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Hennepin County's Experience with Heavy-Duty Ethanol Vehicles

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Executive Summary

From November 1993 to October 1996, Hennepin County, which includes Minneapolis, Minnesota, field-tested two heavy-duty snowplow/road maintenance trucks fueled by ethanol. The overall objective of this program was to collect data from original equipment manufacturer (OEM) alternative fuel heavy-duty trucks, along with comparable data from a similarly configured diesel-powered vehicle, to establish economic, emissions, performance, and durability data for the alternative fuel technology. The U.S. Department of Energy (DOE) provided funding for the project through the National Renewable Energy Laboratory (NREL) and the American Trucking Association (ATA) Foundation's Trucking Research Institute (TRI). This is the second of three ethanol demonstrations that NREL has funded. The first demonstration took place in Decatur, Illinois, at Archer Daniels Midland (ADM) Trucking, Incorporated. Applicable data from the ADM report also appear in this report.

The two trucks, International Paystar models F5070, were equipped with a U.S. emissions-certified Detroit Diesel Corporation (DDC) model 6V-92TA ethanol engine. The engine is rated at 300 horsepower and is fueled by E95, a fuel composed of 95% anhydrous ethanol and 5% light hydrocarbon denaturant. These ethanol trucks, along with an identical third truck equipped with a U.S. emissions-certified DDC 6V-92TA diesel engine, were operated year round to maintain the Hennepin county roads. In winter, the trucks were run in 8-hour shifts plowing and hauling snow from urban and suburban roads. For the rest of the year, the three trucks were used to repair and maintain these same roads.

As a result of this project, a considerable amount of data was collected on E95 fuel use, as well as maintenance, repair, emissions, and operational characteristics. Maintenance and repair costs of the E95 trucks were considerably higher primarily due to fuel filter and fuel pump issues. From an emissions standpoint, the E95 trucks emitted less particulate matter and fewer oxides of nitrogen but more carbon monoxide and hydrocarbons. Overall, the E95 trucks operated as well as the diesel, as long as the fuel filters were changed frequently.

This project was a success in that E95, a domestically produced fuel from a renewable energy source, was used in a heavy-duty truck application and performed the same rigorous tasks as the diesel counterparts. The drawbacks to E95 as a heavy-duty fuel take the form of higher operational costs, higher fuel costs, shorter range, and the lack of over-the-road infrastructure.

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Introduction

The American transportation sector uses more than 30% of all the energy consumed annually in this country. Conventional hydrocarbon fuels, primarily gasoline and diesel fuel, represent the current sources of energy for transportation. Naturally occurring hydrocarbon reserves, however, exist in finite quantities and are very limited in geographic extent. Proven worldwide hydrocarbon reserves are being depleted faster than they are being discovered, and more than 50% of the petroleum used for energy in America each year is imported.

Heavy-duty trucks and urban transit buses account for a significant portion of the U.S. transportation sector. For the most part, these vehicles are powered by compression-ignition diesel fuel engines, which typically emit high levels of oxides of nitrogen (NO_x) and black particulate smoke during operation. The black smoke is not only unsightly, but has proven to be carcinogenic.

Ethanol, also known as ethyl alcohol, is a renewable energy resource generated by biologically fermenting simple glucose sugars. At this time, the ethanol industry in the United States has an annual production capacity of approximately 1.6 billion gallons. Although ethanol can be made from a wide variety of feedstocks, corn is generally used to produce ethanol in this country because of its abundance and relatively low price considering the amount of ethanol that it yields.

Ethanol has been successfully used as an additive in gasoline for many years. This fuel formulation, also called Agasohol,≅ is composed of 90% unleaded gasoline and 10% ethanol. In this application, ethanol can be considered a petroleum extender, an octane enhancer, and an oxygenate additive to gasoline.

From an emissions standpoint, numerous studies have shown that gasoline blended with 10% ethanol reduces carbon monoxide (CO) emissions from internal combustion engines by as much as 25%. Ethanol-blended gasolines are being used in many of the nation=s cities currently in nonattainment for CO levels. Until recently, very little was known, however, about emissions from vehicles designed to operate on higher percentage blends of ethanol fuel.

Until the 1990s, the use of high-percentage blends of ethanol fuels for transportation was very limited. Henry Ford was the first American automobile manufacturer to see the potential of ethanol as a fuel in the early 1900s. Many of his early Model A automobiles were capable of operating on ethanol fuel rather than gasoline. Since then, only a few isolated testing programs (most performed by vehicle and engine manufacturers and containing proprietary information) have been designed to test, demonstrate, and evaluate the use of ethanol as a viable alternative transportation fuel in light-, medium-, and heavy-duty vehicles.

The overall objective of this project was to demonstrate and collect data on the use of a high-percentage ethanol blend of fuel in a heavy-duty truck application. This project also represents the first public demonstration of the use of ethanol fuels as a viable alternative to conventional diesel fuel in a heavy-duty snowplow/road maintenance application.

Background

It is an impressive sight to see a 60,000-pound snowplow rolling back a layer of snow in a perfect arc to the roadside. Snowplowing is an extremely demanding assignment that can test the limit of a heavy-duty truck design. Snowplow/maintenance trucks work as part bulldozer and part dump truck, often in extreme cold, loaded to their capacity, cutting through ice and snow. Hennepin County in Minneapolis, Minnesota, offers a perfect cold weather environment for testing alternative fuel heavy-duty trucks.

Hennepin County is an urban county of a little more than 1 million people; it makes up about half the Minneapolis/St. Paul metropolitan area. The city of Minneapolis is the county seat. The county has largely typical midwestern topography with a mix of flat farmland, lakeshore, and moderate rolling hills. Much of the county road system comprises multi-lane city streets with curb and gutter, medians, center islands, multiple turn lanes, and traffic control devices. A small portion of the system remains essentially rural with two-way roads, unpaved shoulders, and little in the way of traffic control other than an occasional stop sign.

In 1993, the county began field-testing two ethanol-powered trucks with an identically specified diesel control truck. The county vehicle numbers were 3221, 3228, and 3220, respectively. For the remainder of this report, we will refer to them as ethanol #1, ethanol #2, and diesel control, respectively. The demonstration ran for 3 years from November 1993 through October 1996. The trucks were used by the Department of Public Works Division of Road and Bridge Maintenance Operations. To ensure uniformity and consistency in reporting data from drivers, we asked for volunteer drivers who were willing to stay with the trucks for the full 3 years of the study. We were fortunate that long-term, experienced, and proficient drivers volunteered for the project. Collectively, the three drivers have 62 years of experience driving heavy-duty trucks. They provided weekly data on the performance of the trucks and on the fuel usage. The drivers completed a standard form provided by the ATA, shown in Appendix 1.

All the heavy-duty trucks owned by Hennepin County are used to maintain the county's highway system. This system includes about 600 miles of roads with about 1600 lane-miles.

The Class 8 dump trucks are equipped in the winter with a 12-ft reversible front plow, a 10-ft underbody scraper blade, and a tailgate spreader.

