger Hochbahn AG, BP, Hamburgische Electricitäts-Werke	Transport for London's, London Buses, British petroleum	Autobus de la ville de Luxembourg, Shell hydrogen, Air Liquide
Operator of buses	GVB Amsterdam	Transports Metropolitans de Barcelona	Hamburger Hochbahn	London Buses	Autobus de la ville de Luxembourg
Infrastructure	On site electrolyzer using renewable resources	Solar panels with electrolyzer for backup	On site electrolyzer using remote wind turbines	Hydrogen produced off site and trucked in as a liquid	On site steam reformer with capacity for trucked in hydrogen
Special Conditions		Hilly topography High temperatures		Stop and go traffic at low speeds	Stringent topology
Population	720,000	1.4 million	1.7 million	7.1 million	240,000
Current fleet size	288 buses 55 lines	850 buses 80 lines	112 lines	5,500 buses 700 lines	22 lines

	Madrid	**Porto**	**Stockholm**	**Stuttgart**	**Perth**
Motivation	Air quality	Instituto Superior Tecnico	Environmental and Health concerns	Nationwide hydrogen RD&D effort	National push for zero emission vehicles
Participating Companies	Empresa Municipal de Transportes de Madrid, Air Liquide, Gas Natural, Repsol-YPF	Instituto Superior Tecnico, Sociedade de Transportes Colectivos do Porto, BP	Environmental and Health Protection Administration, Stockholm Transport, Busslink i Sverige AB, Birka Energi	University of Stuttgart, BP, Stuttgarter Strassenbahnen AG, Neckarwerke Stuttgart AG	Transperth Public Transportation, Smarttrack, BP, Murdoch University
Operator of buses	Empresa Municipal de Transportes de Madrid	Sociedade de Transportes Colectivos do Porto	Busslink i Sverige	Stuttgarter Strassenbahnen	Transperth Public Transportation
Infrastructure	On site steam reformer with capacity below maximum demand	On site steam reformer	On site electrolyzer with power from hydro plants	Steam reformer running at less than full capacity	Hydrogen trucked in from oil refinery
Special Conditions	High temperature Congested traffic	Hilly topography High temperatures	Cold climate	Long distances Hills over 10% High speeds	High speeds Long distances
Population	2.8 million	290,000	1.2 million	580,000	1.3 million
Current fleet size	1,824 buses	608 buses 78 lines	1,800 buses	235 buses 55 lines	320 buses

Table 1: Details for Cities in the CUTE project

As seen in figure 1, the cities participating in the CUTE project are very diverse. They have different motivations for joining the project and will be implementing a variety of hydrogen production/distribution systems. The different motivations fall into three categories: environmental concerns, technological advancement, and traffic reduction, though there is overlap between those three. The major hydrogen production methods are steam methane reforming and electrolysis from green electricity.

Many of the cities have very bad air pollution, London probably being the worst. Amsterdam, Perth, Stockholm and Madrid also fall under this category. Their goal is to reduce the emissions of the city buses to help combat this issue. If they can't reduce the life cycle emissions, the goal is to at least move the emissions out of the city. Ken Livingston, mayor of London, states, "London's air quality needs to improve and my Transport and Air Quality Strategies make it clear that we need to promote clean, environmentally-friendly vehicle technology to tackle pollution problems."[9]

Other cities cite a problem with traffic congestion as their reason for joining CUTE, particularly Hamburg and Luxembourg. The mayors feel that the current diesel buses are unattractive because they are dirty and noisy. By introducing clean, quiet HFC buses, it would make public transportation more attractive and convince more people to use the city buses. Paul Helminger, mayor of Luxembourg, comments on the CUTE project, "The citizen will profit from this highly advanced technology by getting a far better quality of public transport . . ."[10]

Finally, there are cities, specifically Barcelona, Porto, and Stuttgart, which see this project as a chance to demonstrate the scientific ingenuity of its citizens. With the move to fuel cells, companies need to keep up with the technology or they will lose their competitive edge. This project gives city industries experience with fuel cells that will both improve their understanding of the technology while increasing their attractiveness to future contractors. Joan Clos I Matheu, mayor of Barcelona comments, "Barcelona has always been a pioneering city in the adoption of all the technical and scientific advances which contribute to the improving the citizens' quality of life."[11]

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[9] Clean Urban Transport for Europe: General Information Brochure pg 11
[10] Clean Urban Transport for Europe: General Information Brochure pg 13
[11] Clean Urban Transport for Europe: General Information Brochure pg 7

Madrid, Porto, Stuttgart, and Luxembourg will be using a SMR for hydrogen production. The steam reformers will be of varying capacity to test the scalability of the steam reforming process. Stockholm, Amsterdam, Barcelona, and Hamburg will be using an on site electolyzer running on green electricity. The electricity generation varies from city to city, depending on what renewable sources are available. On days when renewable energy is not available, e.g., cloudy days with solar panels, electricity will be taken from the grid or hydrogen will be trucked in from off site. London and Perth will use hydrogen trucked in from off site all the time. This variety of technologies is done on purpose in order to generate a wide range of test data from the project.

Each city also has intrinsic properties that allow for diverse testing conditions. While the Citaro buses have performed as well as diesel buses in benchmark tests, those benchmarks only simulate real driving conditions and it will be necessary to drive the HFC buses in actual city streets to be certain their performance is adequate to replace diesel buses. Actual use in a city's mass transit system will also produce some preliminary data as to the Citaro's maintenance costs and how they are affected by different driving conditions.

One varying condition is the climate of each city. Barcelona, Madrid, and Porto have hot climates. Stockholm, on the other hand, gets very cold in the winter. It is possible that hot temperatures will cause the HFC system to overheat. The HFC also might struggle to maintain power to both the drive train and the air conditioning. The cold weather in Stockholm might increase the time necessary for the buses to warm up before driving them. PAFCs run at around 200 degrees Celsius. There could also be other, unforeseen problems stemming from extreme climates.

