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Decision Analysis Using Value-Focused Thinking to Select Renewable Alternative Fuels

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VALUE-FOCUSED THINKING TO SELECT

RENEWABLE ALTERNATIVE FUELS

THESIS

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Abstract

The United States relies on imported oil as a result of domestic petroleum consumption rates greatly exceeding production rates. Alternative fuels are a major force in the effort to reduce petroleum consumption in the transportation industry. The transportation industry also accounts for 1/3 of all greenhouse gas emissions and nearly half of all cancers attributed to outdoor sources of pollutants.

The purpose of this research was to evaluate the economic and environmental feasibility of renewable alternative fuels and associated blends (ethanol, methanol, 100% biodiesel {B100}, 20% biodiesel {B20} and e-diesel) compared to non-renewable alternative fuels (compressed natural gas and propane) and conventional fuels (gasoline and diesel) using the decision analysis approach of Value-Focused Thinking (VFT). Specifically, this thesis sought to answer three sets of research questions addressing the appropriate methodology for selecting renewable alternative fuels, the justification for using renewable alternative fuels and the suitability of using the developed model at differing geographic locations.

The research questions were answered through a comprehensive literature review, and the development and utilization of the model. The culmination of this effort was the development of a complete and non-redundant VFT model that can be used by installation commanders, environmental managers, or transportation officers to select renewable alternative fuels for their government vehicles. Recommendations to utilize renewable alternative fuels through this decision analysis tool are also discussed.

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To my late Grandmother

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Nomenclature

AFB – Air Force Base

AFCEE – Air Force Center for Environmental Excellence

AFT – Alternative Focused Thinking

AHP – Analytical Hierarchy Process

ASTM – American Society for Testing and Materials

B100 – 100% biodiesel

B20 – Blend of 20% biodiesel, 80% diesel fuel

BTU – British thermal unit

C_2H_5OH – Ethanol

CAAA – Clean Air Act Amendments

CNG – Compressed natural gas

CO – Carbon monoxide

CO_2 – Carbon dioxide

DESC – Defense Energy Support Center

DOE – Department of Energy

EPA – Environmental Protection Agency

EPAct – Energy Policy Act of 1992

E10 – Gasohol (blend of 10% ethanol, 90% gasoline)

E85 – Blend of 85% ethanol, 15% gasoline

FFV – Flexible fuel vehicle

FY – Fiscal year

GHG – greenhouse gas

GOV – Government Owned Vehicles

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation

H_2 – Hydrogen

HCNG - Hydrogen and compressed natural gas (Hythane)

LCA – Life cycle assessment

LNG – Liquefied natural gas

M85 – Blend of 85% methanol, 15% gasoline

MOVES – Motor Vehicle Emission Simulator

MTBE – Methyl tertiary butyl ether

NAAQS – National Ambient Air Quality Standards

NO_2 – Nitrogen dioxide

NO_x – Nitrogen oxides

O_3 – Ozone

PM – Particulate Matter

POLCAGE – Possibilistic Life Cycle Analysis using GREET and Environmental Design of Industrial Products

ppm – Parts per million

RFG – Reformulated gasoline

SDVF – Single dimension value function

SO_2 – Sulfur dioxide

SO_x – Sulfur oxides

ULSD – Ultra-low sulfur diesel

US – United States

USDA – United States Department of Agriculture

VFT – Value-Focused Thinking

VOC – Volatile organic compound

DECISION ANALYSIS USING VALUE-FOCUSED THINKING TO SELECT RENEWABLE ALTERNATIVE FUELS

I. Introduction

1.1 Background

Petroleum, a non-renewable fuel, accounts for approximately 95 percent of the world's transportation and 40 percent of all commercial energy generation (Aleklett *et al*., 2003). Despite technological advances, major oil companies are having difficulty finding new sources of oil. World oil consumption has risen steadily over the past few decades while oil discoveries have diminished (Campbell, 1996). At the current consumption rate, many geophysics and environmental experts believe the world will run out of oil in the next century (Deffeyes, 2001:1). In order to stop an impending world oil shortage, the United States (US) dependence on oil must be reduced and new energy alternatives must be developed and implemented.