The trucks are International Paystar 5000, model F5070, with the following specifications:

GVWR	49,500	Transmission: Fuller RTX11708LL
Wheelbase	188 in.	8 speed w/double low
Cab-to-Axle	120 in.	14.56:1 max. reduction
Front Axle	18,000 & set back	
Rear Axle	38,000 4.78 ratio	Body: 15-ft Aluminum
Engine	6V-92TA DDEC	Telescopic Hoist
	300 h.p. @ 2,100 rpm	Engine Power Take Off (PTO)
	50 ft. lb. torque @ 1,300 rpm	

This configuration is standard for county dump trucks, and this truck is the workhorse of the county fleet. The three Navistar trucks were purchased with non-U.S. emissions-certified DDC 6V-92TA diesel engines. Navistar, the chassis OEM, did not offer the ethanol or diesel versions of the DDC 6V-92TA with U.S. emissions certification as a commercial option. Consequently all three trucks were repowered with U.S.-emissions-certified 6V-92TA engines by the local DDC dealer; two with the ethanol version and one with the diesel.

All the heavy-duty trucks owned by Hennepin County are purchased primarily for the snowplowing function. The complete snow and ice control operation is essential to maintaining a transportation network in Minnesota. The typical winter duty cycle consists of snowplowing, snow removal, and ice control. For this reason, the county road system is divided into segments so that one truck can plow the full segment in one 8-hour shift. One truck and driver are assigned to each of these segments or routes. The routes for the three trucks in this demonstration project were:

- Diesel control—The most rural route in the project. At least half the route consisted of two-lane roads with no curb and gutter. The remainder of the route was a mix of two-lane roads without curb and gutter, and two-lane or four-lane suburban streets with curb and gutter.

- Ethanol #1—All urban streets, four lanes with both right and left turn lanes, traffic signals, and curb and gutter.

- Ethanol #2—Mostly urban streets, four lanes with turn lanes, traffic signal, curb and gutter. Some sections are two lanes with no curb and gutter.

Appendix 2 contains a map of Hennepin County and these routes.

In a standard duty cycle, the drivers are called to start plowing at 2:45 a.m. The driver loads his truck and begins to plow, clearing the main road lanes first and then spending the rest of the – 8-hour shift plowing the shoulders or clearing the roadway full width to the curbs and any turn lanes. The beauty of the dump truck, of course, is that the driver can spread salt/sand mix or salt to control ice while he is plowing. Subsequent shifts will either repeat this cycle, or move into more intensive clean-up plowing, either on an early start or during regular work hours.

Other typical winter work cycles include hauling materials from one location to another. Salt, for example, is frequently moved from the county's main supply, at the department's headquarters, to the outlying truck stations so those facilities have adequate quantities for their snow removal activities. When there is no snow, the drivers may begin by patrolling their assigned routes looking for icy spots and salting them. When the plowing and salting is done, the drivers will often assist with Public Works projects, which generally entail hauling aggregates, street sweepings, dirt, trees and brush, broken and removed concrete, construction refuse, gravel fill, and snow.

Later in the winter, when the snow has narrowed the streets, the trucks help in joint city/county operations to make the streets more passable. A city identifies the street most in need of widening, and provides a grader, an operator, and other laborers. The grader cuts out the snow/ice that has accumulated at the road edge and forms it into a windrow. The county provides a large loader-mounted snow blower and several tandem-axle dump trucks. The blower moves down the windrow and blows the snow into the dump bodies of the trucks. One truck follows another, pulling under the blower shoot as soon as the lead truck is loaded and out of the way. The combined operation efficiently widens the streets. The trucks then haul and dump the snow in a city-designated storage area.

The winter weather during the 3-year project is described below.

1993-94	Total snowfall: 55.7 inches Average temperature: 12.4 degrees F Temperature range: -26 to 34 degrees F
1994-95	Total snowfall: 29.6 inches Average temperature: 22.6 degrees F Temperature range: -5 to 38 degrees F
1995-96	Total snowfall: 55.5 inches Average temperature: 16.7 degrees F Temperature range: -16 to 36 degrees F

In the summer, these trucks become essential tools in the county's paving and pavement maintenance programs. As a rule, the county contracts most major road work except for bituminous overlay and seal coat programs, which are completed by county employees and equipment. In this operation trucks make continuous rounds to haul millings (created during resurfacing process) to a disposal site, deliver hot asphalt to the paver, or take seal coat chips to the seal coating operation.

The summer and winter work cycles described above were consistent throughout the demonstration and were performed by the diesel control and ethanol trucks alike.

Engines

The DDC Model 6V-92TA (with the TA denoting turbocharged and aftercooled) powerplant was selected as the engine for the two ethanol trucks. The 6V-92TA alcohol fuel engine is a vee-configuration, six cylinder, two-cycle motor capable of producing up to 300 horsepower. The methanol version of the engine was first developed in 1986 and emissions certified (by the U.S. Environmental Protection Agency [EPA] and the California Air Resources Board [CARB]) in 1991 for use in urban transit buses in California. DDC=s previous experiences with the methanol 6V-92TA engine aided the development and subsequent emissions certification of the ethanol --6V-0-92TA in 1992. DDC considered both alcohol engines and standard production engines.

DDC selected the 6V-92TA engine to develop as an alcohol fuel engine for at least two reasons: (1) the 6V-92TA diesel engine was used in about 80% of the urban transit buses currently on the road, and (2) the two-cycle engine was easier to convert to alcohol fuel than a four-cycle engine. A two-cycle engine removes combustion products close to the bottom of the piston stroke by means of a blower that pushes out the exhaust gases (called Ascavenging≅). Scavenging causes mixing of hot exhaust gases with the new fuel mixture to be combusted. The presence of these hot exhaust gases in the cylinder raises the fuel temperature, making compression ignition of low-cetane-number fuels (such as ethanol) possible. As a result, two-cycle engines have a distinct advantage over four-cycle engines in compression igniting fuel with high auto-ignition temperatures.

DDC also modified some of the components on the ethanol 6V-92TA engines. The first of these major modifications was to the Detroit Diesel Electronic Controls (referred to as DDEC II), which contains the electronic control module (ECM) and the electronic unit (fuel) injectors (EUI). The ECM is the on-board computer for the engine that controls various engine operations under continuously varying conditions to optimize performance, fuel economy, and emissions. The ECM receives electronic signals from the truck=s driver in addition to engine-mounted sensors. The electronic hardware in the ECM contains a PROM (Programmable Read Only Memory) encoded with the specific engine performance characteristics (such as horsepower rating, torque curve, and maximum engine speed. To use ethanol fuel, the ECM must be specifically programmed for ethanol fuel at the factory or by a DDC field engineer.

The second part of the DDEC II unit, the EUI, contains an electronically controlled solenoid valve that meters and times fuel input to the cylinders. Because ethanol contains only about 60% of the energy of diesel fuel per unit volume, more ethanol fuel is required to generate the same amount of power in the engine. This is accomplished by using two larger (relative to diesel) ethanol-resistant fuel pumps and by increasing the diameter of the holes in the injector tip. The EUI can then inject the proper amount of ethanol fuel into the cylinder at the right time without reducing the engine performance.

Next, the bypass air system was modified. This system provides the correct metering and mixing of retained hot exhaust gases and fresh air in order to achieve the proper ethanol compression-ignition temperature. The bypass air system is controlled by the DDEC II unit and changes system settings based on changes in engine operating conditions.

The ethanol 6V-92TA engines also use a glow plug system that has been modified for use with the DDEC II system. The glow plugs are electronically heated and are used to help start the engine. The glow plugs remain on (heated) for 1 minute prior to starting the engine and remain on until the engine coolant reaches normal operating temperature.