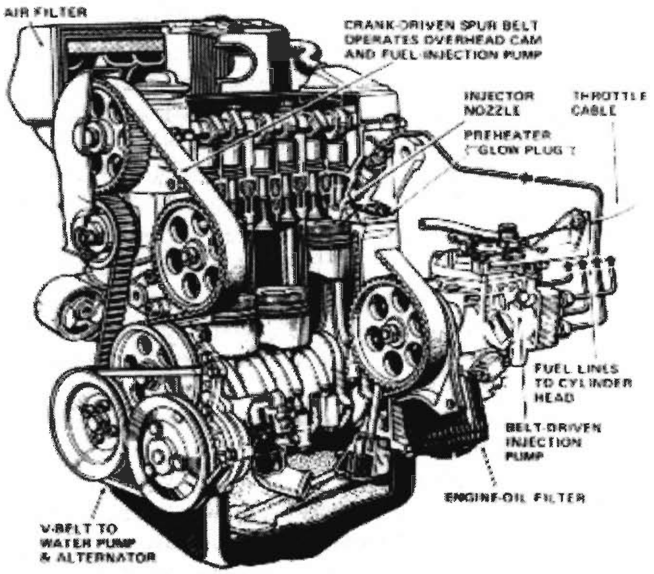
Another varying condition is the bus's average speed. Madrid and London have congested traffic and will require the buses to drive in stop and go conditions. This will increase the strain on the bus, possibly causing increased breakdowns and higher maintenance costs. The buses will also never be able to reach high speeds in traffic. Stuttgart and Perth, on the other hand, will require the buses to travel longer distances through less traffic. To compete with diesel buses in these cities, the Citaro will have to be able to sustain high speeds for long periods of time.

Finally, topography might have an effect on the performance of the Citaro buses. Barcelona, Luxembourg, Porto, and Stuttgart have a stringent topology. Hydrogen fuel cell vehicles do not yet have the same power as the most powerful diesel engines. Although this is slowing the spread of HFC vehicles to the trucking market, HFC are supposed to have enough power to drive a bus. The toughest test will be while driving over hills. The hills in Stuttgart, with a maximum grade over 10%, will be a good test as to whether or not the Citaro has enough power for stressful roads.

Fuel Supply Options and Associated Emissions

The buses considered in this study are conventional diesel, ultra low sulfur diesel, diesel hybrid, and hydrogen fuel cell buses. HFC buses are categorized by the method the hydrogen is produced, i.e., SMR or electrolysis from green electricity. The ULSD buses are fitted with a catalytic particle trap. Other than the HFC buses, all the buses are commercially available and in use at current. The CUTE project is one of the first times HFC buseswill be operational alongside conventional buses.

The diesel engine was invented by Rudolph Diesel in 1892. It works almost the same as an internal combustion engine, but it is more efficient and tends to have a little more power and durability. Most trucks and buses use diesel engines, as well as ships and tankers. The diesel fuel used in most diesel engines is made by refining crude oil. Many alternatives have also been used produce diesel fuel including biodiesel and synthetic diesel. In fact, Rudolph originally ran his engine on peanut oil[12].



The conventional diesel bus is the base case for this study. It has high emissions and low efficiency when compared to the other vehicles in this study, though the exact figures will be left until the next section. Ultimately, it would be ideal to remove all conventional diesel buses from the road and replace them with alternative vehicles which pollute less and are more efficient, keeping in mind that an 'alternative vehicle' might just be a more efficient diesel engine. The diesel buses in this study used diesel fuel from refining crude oil.

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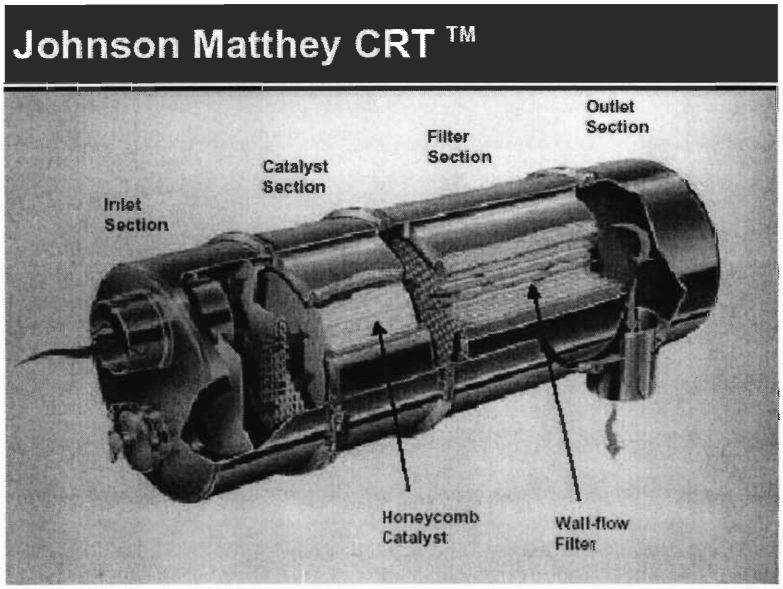
[12] http://www.ybiofuels.org/bio_fuels/history_diesel.html

The hybrid diesel bus is propelled by both an onboard diesel engine electric batteries. The diesel engine is used to recharge the batteries and to provide propulsion when the bus reaches its cruising speed. The acceleration force is provided by the battery. The diesel engine runs at a more constant speed in a hybrid diesel bus thus reducing emissions. The diesel engine in a hybrid vehicle is also smaller than the engine in a comparable conventional diesel vehicle. Many hybrid vehicles also have regenerative braking, a process in which energy is captured from the brakes during deceleration and returned to the battery. While the specific bus considered in this study, the Orion-LMCS V1 Hybrid, supports regenerative braking, it was not used in the benchmarks that produced the emissions presented in this report.

As opposed to hybrid engines, which try to increase the efficiency of a bus, ‘Clean diesel’ is a diesel engine where steps are taken to reduce the emissions without necessarily increasing the efficiency. The two major technologies used in the clean diesel bus in this study are ultra low sulfur diesel and a catalytic particle trap. ULSD is produced from conventional diesel by removing sulfur from the fuel after refining and reducing the sulfur concentration to <15 ppm as opposed to <500 ppm in conventional diesel. This directly reduces the amount of sulfur based byproducts emitted by the vehicle during combustion and has an indirect effect on non sulfur based emissions. The catalytic particle trap works by completing the combustion of incompletely combusted fuels while simultaneously trapping particulate matter from reaching the atmosphere. The effect is a reduction of THC, CO, and PM as compared to a conventional diesel bus. The particle trap used in this study is a



Johnson Matthey CRT. The picture is taken from the 'NYCT Clean Fuel Bus Programs' presentation.