Alternative fuels are a major force in the effort to reduce petroleum consumption in the transportation industry (U. S. Department of Energy, 2004b). Alternative fuels are defined by the Energy Policy Act of 1992 and successive legislation (United States Congress, 1992). They include but are not limited to biodiesel, ethanol, hydrogen, propane and natural gas. Alternative fuel vehicles are defined as vehicles that can operate using any of the preceding non-petroleum fuels.

Propane is by far the most used alternative fuel, while ethanol is the most widely used renewable alternative fuel with a current production of 1.8 billion gallons per year in the US (Bechtold, 1997:24; U. S. Department of Energy, 2004b). Propane is produced in association with either crude oil refining or with the production of natural gas. Ethanol is an alcohol-based alternative fuel produced from starch crops such as corn, barley and wheat. Compared with gasoline, ethanol has a higher octane number and a higher emissions quality. Ethanol can also be blended with gasoline and is used in flexible fuel vehicles (FFVs). FFVs are those vehicles that can use more than one type of fuel or fuel mixture (Bechtold, 1997:174).

Biodiesel is an alternative fuel produced from natural, renewable sources such as new and used vegetable oils and animal fats (Ma and Hanna, 1999:7). Biodiesel is similar to petroleum diesel given that it operates in compression-ignition engines; however, biodiesel is a cleaner burning replacement fuel, non-toxic and biodegradable. The use of biodiesel in diesel engines significantly reduces emissions of sulfates, hydrocarbons, carbon monoxide and particulate matter (Beer, *et al*., 2001:30). The ratio of biodiesel to diesel is directly proportional to the emission reductions. Blends of up to 20% biodiesel mixed with petroleum diesel fuels (B20) can be used in nearly all diesel equipment and FFVs without engine modifications. Higher blends of biodiesel (100% biodiesel, or B100), can be used in many engines built in the past ten years with little or no modification.

Hydrogen has many characteristics that make it appealing compared to conventional fuels and other alternative fuels. Under optimal conditions, hydrogen would be produced from the electrolysis of water (Bechtold, 1997:32). When hydrogen is combusted directly in internal combustion engines, only water vapor is emitted. However, hydrogen currently has the lowest energy content due to its storage density. With respect to fuel cell practicality, hydrogen is still in the beginning research and development stages relative to all other fuels.

Federal mandates have strengthened the emerging market of alternative fuels and promoted research and development. Furthermore, these mandates have lead to the decision of which alternative fuels or alternative fuel vehicles Air force leaders must choose for their government owned vehicles (GOVs). The decision of selecting alternative fuels with respect to the declining supply of oil is an issue that must be commonly addressed in the energy industry. Decision makers must take many issues into consideration including cost, availability, performance, emissions savings and oil preservation ability of the competing fuels. Value-focused thinking (VFT) is one method of multiple objective decision analysis to assist in this process. VFT guides the decision maker through a ten-step process to evaluate alternatives based on what is most important.

1.2 Problem Identification

According to Executive Order 13123, “Greening the Government through Efficient Energy Management,” the federal government is required to reduce greenhouse gas emissions (30% by the year 2010) that contribute to global climate change and air pollution. Each federal agency shall also strive to expand the use of renewable energy sources (Clinton, 1999:Sec. 201). Moreover, Executive Order 13149, “Greening the Government Through Federal Fleet and Transportation Efficiency,” states that all federal agencies are required to reduce petroleum fuel consumption by at least 20% by the end of fiscal year (FY) 2005 (Clinton, 2000:Sec 201). Potentially, through the expanded utilization of renewable alternative fuels, non-renewable natural resources will be conserved, greenhouse gas emissions reduced and money saved. The decision to utilize renewable alternative fuels to meet these goals will be explored through a VFT model. This facilitated method will help the decision maker objectively select the best alternative fuels for use at their respective installations.

1.3 Research Objectives/Questions

The purpose of this research is to comparatively examine the economic and environmental feasibility of renewable alternative fuels and associated blends (ethanol, methanol, biodiesel and other renewable/petroleum mixtures) compared to non-renewable alternative fuels (compressed natural gas and propane) and conventional fuels (gasoline and diesel) using the decision analysis approach of VFT. This effort will provide a tool for installation commanders, environmental managers, or transportation personnel to select renewable alternative fuels for their vehicles. By systematically acquiring the best possible alternative, a decision maker may be able to support his/her argument for use of renewable alternative fuels. Three main focus and associated corollary questions were suggested by the literature reviewed.