Another major modification to the ethanol engine is an increased compression ratio compared to the conventional diesel version. The ethanol engine has a compression ratio of 23:1 compared to 18:1 for the diesel. This increase is needed to ensure complete combustion of the ethanol fuel in the cylinder and to maximize engine performance and torque.

Finally, the fuel systems of the two ethanol trucks were modified. Because ethanol is more corrosive to certain metal, plastic, and rubber parts, stainless-steel fuel tanks and fuel lines were added.

E95 Ethanol Fuel

Ethanol (also called ethyl alcohol) is an oxygenated hydrocarbon with the chemical formula of C2H5OH. Ethanol is a by-product of the fermentation of simple glucose sugar by yeasts. Anhydrous ethanol contains 76,000 Btu of energy per gallon. Energy contents and other properties of ethanol are compared to other fuels in Table 1.

The Aproof≅ of an alcohol is defined as twice the percentage of alcohol in the solution. For example, a mixture of 90% pure ethanol and 10% water is referred to as A180-proof≅ ethanol.

For all practical purposes, there are two types of industrial-grade ethanol: anhydrous and hydrated. Anhydrous ethanol is defined as at least 99.5% pure ethanol, with less than 0.5% water by volume. Anhydrous ethanol is also called A200 proof≅ ethanol or gasoline grade ethanol, as this is the concentration of ethanol blended with gasoline to make Agasohol.≅ Hydrated ethanol is any other ethanol blend containing more than 0.5% water by volume. In either case, fuel-grade ethanol must be denatured with 2% to 5% denaturant to make it unfit for human consumption. Otherwise, it is highly taxed by the U.S. Department of Treasury, Bureau of Alcohol, Tobacco, and Firearms (ATF) as beverage-grade alcohol. Some of the denaturants commonly used include methanol, benzene, toluene, natural gasoline, kerosene, and unleaded gasoline.

The cetane number, also found in Table 1, is a measure of the ease (or difficulty) by which a fuel can be compression ignited. Fuels with high cetane numbers have low autoignition temperatures and short ignition delay times. Ethanol has a low cetane number, less than 5, compared to 40 to 55 for diesel fuel. This indicates that the alcohol fuels have higher autoignition temperatures relative to diesel fuel. This is reflected in the autoignition temperatures of ~600 degrees F for diesel fuel and 793 degrees F for ethanol. Hence, the requirement of glow plugs to autoignite the E95 fuel in the 6V-92TA engines.

Diesel fuel is a complex mixture of hydrocarbons, and the composition can vary from Abatch to batch.≅ Because of this variation, the energy content of #2 diesel fuel is assumed to average about 127,000 Btu per gallon (Btu/gal).

The fuel formulation used in the two 6V-92TA truck engines in this project is a blend of 95% anhydrous ethanol and 5% denaturant. This fuel is called E95, but it can also be called E(d)-100, with the Ad≅ standing for denatured. For consistency, the term E95 will be used throughout this report whenever 95% anhydrous ethanol and 5% denaturant fuel is discussed.

DDC supplied an E95 fuel specification for use with its 6V-92TA engines (shown in Appendix 3), which includes an optional lubrication additive called ALubrizol≅. One problem encountered with using ethanol fuels is that they do not have the inherent lubricating properties

Table 1. Comparison of Properties of Potential Diesel Fuel Components*

Property	DF-2 Diesel	Fischer-Tropsch	Bio-diesel	Gasoline	CNG	Propane HD-5[h]	Methanol	Ethanol	Methylal	Dimehtyl ether	Diethyl ether
Formula	Hydrocarbons ~C10 - ~C21	Principally C_nH_{2n+2}	Various oils and esters	Hydrocarbons C4 – C9	Principally CH_4	Principally C_3H_8	CH_3OH	C_2H_5OH	$CH_3OCH_2OCH_3$	CH_3OCH_3	$C_2H_5OC_2H_5$
Boiling Point, ºF	370 – 650	350 – 670	360 – 640	80 – 437	n.a.	n.a.	149	172	107	-13	94
Reid Vapor Pressure, psi @ 100ºF	<0.2	n.a.	n.a.	8 – 15	n.a.	170	4.6	2.3	12.2[c]	116	16.0
Cetane Number	40 - 55	>74	>48	13 – 17	low	low	low	<5[b]	49	>55	>125[a]
Autoignition Temperature, ºF	~600	~600	-	495	990	870	867	793	459	662	320
Stoichiometric Air/Fuel Ratio, Wt./Wt.	15.0	15.2	13.8	14.5	16.4	15.7	6.45	9.0	7.1	8.9	11.1
Flammability Limits, Vol. %: Rich	7.6	-	-	6.0	13.9	9.5	36.9	19.0	14.9[c]	27.0[d]	9.5 36.0[d]
Flammability Limits, Vol. %: Lean	1.4	-	-	1.0	5.0	2.4	7.3	4.3	3.3[c]	3.4[d]	1.9[d]
Lower Heating Value, Btu/lb	18,200	18,600	16,500	18,500	20,750	19,940	8,570	11,500	10,200	12,100	14,600
Lower Heating Value, Btu/gal	128,700	121,300	120,910	115,400		83,900	56,800	76,000	73,000	66,600	86,500
Lower Heating Value, Btu/SCF					1,033						
Viscosity, centipoise at (temp) ºF	40(68)	2.1(100)	3.5(100)	3.4 (68)	-	-	0.59 (68)	1.19(68)	-	-	0.23(68)
Specific Gravity @ 60ºF	0.860	0.783	0.880	0.750	-	0.506	0.796	0.794	0.86	0.66	0.714
Density, lb/gal	7.079	6.520	7.328	6.246	-	4.21	6.629	6.612	7.16	5.50	5.946
Note (See below)	e	h	b	e	f	h	e	e	c	b	b

***Table compiled by N.R. Sefer, Southwest Research Institute.**

a. Inferred from ignition delay
b. Recent measurement at Southwest Research Institute
c. Naegeli, D. W., and Weatherford, W. D. Jr. "Practical Ignition Limits for Low Molecular Weight Alcohols," Fuels 68, 45 (1989)
d. NFPA 325 M, *Fire Hazard Properties of Flammable Liquids, Gases, Volatile Solids* (1977), Copyright 1977 National Fire Protection Association, Inc. Batterymarch Park, Quincy, MA 02269
e. Table on gasoline and gasohol from *Alcohols and Ethers,* API Publication 4261, second edition, (July 1988).
f. Liss, W.E., et al., "Variability of Natural Gas composition in the US", GRI 92/0123, (March 1992).
g. *Alternative Fuels Special Report, Diesel Progress, Engines and Drives*, (December 1993).
h. Composition information from ASTM D 16353 Standard Specification for LPG. Calculations after Perry's Chemical Engineers' Handbook, 6th ed., (1984).

of petroleum-based fuels. To ensure upper cylinder lubrication, an additive developed in California for the methanol buses, Lubrizol, is added to fuel in very low concentrations. The recommended amount of Lubrizol is 0.06%, by volume, in the fuel mixture. Hennepin County was able to contract an E95 fuel supplier and confirm the DDC recommended fuel specifications, including the specified amount of Lubrizol.