Steam methane reforming involves the extraction of pure hydrogen from methane. The chemical formula for the reaction is:

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

As can be seen from the formula, SMR can produce large amounts of CO_2. The process also can release significant amounts of methane. Otherwise, there are no major emissions from the production of hydrogen, though there are small amounts of emissions along the life cycle from the production and shipping of the feedstock.

With SMR, hydrogen can be produced at the filling station on demand, or it can be produced at a centralized location and distributed among several filling stations. In this study, only on site production is considered since the majority of cities using the SMR technique will be building on site plants. The only extra emissions from off site production are from the transportation of hydrogen from the SMR facility to the filling stations. Centralized production would have lower capital costs since a single plant could serve several filling stations. Due to the scalability of the reforming process, building one plant with the capacity to service 10 filling stations would cost less than building 10 SMR facilities on site, disregarding the price of distributing the finished hydrogen. One large plant would also give more options for processing emissions. However, transporting hydrogen is an added complication that is not present in decentralized production. A centralized SMR does not make the most sense for the purposes of the CUTE project since all the cities are only going to have a single hydrogen filling station.

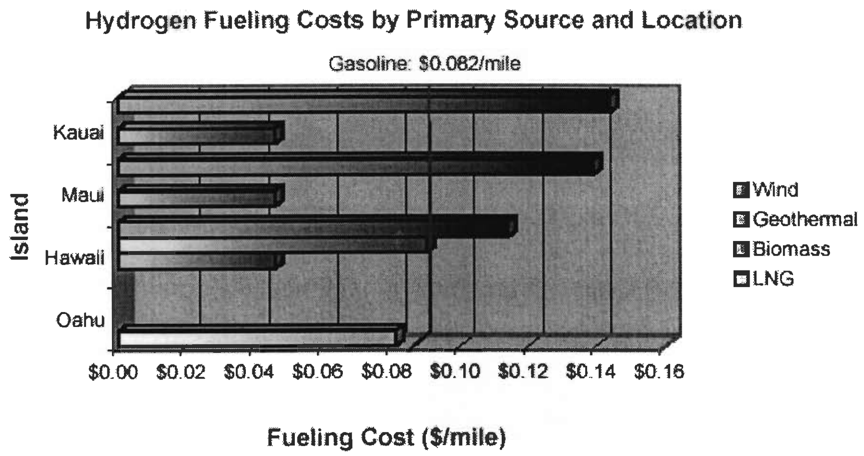
The other hydrogen production option considered in this report is electrolysis of water using green electricity. In this process, electricity is used as a catalyst to break water into hydrogen and oxygen.

$$2H_2O \rightarrow 2H_2 + O_2$$

When green electricity, i.e., electricity from renewable sources, is used, the HFV vehicle will have no emissions along its whole life cycle, disregarding emissions from the construction of the buses, power plants, and infrastructure. Using non-green electricity would logically be almost as harmful environmentally as using a diesel bus, though no such study is included in this report. Reason being that the electricity produced would have large emissions associated with it, and the electrolysis process is not terribly efficient (about 65%). As such, using green electricity will be preferable and electricity from the grid will only be used when renewable sources are not available.

One major advantage to using electrolysis is the portability of the process. It is easy to transport energy as electricity as opposed to transporting the same energy in hydrogen form. On site hydrogen production will be used in all the cities implementing electrolysis plants. Another advantage to electrolysis is the low capital cost of an electrolysis facility relative to a SMR plant.

The biggest problem with electrolysis is the operating costs. They require a large input of electricity, which is very expensive compared to the price of the feedstock at a SMR site. As the technology stands now, the hydrogen produced from a SMR plant will be slightly cheaper than fuel produced from an electrolyser[13]. Although price is not the focus of this study, it's still an important factor to consider. It might be nice if every industry used environmental impact as their main decision making tool, but usually expenses play a bigger role. The above figure, taken from the report "Assessing the feasibility of Hydrogen and Fuel Cells in Hawaii", compares the cost of operating vehicles in Hawaii as related to the source of fuel. Another drawback is that using green electricity directly in the power grid might be a more productive way of reducing overall emissions than using it to replace a diesel bus[14].



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[13] "Nurturing a Clean Energy Future in Hawaii: Assessing the Feasibility of the Large Scale Utilization of Hydrogen and Fuel Cells in Hawaii" (June 2001) pg E1

[14] Jones, Mike. Providing Cleaner Fuels: Hydrogen

Methodology

This study considers the emissions from 3 different types of diesel buses along with HFC buses running on hydrogen from 2 sources. The emissions included are CO2, NOx, CO, particulate matter, and hydrocarbons. The latter is divided into methane and non-methane where the data was available. Upstream emissions are evaluated as well as combustion emissions. Emissions from the construction of the vehicles and supporting infrastructure are not included. The majority of a vehicle's emissions come during the driving phase of its life, so it seemed practical to leave the construction phase out of this study given the types of emissions being analyzed. While the construction of refineries and SMR facilities can have somewhat significant emissions – especially particulate matter from the concrete[15] – it was determined that these emissions from both types of facilities were similar enough to not include the added complexity of the construction emissions. All life cycle emissions included are converted to grams per mile traveled.

The upstream emissions for diesel and ULSD fuels come primarily from the Australian report "Comparison of Transport Fuels"[16]. The life-cycle analysis in that report considers emissions from a fuel's Extraction, Production, Transport, Processing, Conversion, and Distribution. Further information can be obtained from page 2 of that report. While the emissions from an Australian life cycle analysis will be slightly different from the European cities included in this report, it was decided that the emissions were close enough. None of the European studies researched included the desired emissions from both diesel and ULSD. The numbers in the Australian report were similar to corresponding reports conducted in America or Europe.