(1) Are renewable alternative fuels justified when compared to gasoline, diesel fuel and non-renewable alternative fuels according to the VFT model? What are the environmental benefits of using renewable alternative fuels?

(2) Is it more cost effective to use renewable alternative fuels in different regions of the United States? Which renewable alternative fuels are more suited for certain regions of the United States? What agencies/organizations are involved in providing

guidance and making the decision to use renewable alternative fuels on each Air Force installation?

(3) What methodologies are available for analyzing the selection of renewable alternative fuels? What are the steps involved to employ each methodology? What are the appropriate measures that comprise a model to select renewable alternative fuels in the Department of Defense? How do changes in the model parameters affect the outcome of the model?

1.4 Research Approach

The goal of this research is to define and develop a VFT model that guides a decision maker such as the base commander, Logistics Readiness Squadron Commander or Civil Engineering Environmental Flight Commander in methodically assessing different renewable alternative fuels for GOVs on an Air Force installation. Development of the model will begin with a literature search to identify potential model parameters and compile background information on renewable alternative fuels. A proxy decision maker will be consulted to define other performance measures. This decision maker will then weight all performance measures based on relevance and scores will be determined using a value hierarchy (Kirkwood, 1997:68). Examples of these measures could include: initial cost, operational and maintenance cost, conversion cost, greenhouse gas emissions, fuel source, safety, fuel economy, vehicle availability, fuel availability, octane rating, and energy security impacts. Sensitivity analysis will illustrate the impact on the ranking of different fuel alternatives based on assumptions on the model.

1.5 Scope

This research will compare the value of different renewable alternative fuels with non-renewable alternative fuel and conventional fuels at different geographic locations of current Air Force installations using one particular decision analysis strategy, VFT. The renewable alternative fuels are ethanol (E85), methanol (M85) and biodiesel (B100). Two renewable/petroleum blends (e-diesel and B20) are also considered. The non-renewable alternative fuels are compressed natural gas and propane and the two conventional fuels are gasoline and diesel fuel. Chapter 2 provides a literature review of information concerning each fuel. Although this model is designed for fuels currently utilized in today's fuel market, it will be developed to accommodate future renewable alternative fuels. Another potential renewable fuel source such as hydrogen is not included because it is not a mature alternative fuel source and is still considered to be in the developmental stage. However, pending technological advances in the near future, this energy source can be included in this model.

1.6 Significance

The use of alternative fuels will meet the directives from Executive Orders and will significantly reduce harmful pollutants and exhaust emissions. Alternative fuels such as biodiesel will also decrease the United States' dependence on imported petroleum and simultaneously develop a market for excess vegetable oils and animal fats. The development of a VFT model will help commanders choose the best alternative fuel for GOVs. This research and development of an appropriate model will give insight to Air Force leaders when making decisions concerning which alternative fuels best suit their installation's needs.

1.7 Summary

This chapter discussed the current predicament associated with increased world petroleum consumption and decreased oil discoveries and production. The utilization of alternative fuels is part of the solution to this worldwide problem. Air Force employment of alternative fuels in GOVs will fulfill mandates from Executive Orders and the Energy Policy Act (EPAct) of 1992 in addition to reducing oil consumption. These mandates suggest that the use of alternative fuels will reduce harmful exhaust emissions. The decision to use alternative fuels will be explored through the multiple objective decision analysis tool VFT.

The following chapter will further discuss the history of automobile fuels and environmental policies regarding the concerns of petroleum based fuels. Chapter 2 will also include information about many alternative fuels including natural gas, biodiesel, ethanol, methanol and hydrogen. In addition, chapter 2 will compare and contrast different air emissions testing models such as GREET and MOVES. It will also compare multiple objective decision analysis methods of Alternative Focus Thinking, the Analytical Hierarchy Process and VFT and will explain why VFT is a suitable tool for this research.