Data Collection

The overall objective of this program was to collect data from OEM alternative fuel heavy-duty trucks, along with comparable data from a similarly configured diesel-powered vehicle to establish emissions, performance, and durability data for alternative fuel technology. The data were collected from drivers and mechanics on paper forms provided by TRI, and then forwarded to NREL. TRI compiled the data and entered the information into NREL=s Alternative Fuels Data Center (AFDC) via modem.

Fuel Economy: E95 versus Diesel

Assuming #2 diesel fuel contains about 127,000 Btu/gal and E95 fuel contains 78,000 Btu/gal, the ethanol trucks should travel about 60% of the distance the diesel trucks travel on a gallon of fuel, if the trucks have the same thermal efficiency. On a volume basis, the average fuel economy over the project was 4.6, 2.6, and 2.2 miles per gallon (mpg) for the diesel control, ethanol #1, and ethanol #2, respectively (shown in Figure 1). The ethanol trucks traveled about 48% to 57% of the distance traveled by the diesel trucks. This indicates that the thermal efficiency of the ethanol trucks was somewhat less than that of the diesel truck. Although plowing snow represents only a fraction of the miles driven in a month, it is not unusual to see the overall fuel economy of a truck drop by one or two miles per gallon in the winter months. Both ethanol trucks dropped to 1 mpg at some time during the project.

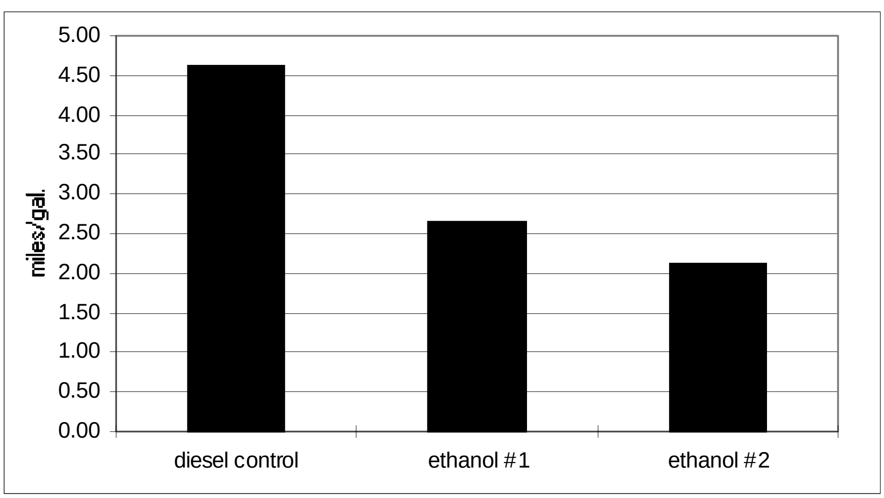

Figure 1. Average Fuel Economy

Fuel Cost: E95 versus Diesel

The cost of ethanol fuel is high, about twice as much as diesel. In the beginning of the project, diesel cost the county $0.80/gallon and ethanol $1.40/gallon. At the project end, diesel cost $0.90/gallon and ethanol cost $1.80/gallon. The county cost is a delivered price for bulk purchases and includes a state fuel tax of $0.20/gallon. The county does not pay federal fuel tax. The most comprehensive picture of fuel costs is illustrated in the comparison of fuel cost per mile by year (shown in Figure 2). This graph indicates that, from 1994 on, the E95 fuel cost was three to four times more (per mile) than the diesel fuel cost.

Application of the alcohol tax credit can greatly reduce the cost of ethanol and the operation costs of a fleet of ethanol vehicles. Congress developed the alcohol fuel credit in response to the energy crisis of the late 1970s and early 1980s. The intent was to foster growth of the alcohol industry by subsidizing non-petroleum-based alcohol used as fuel so the cost for the end user would be comparable to traditional hydrocarbon fuels. The tax credit is accomplished in two ways: (1) by granting a $0.054 per gallon partial excise tax exemption for 10% alcohol blended fuels (gasohol) and (2) by allowing a $0.54 per gallon income tax credit for ethanol used as a fuel. The income tax credit is available to taxpayers who: (1) Aproduce≅ or blend an alcohol mixture, or (2) sell or use for business 100% straight alcohol placed in the vehicle=s fuel supply tank by the taxpayer. Because E95 fuel is composed of 95% ethanol and 5% denaturant, 95% of the $0.54 (or $0.513 per gallon E95) per gallon tax credit can be taken. However, because Hennepin County is a state agency and exempt from federal taxes, it cannot file for the alcohol tax credit.

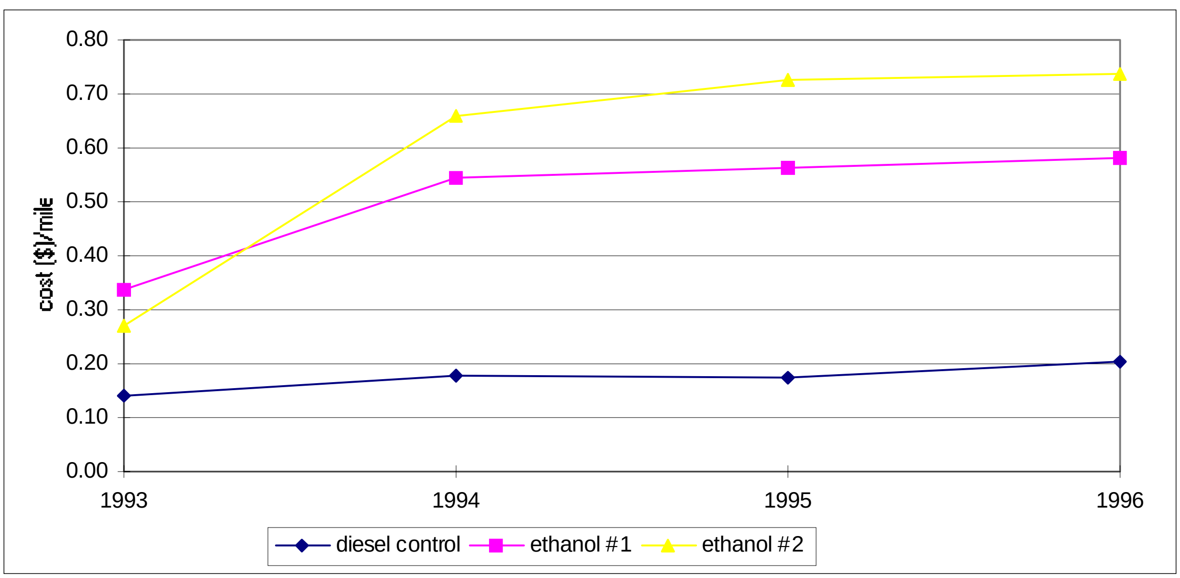

Figure 2. Fuel Cost per Mile by Year

E95 Availability

Minneapolis-St. Paul is a major metropolitan center in the agricultural Midwest. The area has a history of supporting ethanol production and its use as an automotive fuel. There has been a long-standing promotion of gasohol, a 10% blend of ethanol and unleaded gasoline. The county has used gasohol in its automotive fleet since 1983. In addition, the cities are also a moderate nonattainment area for carbon monoxide and the Clean Air Act requires that this area use an oxygenated fuel during winter months. For this application, ethanol has been the oxygenate of choice. These factors have combined to produce plentiful supplies of ethanol in the metropolitan area.