The upstream emissions from SMR were taken from the National Renewable Energy Laboratory report "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming"[17]. That report considers the emissions from production and transport of natural gas, the electricity generation to run the reformer, the plant operation, and the construction/deconstruction of the plant. The emissions from

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[15] "IEA Agreement on the Production and Utilization of Hydrogen". (Golden, CO. 2001) pg. 16

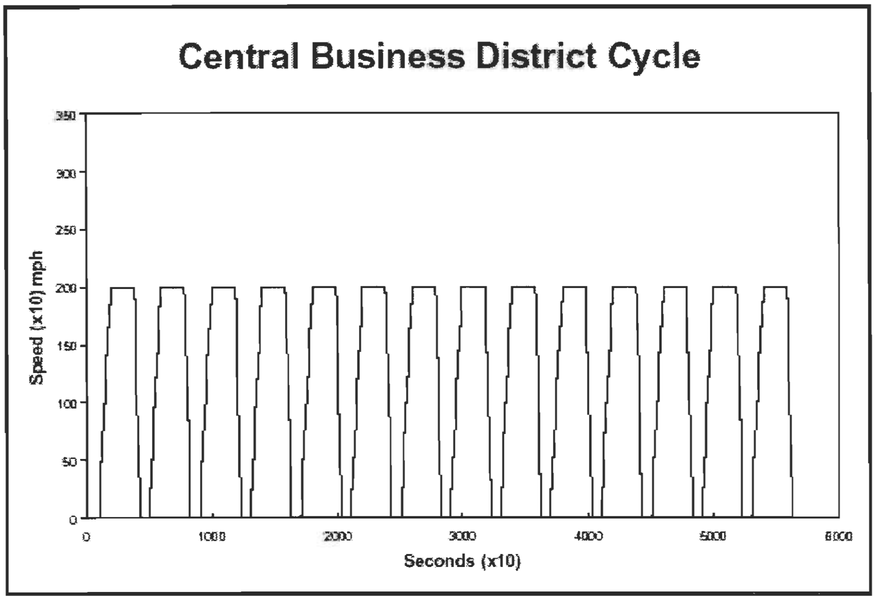
[16] "Comparison of Transport Fuels". CSIRO Energy Technology.

[17] "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming". Golden, CO

construction/destruction were subtracted from the totals. The study is on a SMR plant with a greater capacity than most of the plants that will be used in the CUTE project. The process it uses, however, is scalable and believed to be the same one used in CUTE. Therefore, it has been assumed that the emissions per kilogram of hydrogen will be at least as high in a smaller plant as they are in the larger plant.

The emissions from a renewable power plant as well as from the HFC buses are assumed to be zero for this study. Every study read while researching this paper listed the fore mentioned emissions as either zero or negligible. While there are life-cycle emissions from the construction of a renewable power plant and a HFC bus, these are not considered in the case of the diesel buses so they are left out for consistency in the case of the HFC vehicles.

The emissions for both the hybrid diesel and conventional diesel bus were taken from the Northeast Advanced Vehicle Consortium report "Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project: Final Emissions Report"[18]. The emissions used are from the Central Business District (CBD) route. This drive cycle was chosen because it most resembles the drive cycles used to determine the efficiency of the HFC engine. While other drive cycles are more accurate in portraying the patterns of city buses, this realism was sacrificed for consistency with the Citaro buses. The buses used are the Orion-LMCS V1 Hybrid Diesel and the NovaBUS RTS Diesel Series 50. Both were running of ordinary diesel fuel during the emissions testing.



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[18] "Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project: Final Emissions Report"(Boston,MA 2000)

The emissions from the ULSD bus were taken from a NYC transit Department of Buses' presentation on July 11, 2001 entitled "NYCT Clean Fuel Bus Programs". NYCT presented the emissions data from a Series 50 bus equipped with a Johnson Matthey CRT catalyzed filter and running on ULSD. This bus was also running on a CBD cycle.

The life cycle emissions from the HFC buses are based on the DaimlerChrysler report that the vehicles will have a range of around 250km while having a fuel capacity of 40kg. This comes out to 3.88 mi/kg. The total miles traveled by the bus fleet of all involved countries is based on the Department of Transportation's report that the average bus in the United States travels 9370 miles a year. The two Cities that did not have an exact number of buses available were assumed to have 10 buses per line. The end result was rounded to 11500. The number of vehicle-miles per year was computed as 9370*11500. This figure is probably the biggest source of error in this report. It would have been best to use the exact vehicle-miles figures from each city, but those numbers were not available. Other conversions used are listed in Appendix A.

In order to predict the effect of changing the bus fleet of the CUTE cities to alternative fuel options, the conventional diesel was taken as the base case. Then, it was determined what the emissions would be if varying percentages of the alternative vehicle were used and the remaining buses were diesel. This study does not consider different combinations of alternative vehicles, e.g., 10% diesel, 50% ULSD, and 40%HFC. This technique was chosen for ease, but it is not the most accurate measure of the effectiveness of using new engines. For example, every bus in London currently uses ULSD and is, or is in the process of being, fitted with a particle trap. The emissions reduction in London, then, should use ULSD as the base case, not conventional diesel. With that said, the majority of buses in the CUTE cities are conventional diesel buses. While the vehicle comparison in this report may not be entirely accurate, the numbers are still felt to be significant.

Results

Tables 2, 3, and 4 give the production emissions, combustion emissions, and total emissions for each of the vehicles, respectively. Production emissions are measured in grams of pollutant per kg of fuel produced. Combustion and Total emissions are measured in grams of pollutant per mile traveled by the end vehicle. Table 4 has a graph on the following page. In that graph, some emissions are multiplied or divided by a factor of 10 to make everything the same scale. This is noted on the chart itself.

	CO2	CH4	CO	THC	NOx	PM
Diesel	363	0.0137	0.437	1.084	1.9	0.355
ULSD	414	0.0137	0.495	1.235	2.17	0.37
Hydrogen (SMR)	10,620.60	59.8	5.7	76.6	12.3	0.708
Hydrogen (electrolysis)	<.01	<.01	<.01	<.01	<.01	<.01