II. Literature Review

This chapter provides background information on conventional petroleum based fuels, alternative fuels and renewable alternative fuels. It will first explore a brief history of automobile fuel and the petroleum industry. The current world oil shortages will be discussed and will be followed by an explanation of current environmental policies and hazardous air pollutants related to mobile sources. Next, a breakdown of gasoline and diesel fuel utilization and characterization will follow. The chapter also explores relevant published research pertaining to alternative fuels such as natural gas and renewable alternative fuels such as ethanol, methanol and biodiesel. It will also discuss the advantages and disadvantages of these different fuels and how emissions from these fuels were measured in models found throughout the literature review process. Finally, multiple-objective decision analysis will be discussed. The Analytical Hierarchy Process (AHP) and the value-focused thinking (VFT) process are introduced to provide an understanding of the methodology considered for this research effort.

2.1 Historical Perspectives

The invention and development of the automobile as the primary mode of personal transportation in the early 1900s required a parallel development of the fuels to power those machines. Hydrocarbon fuels, coal gas, and kerosene made from petroleum competed as energy sources as automobile engines demanded unprecedented amounts of fuel (Weidou and Johansson, 2004:1225). Two major problems arose from this new petroleum market. Early refiners could convert merely a small proportion of their crude oil to gasoline due to technology shortfalls. The second problem arose from the shortage of quality fuel due to the increasing usage of automobiles. This led to the false prediction that there would be no more petroleum by 1940. In, 1956, Dr. M. King Hubbert predicted that "oil production would peak in the early 1970s" (Deffeyes, 2001:1). He built a model that analysts still use today to estimate world oil production rates. Many oil industry geologists and analysts predict the world's production of petroleum will peak in the year 2003 and supply of petroleum will last until about 2040 (Deffeyes, 2001:146).

2.2 Environmental Issues

2.2.1 Global Warming.

Concerns about global warming, carbon monoxide pollution and ground level ozone (smog) formation may force a fundamental shift in the role of alternative fuels in the energy market. Strong scientific evidence states that climate change occurs and is accelerating due to human activity (Masters, 1990:453). The 1990s was the warmest decade worldwide and 2002 was the second warmest year since records began (Secretary of State for Trade and Industry, 2003:5). Increasing evidence shows that the rising temperatures result from an increase in atmospheric concentrations of greenhouse gases (carbon dioxide) released by burning fossil fuels such as coal, oil and gas (Greene and Schafer, 2003:2). In 1990, the transportation sector accounted for 22% of global carbon dioxide emissions (Azar, 2003:961). As greenhouse gas concentrations rise well above their natural levels, the additional warming that will occur could threaten human society through flooding of coastal areas, increased storm activities and resulting in the spread of disease.

2.2.2. Environmental Policies.

In 1999, President Clinton pushed the use of alternative fuels through government mandates. Executive Order 13149 (Greening the Government Through Federal Fleet and Transportation Efficiency), asserts that all federal agencies are required to reduce annual petroleum fuel "consumption by at least 20% by the end of FY 2005" based on FY 1999 petroleum figures (Clinton, 2001:Sec 201). Reducing petroleum consumption will help promote the alternative fuel market, encourage research and development of new technologies, enhance the country's energy self-sufficiency and security, and reduce the amount of greenhouse gases and other air pollutants in the atmosphere. All this can be accomplished through the use of renewable alternative fuels.

The Energy Policy Act of 1992 (EPAct) also promotes the use of renewable alternative fuels. A fuel credit can be earned for every alternative fuel vehicle purchased in excess of the required amount for that government agency (United States Congress, 1992:Sec 508). A fuel credit is used to measure compliance with the EPAct. Congress recently passed a bill allowing federal agencies to obtain one fuel credit for every 450 gallons biodiesel consumed (United States Congress, 1998:Sec 7).