The county bid this fuel the same as all other bulk fuel purchases and never experienced any delays in delivery. The supplier was able to provide E95 that met the manufacturer's specification, as shown in Appendix 3, with the recommended additive ALubrizol≅ (part no. 23509970). The Lubrizol is added to the fuel as a detergent, to eliminate lube oil contamination of injectors, and to increase fuel lubricity. The county is convinced it did not have any maintenance problems that resulted from poor fuel quality.

Maintenance and Repair Data

The total maintenance and repair cost for the diesel control truck was $21,549 as opposed to $26,101 and $22,512 for ethanol #1 and ethanol #2, respectively (shown in Figure 3). The higher costs for the ethanol trucks were evident in each year throughout the project except in 1996 (shown in Table 2). The higher cost for the diesel control in 1996 was primarily due to component replacement costs, which is directly related to the difference in accumulated mileage.

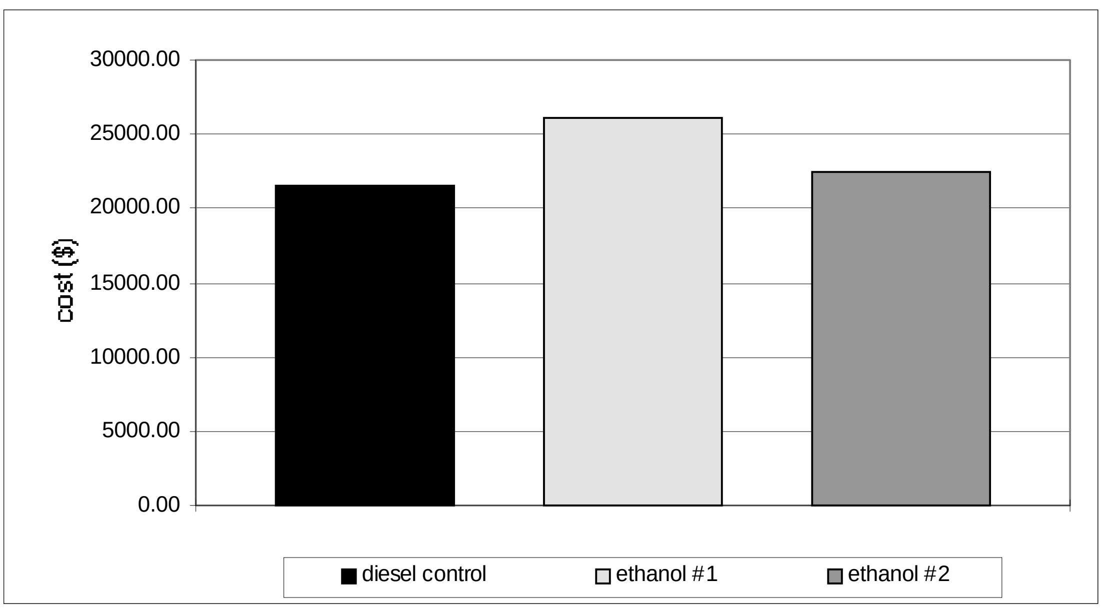

Figure 3. Total Maintenance Cost by Truck

The usage of the three trucks did vary more than intended. The mileage on the three trucks at end of the project was 81,861 for the diesel control, 61,002 for ethanol #1, and 32,526 for ethanol #2. The reason for the unexpected variance was that we had, for consistency, assigned specific drivers to each vehicle for the duration of the test. The lesser availability of one of the drivers during the project caused a difference in truck usage. To factor in the difference in accumulated mileage, the total maintenance cost per mile was charted for the three trucks. Over the life of the project, the costs per mile were $0.26, $0.43, and $0.69 for the diesel control, ethanol #1, and ethanol #2, respectively (shown in Figure 4).

Table 2. Repair Costs by Year and System

	1993 Repair Costs			1994 Repair Costs		
	Diesel control	ethanol #1	ethanol #2	diesel control	ethanol #1	ethanol #2
Cab/Body	0.00	21.50	215.02	47.95	1,431.63	448.42
PM'S	180.51	0.00	0.00	379.26	401.91	329.32
Chassis GRP	553.23	918.30	75.25	198.66	645.41	556.18
Drive Train	0.00	0.00	0.00	258.00	64.50	96.75
Electrical	0.00	0.00	0.00	1,406.97	803.65	1,352.35
Power Plant	62.09	807.94	402.08	488.00	2,157.12	1,905.16
Accessories	187.22	260.66	238.00	1,865.73	2,802.66	2,630.36
Special Appl.	78.81	238.14	143.31	0.00	129.00	0.00
Hydraulics	107.50	0.00	21.50	190.36	374.11	237.95
Misc. Work	4,256.39	4,312.27	4,526.91	1,061.75	778.20	1,055.20
Misc.-New Prep	377.17	0.00	0.00			
Total-Prep	1,546.53	2,246.54	1,095.16			
Total	**5,425.75**	**6,558.81**	**5,622.07**	**5,896.68**	**9,588.19**	**8,611.69**

	1995 Repair Costs			1996 Repair Costs		
	Diesel control	ethanol #1	ethanol #2	diesel control	ethanol #1	ethanol #2
Cab/Body	630.26	383.74	270.95	1,008.75	671.06	577.01
PM'S	401.21	570.29	519.43	187.22	232.50	239.65
Chassis GRP	1,425.38	299.11	451.47	2,102.76	2,165.10	183.88
Drive Train	68.55	64.50	86.00	21.50	296.64	21.50
Electrical	745.04	1,491.89	1,289.03	1,293.96	799.17	912.92
Power Plant	983.16	1,615.15	384.22	1,411.54	1,197.77	1,775.22
Accessories	534.36	781.25	630.67	1,058.95	680.97	601.00
Special Appl.	0.00	179.34	53.75	32.25	64.50	251.18
Hydraulics	343.15	103.24	334.71	654.25	560.87	643.37
Misc. Work	704.99	1,079.91	2,325.26	498.90	1,028.81	1,253.76
Total	**5,836.10**	**6,568.42**	**6,345.49**	**8,270.08**	**7,697.39**	**6,459.49**