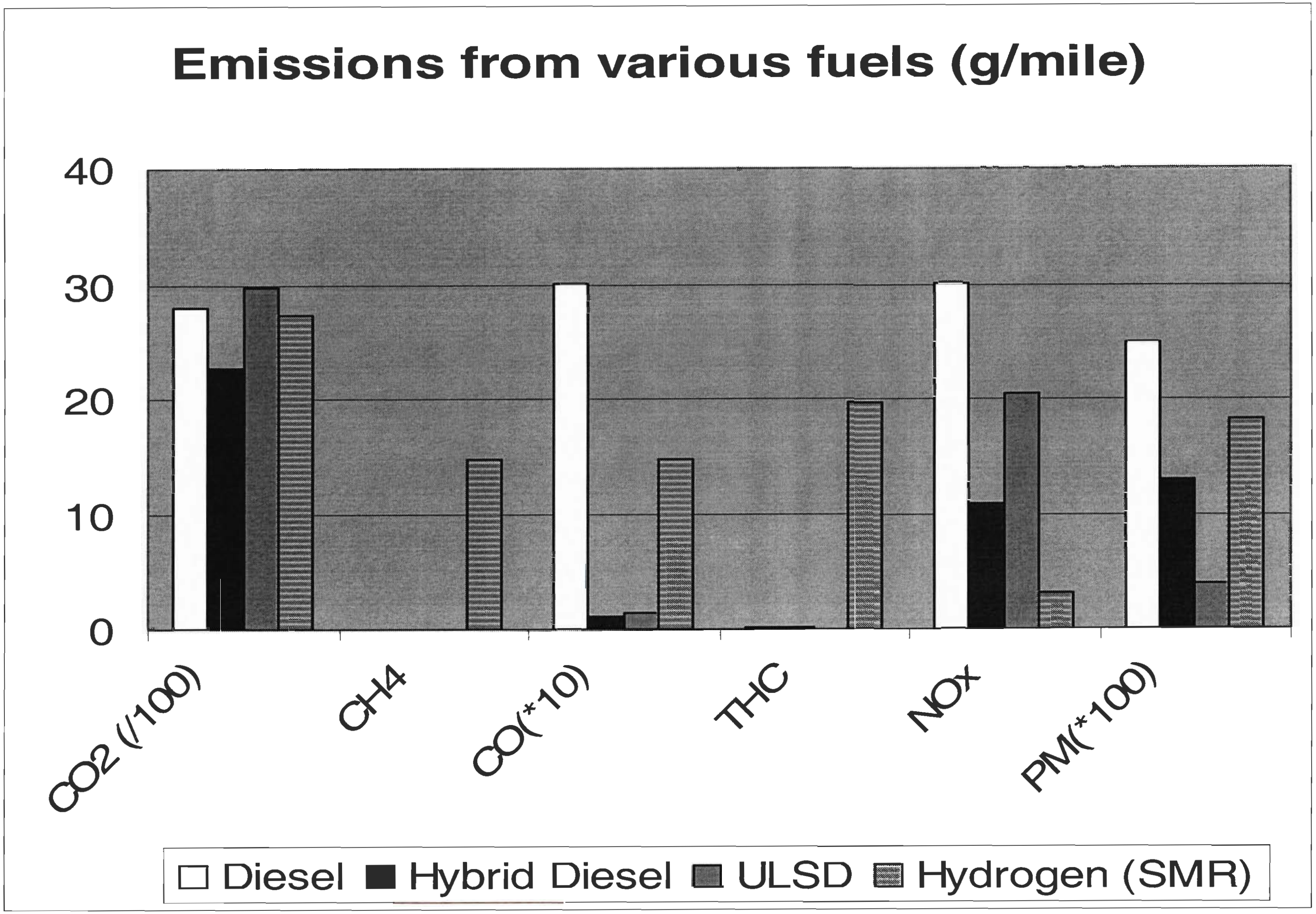
Table 2: Production Emissions (g/kg)

	CO2	CH4	CO	THC	NOx	PM
Diesel	2779	0	3	0.14	30.1	0.24
Hybrid Diesel	2262	0	0.1	0.08	19.2	0.12
ULSD	2960	?	0.12	0.015	25.1	0.024
Hydrogen (SMR)	0	0	0	0	0	0

Table 3: Combustion Emissions (g/mi)

	CO2	CH4	CO	THC	NOx	PM
Diesel	2793	0.0005	3.016	0.181	30.2	0.25
Hybrid Diesel	2273	0.0004	0.11	0.114	19.3	0.13
ULSD	2975	?	0.139	0.061	25.2	0.04
Hydrogen (SMR)	2734.8	15.3985	1.467	19.725	3.17	0.18

Table 4: Total Emissions (g/mi)


Emissions from various fuels (g/mile)
40
30
20
10
0
CO2 (/100)
CH4
CO(*10)
THC
NOx
PM(*100)
☐ Diesel
■ Hybrid Diesel
■ ULSD
▤ Hydrogen (SMR)

Tables 5 through 9 show the annual emissions from the bus fleets in the CUTE project after converting varying percentages of conventional diesel buses to alternative fuel buses. Each table only considers a single pollutant, is measured in kg/year or Mkg/year, and has a corresponding graph on the following pages.

	0%	10%	20%	50%	100%
Diesel	300.96	300.96	300.96	300.96	300.96
Hybrid Diesel	300.96	295.957	289.753	272.954	244.927
ULSD	300.96	302.921	304.882	310.766	320.571
Hydrogen(SMR)	300.96	300.333	299.706	297.824	294.688

Table 5: CO_2 Emissions for Partial Conversion of Bus Fleet (million kg per year)

	0%	10%	20%	50%	100%
Diesel	324989.08	324989.08	324989.08	324989.08	324989.08
Hybrid Diesel	324989.08	293675.477	258361.874	168421.065	11853.05
ULSD	324989.08	293987.967	258986.853	169983.513	14977.945
Hydrogen(SMR)	324989.08	308306.451	287623.822	241575.935	158162.789

Table 6: CO Emissions for Partial Conversion of Bus Fleet (kg per year)

	0%	10%	20%	50%	100%
Diesel	19503.66	19503.66	19503.66	19503.66	19503.655
Hybrid Diesel	19503.66	18781.737	18059.774	15893.865	12284.07
ULSD	19503.66	18210.6355	16917.571	13038.3575	6573.055
Hydrogen(SMR)*	0.019504	0.23007852	0.44065333	1.07237776	2.125