2.2.3 Air Quality Standards.

The Clean Air Act Amendments (CAAA) of 1990 set National Ambient Air Quality Standards (NAAQS) that forced the use of cleaner-burning automotive fuels (United States Congress, 1990). The Environmental Protection Agency (EPA) uses six criteria pollutants as indicators of air quality and has established maximum threshold concentrations for each. Areas that do not meet the standard may be designated as non-attainment areas and are required to implement plans in order to reach acceptable levels or will be subject to penalties. The six criteria pollutants are ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particulate matter (PM) and lead. Sulfur dioxide and lead are not of major concern with automobile sources due to earlier regulations that essentially eliminated sulfur and lead emissions from vehicles. The EPA recently set new federal emission standards for passenger cars, light trucks and larger passenger vehicles that focus on reducing emissions of PM, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (Environmental Protection Agency, 1999:iii). These emissions are measured in units of grams per mile, vastly different than the NAAQS which are measured in parts per million.

2.2.4 Greenhouse Gases.

The first challenge faced by the world pertains to the environment. Climate change is real. Levels of carbon dioxide (CO_2) in the atmosphere, one of the main causes of climate change, have risen by more than a third since the industrial revolution and are now rising faster than ever before (Masters, 1998:477). This has led to rising temperatures: over the 20th century, the earth warmed up by about 0.6ºC, largely due to increased greenhouse gas (GHG) emissions from human activities. The 1990s were the warmest decade since records began. In this century, without action to reduce emissions, the earth's temperature is likely to rise at a faster rate than any time in the last 10,000 years or more.

2.2.5 Ozone.

Lower atmospheric ozone (O_3) is a known human toxic and is the major component of smog. Ozone is formed when volatile organic compounds (VOCs) and nitrogen oxides (NO_x), react in the presence of sunlight (Masters, 1998:487). Both VOCs and NOx are emitted from manmade sources including automobile exhaust, evaporation of solvents and gasoline, chemical manufacturing, and petroleum refining (United States Congress, 1990:31).

In high concentrations ozone can damage lung tissue and reduce lung function. Several studies over the past five years have shown temporary loss of some lung function after only two hours of exposure at concentrations between 0.12 and 0.16 parts per million (ppm), among moderately to heavily exercising children and adults in urban areas (Office of Technology Assessment, 1990:32). Ozone levels in some non-attainment areas have been recorded as high as 0.36 ppm (Office of Technology Assessment, 1990:33). Ozone in the air, however, does not necessarily equate to ozone in people's lungs. Concentrations vary with time of day and location. People vary in the amount of time they spend indoors, where concentrations are lower. The NAAQS for ozone is 0.12 ppm, measured as a one hour average concentration over three consecutive years. Nationwide, an estimated 34 million people are actually exposed to ozone above 0.12 ppm, on average about 9 hours per year (Code of Federal Regulations Title 40, 1999:Sec 50.9).

2.2.6 Nitrogen Dioxide.

Nitrogen dioxide (NO_2) is a brownish, highly reactive gas present in all urban atmospheres. Highway vehicles and electric utilities account for two-thirds of the nitrogen dioxide emissions in the United States (Environmental Protection Agency, 1999:III-7). Nitrogen oxides are not only a precursor to ozone formation, but also for acid rain, which can affect aquatic and terrestrial ecosystems. At high concentrations, nitrogen dioxide can irritate lungs, cause bronchitis and pneumonia and lower resistance to respiratory infections (Office of Technology Assessment, 1990:40). In southern California highway vehicles can account for about 30 to 45 percent of local nitrogen dioxide emissions. The NAAQS for nitrogen dioxide is 0.053 ppm, measured as an average concentration over one calendar year (Code of Federal Regulations Title 40, 1999:Sec 50.11).

2.2.7 Carbon Monoxide.

Carbon monoxide (CO) is a colorless, odorless poisonous gas produced by incomplete combustion of carbon in fuels (Masters, 1998:340). Carbon monoxide is absorbed by the lungs and attaches itself to hemoglobin in red blood cells, much like oxygen. However, blood will bond with carbon monoxide 200 times more readily than oxygen. Relatively low concentrations in the atmosphere may accumulate in the victim's blood over a period of time with serious or fatal results. Carbon monoxide can cause permanent neurological dysfunctions in moderate levels and can cause death at higher levels. The NAAQS for carbon monoxide is 9 ppm, measured as an eight hour average concentration over two consecutive years (Code of Federal Regulations Title 40, 1999:Sec 50.8).