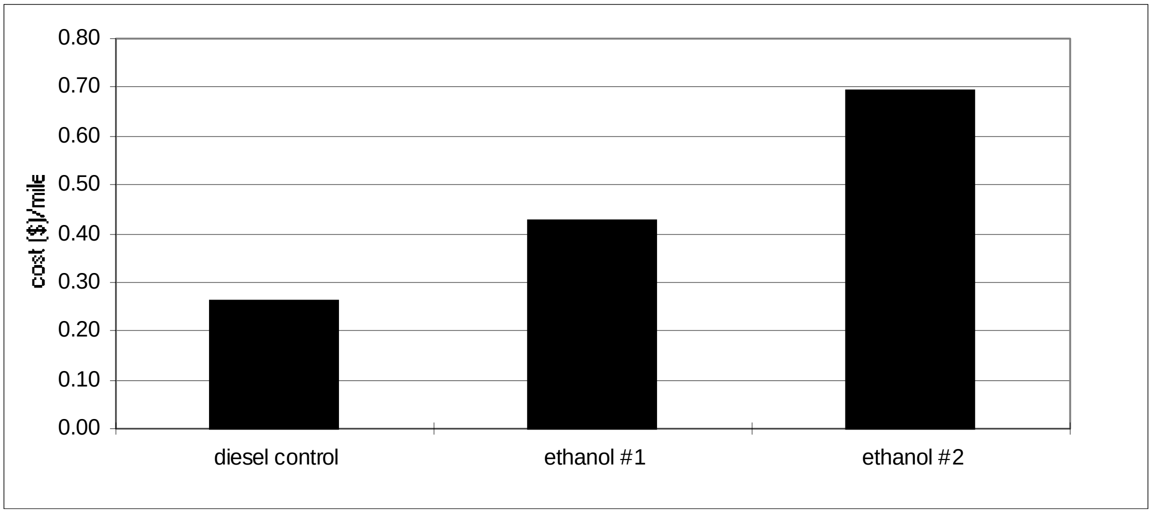

Figure 4. Total Maintenance Cost per Mile

To determine whether these costs resulted from the alternative fuel, the repair costs were broken down by truck systems. Table 3 shows the total maintenance cost by truck system. The detailed components that make up these systems can be seen in Appendix 4, which details repair costs by system and year. The most expensive systems for the 3 vehicles were chassis, for the diesel control, and power plant for both ethanol #1 and ethanol #2. Power plant maintenance and repair ranked number 4 for the diesel control. This can also be seen graphically in Figure 5.

Table 3. Total Maintenance Cost by Systems

	diesel control	ethanol #1	Ethanol #2
Cab /Body	1,686.96	2,507.93	1,511.40
PM'S	1,148.20	1,204.70	948.36
Chassis GRP	4,280.03	4,027.92	1,406.82
Drive Train	348.05	425.64	204.25
Electrical	3,445.97	3,094.71	3,554.30
Power Plant	2,944.79	5,777.98	4,466.68
Accessories	3,646.26	4,525.54	4,100.03
Special Appl.	111.06	610.98	448.24
Hydraulics	1,295.26	1,038.22	1,237.53
Misc.-New Prep	2,642.81	2,886.92	4,634.22
Total	**21,549.39**	**26,100.54**	**22,511.83**

The difference in maintenance and repair costs between the diesel control and the ethanol trucks is mainly attributable to the E95 fuel. Most of the components that are unique to the ethanol trucks are in the power plant system. The few remaining ethanol-specific components are categorized in cab/body or electrical and are insignificant relative to the non-ethanol component costs that make up those systems.

Most of the power plant repairs on the ethanol trucks were fuel system repairs. Both the primary and secondary fuel filters had to be replaced frequently. The fuel filters for the ethanol engines are much less porous than the diesel fuel filters to stop fine dirt from damaging the injectors and cylinders. The DDC 6V-92TA ethanol engine requires a 10- micron primary and a 1-micron secondary filter, where the DDC 6V-92TA diesel engine only requires a 40-micron primary and 5-micron secondary filter. Because of the smaller porosity, ethanol filters tend to clog more frequently from dirt and debris that enter the fuel system in the normal course of operation. The finer filters are required because ethanol does not have the lubricating properties inherent to petroleum-based fuels. Consequently, engines that burn ethanol are far less tolerant of impurities. We replaced the filters once each year on the diesel truck compared to eight or nine times for the ethanol trucks. Although the primary ethanol filter price came down $72 during the project, the ethanol filters, primary and secondary, were still $107 more expensive than the diesel filters. In the end, the primary and secondary ethanol filters cost $73 and $50, respectively. The diesel primary and secondary cost $8 each. The total costs for fuel filter replacements were $48, $1,843, and $1,667, for the diesel control, ethanol #1, and ethanol #2, respectively.

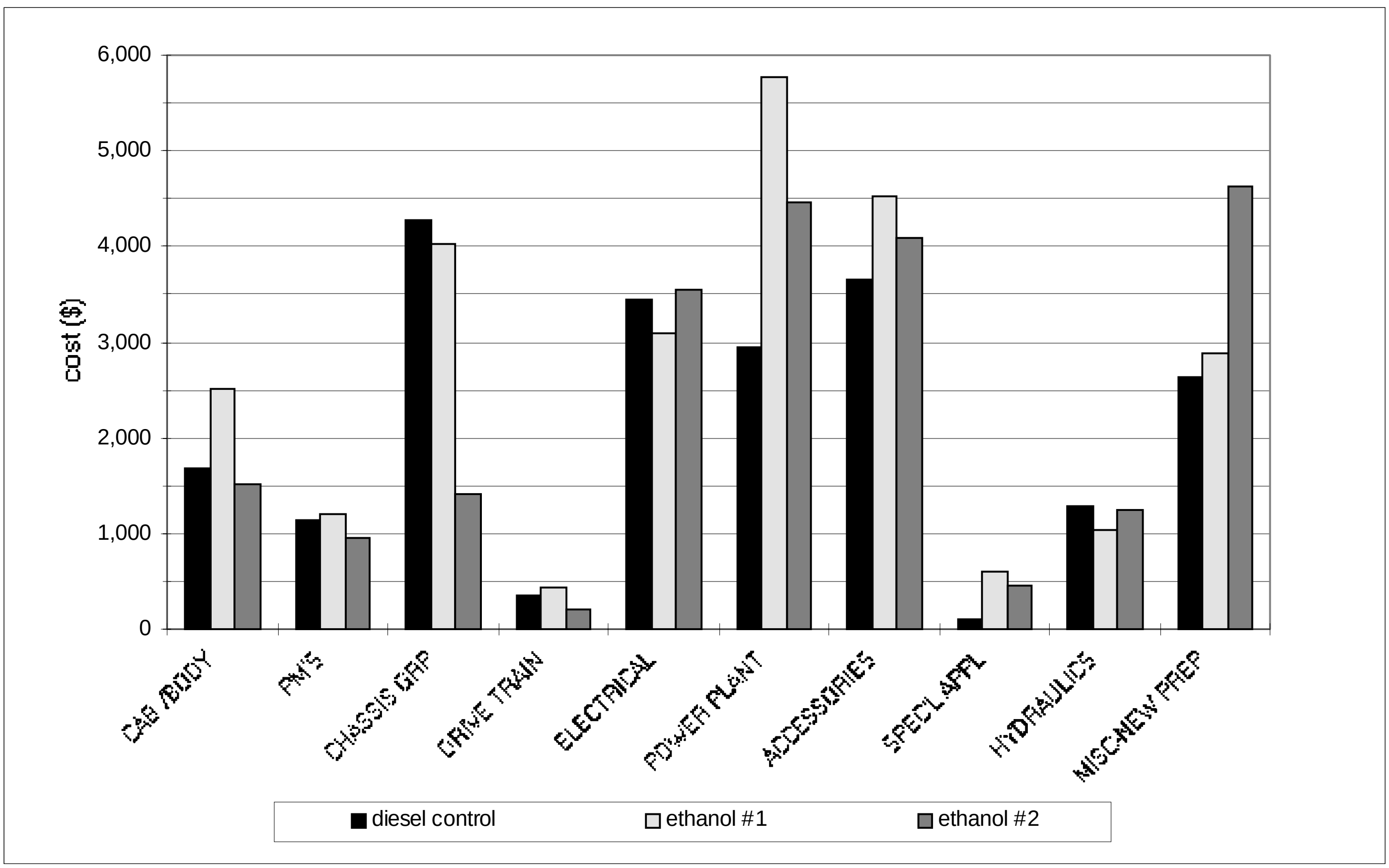

Figure 5. Total Maintenance Cost by Systems

The ethanol trucks also experienced fuel pump and fuel sending unit problems. Ethanol fuel pumps differ from diesel fuel pumps. They need to deliver almost twice as much fuel as a diesel fuel pump as a result of the lower heating value of ethanol. They also require special alcohol-resistant components. Both ethanol trucks required fuel pump replacements during the project. The fuel pump was replaced under warranty on ethanol #1 and the county replaced the fuel pump on ethanol #2. The total bill for this one repair was $1,229, making it one of the more expensive repairs. Both trucks also had recurring problems with the fuel sending units and other miscellaneous fuel system repairs. In total, fuel system repair costs for the ethanol trucks were $2,782 and $2,623, compared to $205 for the diesel truck. These costs account for most of the difference in repair costs for the three trucks.