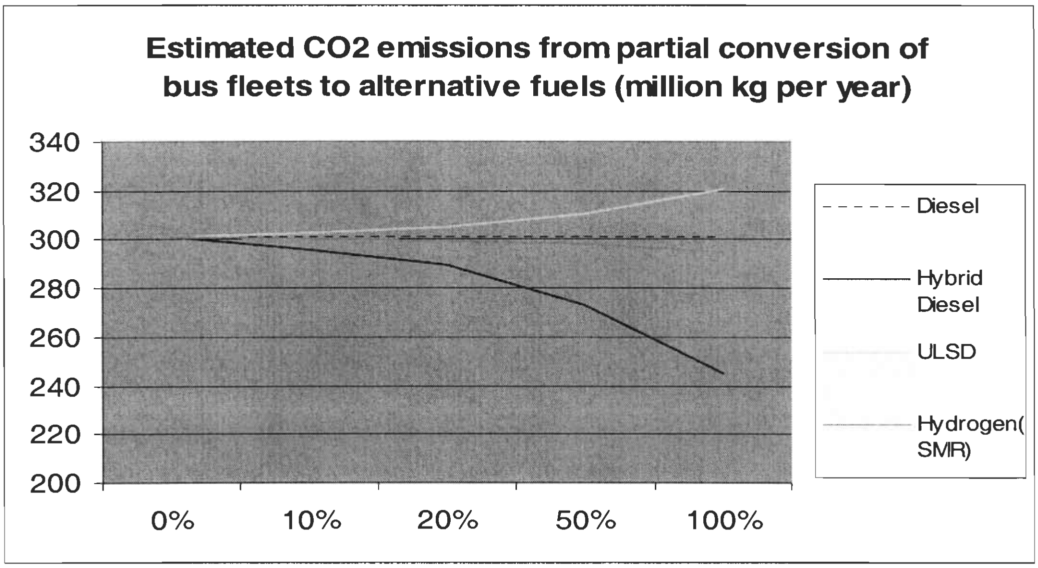
Table 7: THC Emissions for Partial Conversion of Bus Fleet (kg per year)
* - Emissions are in million kg per year

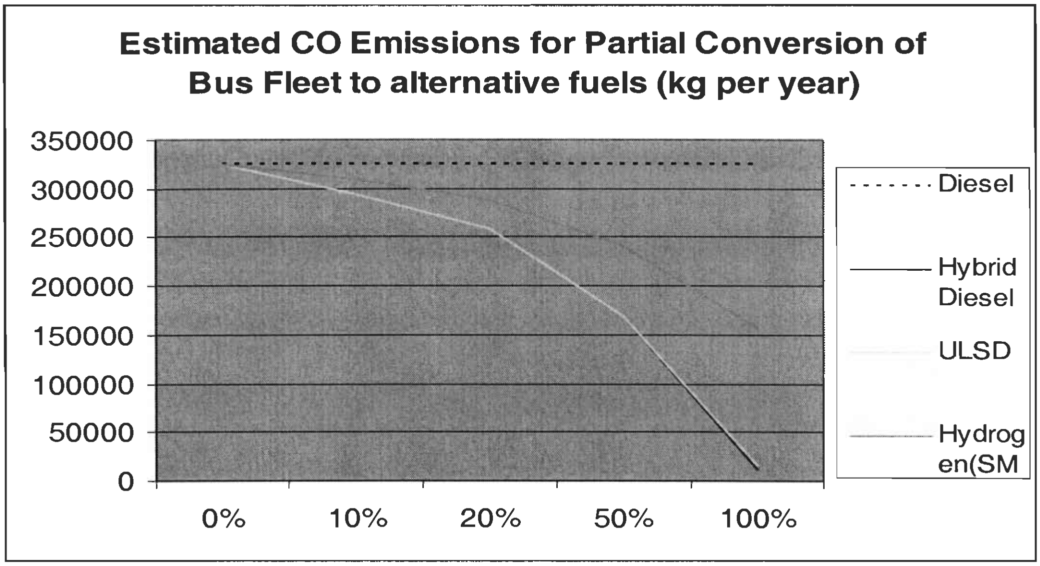
	0%	10%	20%	50%	100%
Diesel	3.254201	3.254201	3.254201	3.254201	3.254201
Hybrid Diesel	3.254201	3.13674805	3.0192951	2.66693625	2.0796715
ULSD	3.254201	3.2003235	3.146446	2.9848135	2.715426
Hydrogen(SMR)	3.254201	2.96293924	2.67167747	1.79789218	0.34

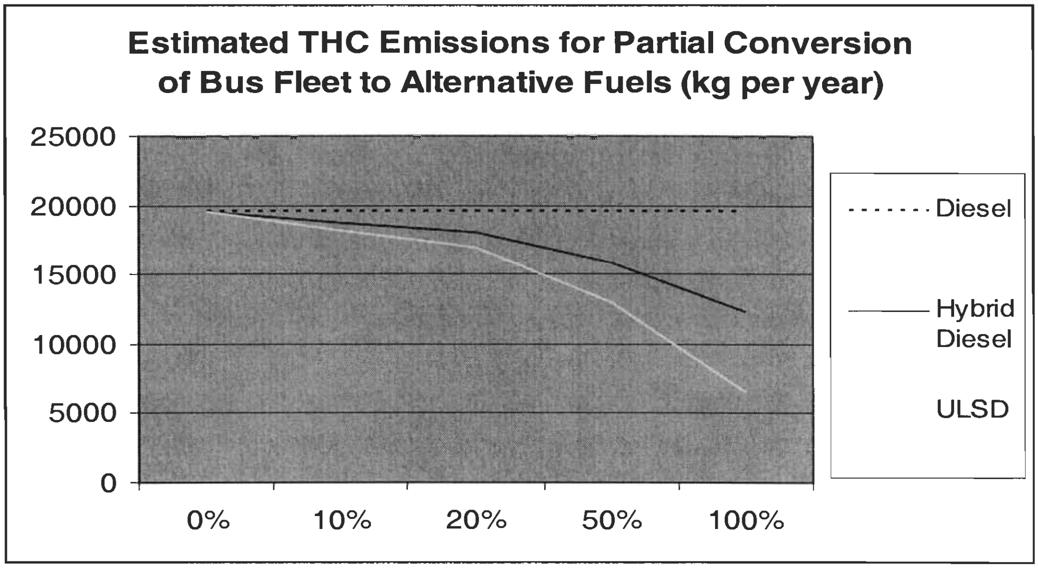
Table 8: NOx Emissions for Partial Conversion of Bus Fleet (million kg per year)

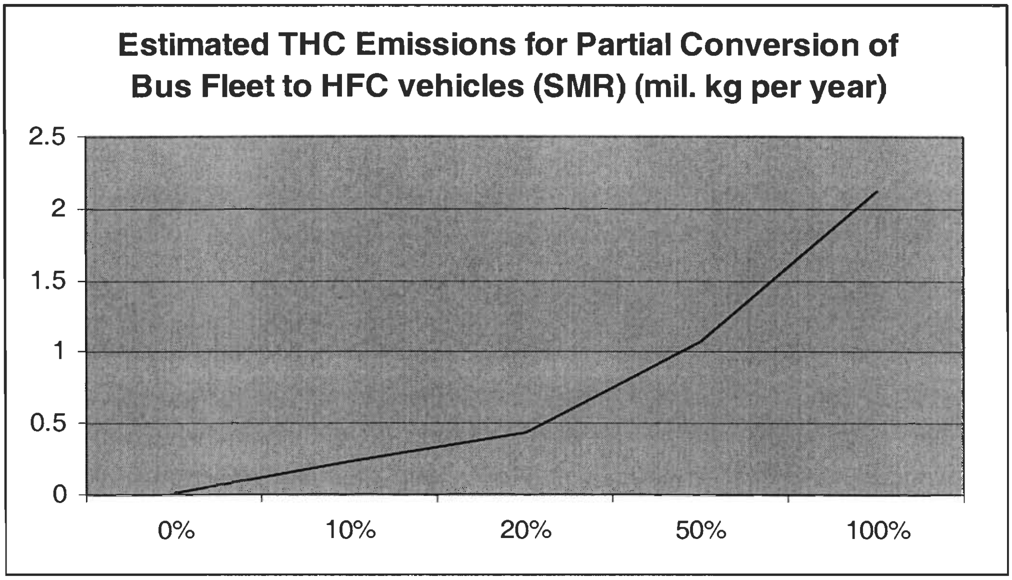
	0%	10%	20%	50%	100%
Diesel	26938.75	26938.75	26938.75	26938.75	26938.75
Hybrid Diesel	26938.75	25645.69	24352.63	20473.45	14008.15
ULSD	26938.75	24675.895	22413.04	15624.475	4310.2
Hydrogen(SMR)	26938.75	26209.2487	25479.7473	23291.2433	19643.74

Table 9: PM Emissions for Partial Conversion of Bus Fleet (million kg per year)

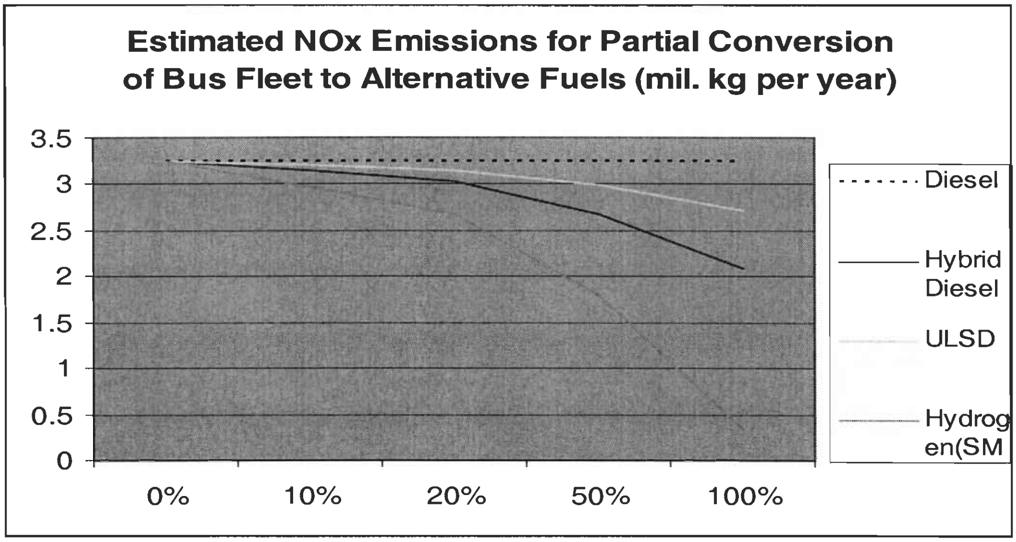

Estimated CO2 emissions from partial conversion of bus fleets to alternative fuels (million kg per year)


Estimated CO Emissions for Partial Conversion of Bus Fleet to alternative fuels (kg per year)

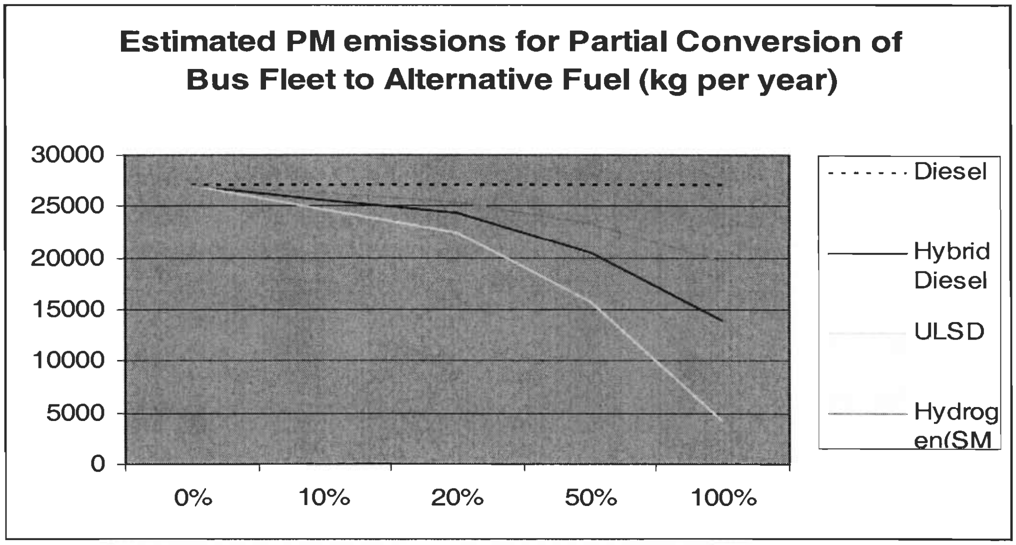

Estimated THC Emissions for Partial Conversion of Bus Fleet to Alternative Fuels (kg per year)



Estimated THC Emissions for Partial Conversion of Bus Fleet to HFC vehicles (SMR) (mil. kg per year)



Estimated NOx Emissions for Partial Conversion of Bus Fleet to Alternative Fuels (mil. kg per year)



Estimated PM emissions for Partial Conversion of Bus Fleet to Alternative Fuel (kg per year)