Both ethanol trucks also had recurring problems with the electronic engine controls, but the problem was particularly troublesome on ethanol #2. The self-diagnostic codes (instrument panel warning system) repeatedly displayed false alarms for the cooling system and crankcase oil pressure. The county referred these problems to the dealer because they developed while the trucks were under warranty. The initial response from the dealer was that these were indeed false codes and the ECM was reset. When the false codes reoccurred, the dealer thought the problem was caused by bad sensors or a programming glitch with the ECM. Neither of these possibilities developed into a permanent fix and eventually the drivers came to just ignore the warnings.

In 1996, the last year of the project, both ethanol trucks started to require glow plug replacement. Glow plug replacement at this mileage is premature relative to diesel engines. Ethanol #1 had three glow plugs replaced at a total cost of $324.56 and ethanol #2 had four glow plugs replaced at a total cost of $332.97

Although it is not being attributed to E95, it should be noted that ethanol #1 had a catastrophic engine failure at the end of the project. A cylinder head gasket failure allowed antifreeze into the cylinder. According to the engine dealer, the failure of the head gasket could have been caused by a gasket material failure, incorrect cylinder liner height, or incorrect head bolt torque. Although none of these failures can be discounted, the most likely cause is a failure or flaw in the gasket material. We do not believe the failure was fuel related.

Also worth noting, the new vehicle preparation costs are not included in these repair figures. These costs—$3,879, $4,312, and, $4,527 for the diesel control, ethanol #1, and ethanol #2, respectively— are part of the cost of placing a truck in service and are not related to the alternative fuel. Mounting snow control equipment is quite labor intensive and staff time accounts for most of these costs. Because the preparation costs overstate the cost of repairs in the "miscellaneous" category, they were not included in the repair cost analysis.

The complete repair history for all trucks, arranged chronologically and by truck systems, is given in Appendix 5.

Driver Opinion

The fuel delivery system problems were the most troublesome to the drivers. As the fuel filters began to clog, drivers noted hard starting, stalling, hesitation, and cutting in and out. The more clogged the filters became, the more frequently the problems occurred. Sometimes the trucks would stall in traffic, creating a tense situation for the driver.

Fuel range was also a problem for the drivers. The drivers frequently expressed concern about having enough fuel to complete their routes. Although neither of the E95 trucks ever ran out of fuel, the drivers retained a level of nervousness about the short range, especially during the winter months.

The electronic problems were mildly annoying. The recurring false codes weakened the credibility of the diagnostic instrumentation and frequent trips to the engine dealer disrupted the normal work cycle. In the end, the drivers ignored the error messages.

Finally, the drivers reported a lack of power in the ethanol trucks. During the most strenuous assignments, such as hauling sand or aggregate on a grade, the drivers contended that the ethanol trucks had less power than the diesel. However, it should be noted that the county did not quantitatively substantiate these opinions.

Overall, when asked, the drivers stated they would not pick the ethanol trucks if given a choice of which truck to drive.

Oil Sampling

The county has been using oil analysis on its heavy equipment for about 20 years, and has had good luck in extending the oil change interval and in detecting engine problems early. The oil analysis for the ethanol trucks went smoothly with no abnormalities in all instances but one. The last oil sample on ethanol #1 revealed serious problems. However, by the time we received the results, the engine had already failed. As indicated previously, a head gasket failure allowed antifreeze into one of the cylinders causing the failure. Oil analysis results are shown in Appendix 6.

Operational Data

Hennepin County has considerable experience with alcohol fuels including storage and dispensing systems. We have used gasohol since 1983, and experienced all the early system problems inherent with alcohol fuels. In 1986, the county replaced the storage tanks as well as the pumping equipment. Gasohol had been in these tanks exclusively until the E95 demonstration when the county converted one tank solely to E95. This demonstration project lasted 3 years, and we did not have any of the fuel dispensing problems that we had experienced in the early days of gasohol use. We did not replace any storage or pumping components throughout the project term, nor were there any reports from employees of any problems related to the E95.

Ethanol fuel is as easy to use as any conventional petroleum fuel. For Hennepin County, the conversion could not have been easier. There were no capital costs and no lengthy construction or installation projects. In fact, from the drivers' point of view, the larger fuel tank, fill time, and different fuel smell are the only differences they noticed at the pump.

In terms of cold weather fueling, E95 performed better than diesel. The county has experienced, during extreme cold weather, some gelling problems when fueling with diesel, which was not evident with E95. Hennepin County did not experience any cold starting problems with E95 because all the snow plow units were stored in heated garages.

Safety

The county did not experience any safety incidents with E95. Because it is not extremely toxic even in the denatured state (95% ethyl alcohol, 5% unleaded gasoline), it does not require any precautions beyond those needed for gasoline.

Emissions

West Virginia University (WVU) tested the emissions of the trucks twice during the project. The WVU transportable heavy-duty truck dynamometer was brought on site to test the emissions of the ethanol trucks as well as the diesel control truck.

The data generally show that oxides of nitrogen are slightly lower for the ethanol vehicles than for the diesel vehicle, and that particulate matter levels are significantly lower for ethanol. The diesel emissions levels remained consistent from year to year, and offered lower carbon monoxide emissions than the ethanol trucks, whereas the carbon monoxide emissions from ethanol #2 rose by a factor of three between 1994 and 1995. It is possible that catalytic converter efficiency had degraded on this vehicle, because hydrocarbon emissions also rose. Although the diesel vehicle had lower hydrocarbon emissions than the ethanol vehicles, it was evident that unburned ethanol was present as a significant fraction of the total hydrocarbon emissions of the ethanol vehicles. However, because oxides of nitrogen and particulate matter may be considered the emissions of concern for the heavy-duty fleet, the ethanol-powered vehicles have an advantage over their diesel counterparts relative to emissions. The complete WVU test results and summary are in Appendices 7 and 8.

Conclusions

This project was successful in several ways. First, a heavy-duty engine was developed and emissions certified to run on a high percentage blend of ethanol, a domestically produced and renewable fuel, for use in urban transit buses and over-the-road trucks. To date, the DDC 6V-92TA is the only alcohol fuel engine that can make this claim. Second, the ethanol trucks successfully performed the same rigorous duties as the diesel control trucks in a demanding vocation and harsh winter environment. Third, with some refinement, ethanol engines could prove to be as reliable and durable as their diesel counterparts. From a functional standpoint, the fuel filter clogging issue was the only significant barrier from the fleet administrator and the drivers' viewpoint. Fourth and finally, although E95 trucks emitted more hydrocarbons and carbon monoxide than the diesel trucks, the oxides of nitrogen and particulate matter, the emissions of concern for heavy-duty vehicles, were reduced.

The real hurdles for the widespread use of high percentage blends of ethanol are fuel costs, vehicle range, and infrastructure. Although exact fuel costs will vary by region and tax status, the E95 cost more than three times as much as diesel #2 (on an equivalent energy basis) in this demonstration. The vehicle range was an issue, even in this application where the vehicles covered a relatively small area. With this in mind, over-the-road travel would be impossible without an extensive fueling infrastructure.

APPENDIX 7
Summary of Emissions Testing

Emissions Testing of Hennepin County Snowplows
Nigel Clark, WVU, October 2, 1997

Two ethanol powered and one diesel powered snowplows were subjected to emissions testing by the West Virginia University Transportable Heavy-Duty Emissions Testing Laboratories. The Transportable Laboratories were originally constructed to satisfy the need to gather data on emissions from heavy-duty vehicles without the need to remove engines from the vehicles for testing. The laboratories are transportable to permit testing at the site of truck operation and to ensure that tested vehicles were out of service for as short a time as possible. The laboratory facility arrives on the test site pulled on two trailers, one being a box trailer containing equipment for emissions measurement, data acquisition and control, and the other, a flat bed semi-trailer carrying the power absorber unit. The flat bed is lowered to the ground to provide a chassis dynamometer platform.

The vehicle to be tested is driven onto the flat bed and the wheels of the vehicle are positioned on rollers set in the bed. The outer wheels of the dual wheel set on each side of the vehicle are connected to the drive shafts of the dynamometer units located on each side of the vehicle. Each dynamometer unit consists of speed increasing gearboxes with a power absorber and a flywheel set. The flywheel sets consist of a series of selectable discs to allow simulation of vehicle inertia. During the test cycle, torque cells and speed transducers in the power absorber drive train measure the actual vehicle load and speed.

The full exhaust from the tail pipe of the test vehicle was ducted to a 45 cm diameter dilution tunnel on top of the emissions trailer. The exhaust was mixed with dilution air and the flow was controlled using a blower with critical flow venturis. Heated sampling probes sent diluted exhaust to a number of different gas analysis instruments, via heated lines. Levels of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), and hydrocarbons (HC) were measured continuously. A bulk measurement of particulate matter (PM) was obtained using 70 mm filters weighed after conditioning for temperature and humidity in an environmental chamber. Levels of alcohol and aldehydes were determined using impingers and cartridges, respectively, with subsequent laboratory analysis.

The Hennepin County snowplows had 10-speed unsynchronized transmissions and as such would have had difficulty in following the Central Business District speed-time test schedule that is commonly used for automatic transit buses. The bulk of the testing was therefore undertaken using the West Virginia University 5-peak truck cycle, which has a total distance of 5 miles, a time of 900 seconds, and five peaks, at 20, 25, 30, 35, and 40 miles per hour.

The plows were tested in March and April of 1994, and again in May of 1995. Table 1 provides the vehicle mileage at the time of testing.

Table 2 provides emissions data gathered in 1994, while Table 3 provides 1995 initial and repeat run data.

The hydrocarbons reported for the vehicles are direct readings from the flame ionization detector (FID) of the HC analyzer, which is calibrated using propane. A more representative indication of the hydrocarbon emissions for ethanol vehicles is often expressed as the "organic material hydrocarbon equivalent" (OMHCE), which is calculated as follows to correct for species and to exclude weight of oxygen in the species, with suitable background corrections.

$$OMHCE = (FIDHC) - 0.768\,(CH_3OH) + 0.4621\,(HCHO) = 0.6298\,(CH_3CHO) + 0.6023\,(C_2H_5OH),$$

where C_2H_5OH is ethanol, HCHO is formaldehyde, CH_3CHO is acetaldehyde, and CH_3OH is methanol. In essence, the FID reading is corrected for the calibration with respect to ethanol (C_2H_5OH), which is independently measured using impingers, and is increased by the level of formaldehyde (HCHO) and acetaldehyde (CH_3CHO) measured using cartridges, since these two species do not register with the FID.

The data generally show that oxides of nitrogen are slightly lower for the ethanol vehicles than the diesel vehicle, and that particulate matter levels are significantly lower for ethanol. The diesel emissions levels remained consistent from year to year, and offered lower carbon monoxide emissions than the ethanol trucks, whereas the carbon monoxide emissions from one vehicle (3228) rose by a factor of three between 1994 and 1995. It is possible that catalytic converter efficiency had degraded on this vehicle, because hydrocarbon emissions also rose. The diesel vehicle had lower hydrocarbon emissions than the ethanol vehicles and it was evident that unburned ethanol was present in the exhaust of the ethanol vehicles as a significant fraction of the total hydrocarbon emissions. However, since oxides of nitrogen and particulate matter may be considered the emissions of concern for the heavy-duty fleet, one must conclude that the ethanol powered vehicles offered a solution to emissions inventory reduction.

Table 1. Mileage as Received for the Three Snowplows

Unit No.	**1994**	**1995**
HC - 3221 Ethanol	8842	30,353
HC - 3228 Ethanol	5175	17,170
HC - 3220 Diesel	12,409	43,806

Table 2. Data from 5-Peak Cycle Runs Gathered in 1994

WVU Sequence #	Unit	CO	NO_2	PM	FIDHC	OMHCE	HCHO	C_2H_5OH	CH_3CHO
261	HC-3221 Ethanol	7.4	12.3	0.30	4.98	4.33	0.11	2.41	0.56
259	HC-3228 Ethanol	9.0	14.8	0.45	5.69	5.21	0.15	3.37	0.66
258	HC-3220 Diesel	4.3	13.2	0.83	1.35	---	---	---	---

Table 3. Data from 5-Peak Cycle Runs Gathered in 1995

WVU Sequence #	Unit	CO	NO_2	PM	FIDHC	OMHCE	HCHO	C_2H_5OH	CH_3CHO
431	HC-3221Ethanol	5.1	11.8	0.35	3.86	2.81	0.08	0.62	0.43
434	HC-3228 Ethanol	26.2	12.0	0.56	7.07	6.73	0.29	3.74	1.88
436	HC-3220 Diesel	4.6	13.3	0.85	1.50	---	---	---	---
453	HC-3221 Repeat	7.7	11.3	0.39	4.02	2.88	0.08	0.74	0.54
454	HC-3228 Repeat	31.2	11.7	0.56	7.17	6.86	0.26	4.33	1.57
460	HC-3220 Repeat	5.8	13.0	0.88	1.38	---	---	---	---

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13. ABSTRACT *(Maximum 200 words)* Hennepin County, Minnesota, field-tested two heavy-duty snowplow/road maintenance trucks fueled by ethanol. The objective of this program was to collect data from original equipment manufacturer alternative fuel heavy-duty trucks, along with comparable data from a similarly configured diesel-powered vehicle, to establish economic, emissions, performance, and durability data for the alternative fuel technology. A considerable amount of data was collected, and project participants called the project a success.

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