The only one of the alternative fuels which had significant reduction in CO_2 emissions was hydrogen using electrolysis. The next best engine was the hybrid diesel engine, which could reduce emissions by approximately 60 million kg per year. With 3090 Mtons of CO_2 being produced each year in EU countries[19], the emission savings of a hybrid diesel engine are not significant. When hydrogen is produced using SMR, the CO_2 emissions are almost the same as that of a diesel bus. ULSD fuel has slightly higher emissions. Using hydrogen from electrolysis of green electricity to reduce CO_2 emissions in buses might not be the most efficient use of that green electricity. British Petroleum reports that, while using 1Gwh of renewable electricity to produce hydrogen to replace a gasoline hybrid vehicle would avoid 390 tons of CO_2, using that same electricity to replace coal generated power in the electricity grid would avoid 972 tons of CO_2.[20]

Carbon monoxide emissions can be roughly halved by using a HFC vehicle instead of a conventional diesel engine if the hydrogen is produced by SMR. ULSD and a hybrid Diesel bus, on the other hand, can nearly eliminate CO emissions. Both of the latter two engines can reduce total hydrocarbon emissions as well. The steam methane reforming process, on the other hand, has high hydrocarbon emissions. Most of these hydrocarbons are methane. Methane is a greenhouse gas which is 21 times as harmful as carbon dioxide[21]. The approximately 5 million kg of CO_2 saved by using a HFC vehicle will be more than offset by the additional 2 million kg of CH4 produced.

The HFC vehicles perform well in reducing NOx emissions, reducing emissions by a factor of 13 over a diesel engine. The NOx emissions that do arise from the SMR process can also be produced outside of the city, thereby reducing human exposure to the nitrous oxides and reducing urban smog. Hybrid diesel and ULSD reduce NOx emissions by 1/3 and 2/3 respectively. Urban emissions are unavoidable in these cases since the nitrous oxide is produced at the combustion stage.

ULSD is the most effective fuel in reducing particulate matter emissions. The PM emissions of a conventional diesel engine are about 5 times that of one running on ULSD

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[19] http://www.climnet.org/resources/annex1emissions.htm (April 23, 2003)

[20] Jones, Mike. Providing Cleaner Fuels: Hydrogen

[21] http://www.energychampion.org/bg/GREENHOUSE.htm

and equipped with a particle trap. SMR has a slight emissions advantage over diesel, and hybrid diesel cuts these PM emissions in half.

Conclusions

While there is the potential for zero emissions using HFC vehicles, that reality is far off. The current method of hydrogen production through SMR produces almost as much CO_2 as a conventional diesel bus. While HFC vehicles have lower emissions of NOx, CO, and PM as compared to a conventional diesel bus, other methods less drastic than a complete infrastructure overhaul give similar results. Using electrolysis and green electricity for hydrogen production could eliminate emissions from buses completely. However, that same energy could be more effective in reducing emissions if used directly as electricity instead of indirectly by driving a HFC vehicle. Using green electricity in the transportation sector won't reduce overall emissions until the emissions from electricity production are reduced.

Hydrogen fuel cell buses can be a useful tool in reducing urban emissions, even if they cannot reduce overall emissions at the current time. Hydrogen can be produced off site in unpopulated areas and transported to cities with trucks or through pipelines. With zero emissions at the point of use, HFV could be useful in cleaning up city air and reducing people's exposure to harmful emissions. However, changing the locality of CO_2 emissions has no effect on the greenhouse effect.

In the short term, perhaps the most attractive option for reducing emissions is the ULSD route. Conventional diesel buses can be retrofit with catalytic particle traps. This makes it possible to significantly reduce emissions with minimal capital cost. The ULSD fuel will have no capital costs for the transit authorities to consider, since the current fuel infrastructure can still be used. The costs of producing the ULSD fuel will be reflected by the slightly higher price of ULSD than diesel.

The hybrid diesel bus could be used to replace older diesel buses, instead of replacing them with conventional diesel buses. Over time, the bus fleet of each city can gradually change to hybrid diesel. Currently, hybrid diesel buses carry a larger capital price ($385,000[22]) than a conventional diesel bus ($270,000[23]), but not as large as a HFC

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[22] http://www.cai-infopool.org/cost (April 23, 2003)
[23] http://www.cai-infopool.org/cost

bus ($1.2 million[24]). This larger capital cost will be offset, to some extent, by the cheaper operation price due to less fuel consumption. This assumes identical maintenance costs for the two vehicles, which is unlikely. Exploration of such costs is beyond the scope of this report. The hybrid diesel and ULSD technologies are not mutually exclusive, though they were separated in this report. Combining the two would be a logical step for reducing emissions from diesel engines.

The Citaro buses are a long term solution to the city air pollution problem. Currently, the cost of the bus is almost 5 times the price of a conventional diesel and it requires a complete renovation of bus depots to run them. Still, there are benefits to using HFC vehicles. The Citaro has zero urban emissions and was the only bus in this study to have a significant effect on NOx emissions. The HFC technology is still young and evolving. As fuel cells are mass produced, the prices will most likely drop making HFC buses more competitive with diesel buses from a cost perspective. Many other hydrogen production options are being tested using a variety of different feedstock. Ultimately, electrochemical engines have the potential for increased efficiency over combustion engines. Regardless of the pollution control devices utilized, it is very difficult to make up for gross inefficiency.

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[24] http://www.daimlerchrysler.com/index_e.htm?/news/top/2000/t00406_e.htm

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Appendix A: Key Conversions

Citaro buses

Capacity: 40kg hydrogen

Range: 250 km (155 mi)

efficiency:	3.88 mi/kg H2	0.2575 kg H2 / mi
	6.25 km/kg H2	0.1600 kg H2 / km

Hydrogen

7.43 kg = 1 MBtu

142 MJ = 1 kg

Diesel

7.1kg ~ 1 gallon

128,000 Btu ~ 1 gallon

Energy

1 Btu = 1,055 Joules

Distance

1 mile = 1.61 km

Appendix B: Acronym Definitions

AFC	Alkaline fuel cell
CBD	Central business district
CUTE	Clean urban transport for Europe
EU	European Union
HFC	Hydrogen fuel cell
ICE	Internal combustion engine
IEA	International Energy Agency
MCFC	Molten carbonate fuel cell
NREL	National Renewable Energy Laboratory
NYCT	New York City Transit
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane [fuel cell]
PM	Particulate matter
POX	Partial oxidation
SMR	Steam methane reformer
SOFC	Sulfur oxide fuel cell
THC	Total hydrocarbon
ULSD	Ultra low sulfur diesel