2.2.8 Particulate Matter.

Particulate matter (PM) is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets. Particles can be suspended in the air for long periods of time. Some particulate matter is large enough or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope. Particles that are directly emitted into the air come from a variety of sources such as automobiles, factories, construction sites unpaved roads and burning of wood. The EPA measures two types of particulate matter. PM-10 is any particle under 10 micrometers. PM-2.5 is any particle under 2.5 micrometers (Code of Federal Regulations Title 40, 1999:Sec 50.7). The NAAQS for PM-10 is 50 micrograms per cubic meter over an eight hour average concentration over one year. The NAAQS for PM-2.5 is 15 micrograms per cubic meter over an eight hour average concentration over one year.

2.2.9 Other Air Toxics.

The original air toxics list contains 188 hazardous air pollutants that cause cancer or other serious health effects such as birth defects, or adverse environmental effects (Masters, 1998:361). The EPA estimates that mobile sources of air toxics account for as much as half of all cancers attributed to outdoor sources of air toxics (MacLean and Lave, 2003:11). Benzene, formaldehyde and acetaldehyde are present in gasoline and diesel and are emitted to the air when gasoline evaporates or passes through the engine as unburned fuel. Cars emit small quantities of benzene in unburned fuel, or as vapor when gasoline evaporates. A significant amount of automotive benzene comes from the incomplete combustion of compounds in gasoline such as toluene and xylene that are chemically very similar to benzene (MacLean and Lave, 2003:11). Environmentally, petroleum consumption in the transportation sector has continued to raise both local and global pollution concerns. Although significant advances have been made to reduce exhaust emissions from gasoline and diesel vehicles, mobile sources still account for a large percentage of criteria pollutants in urban centers (Winebrake and Creswick, 2001:3). Volatile organic compounds (VOCs) such as xylene or toluene are also carcinogens, and are emitted from industrial sources. When exposed to sunlight, VOCs can react with NO_x to form smog (Masters, 1998:328).

2.3 Non-renewable Fuels

The sustainability of gasoline and diesel fuel depends on global oil supply. Today, nearly two-thirds of oil consumed in the US is used for transportation and imported oil accounts for more than 50% of domestic oil supplies (Whalen *et al*., 1996:2). Gasoline and diesel are both refined from crude oil. Crude oil spills, especially during transport in oil tankers at sea, pose a major environmental hazard that can contaminate marine and bird life (Beer, 2001:72). Environmental damage from diesel or gasoline itself can also occur, especially from leaks at service stations and refueling depots that have been known to contaminate groundwater supplies.

2.3.1 Gasoline.

In the 1970's, petroleum refining was controlled primarily for gasoline yield and quality. Gasoline is produced through a distillation process from petroleum crude oil. Lead was added to boost the octane rating of gasoline until the mid-1970's when it was phased out by the government for health reasons (MacLean and Lave, 2003:8). Leaded gasoline is still an environmental problem in many third world countries. Today, gasoline is the most popular fuel used in automobiles due to its superior performance and availability compared with alternative fuels; however, it is the greatest pollutant of all automotive fuels. The most important characteristics affecting combustion and leading to emissions are vapor pressure, octane number, and amounts of aromatics and sulfurs (Sawyer *et al*., 2000:2165). The CAAA now requires reformulated gasoline (RFG) with oxygen in order to reduce smog-forming and toxic pollutants in the air. MTBE (methyl tertiary butyl ether) and ethanol are the two most commonly used substances that add oxygen to gasoline to form RFG (Wheals, 1999:485).

2.3.2 Diesel Fuel.

Like gasoline, diesel fuel is derived from the distillation of crude oil. Diesel fuel has two primary advantages over gasoline. It is less expensive to produce and has better fuel economy than gasoline. Diesel fuel is also one of the safest of automotive fuels. High quality diesel fuels are characterized by having low sulfur content, and excellent density, viscosity, boiling point and cold weather properties (Tornevall, 1998:5). The disadvantages of diesel over gasoline are the higher engine cost, odor and poor acceleration (Sawyer *et al*., 2000:9). Unlike gasoline-fueled engines, diesel engines are also a major source of Nitrogen oxides (NO_x) and particulate matter (PM). Diesel exhaust releases particles at a rate about 20 times greater than from gasoline fueled vehicles. Reducing these air emissions will require the use of new pollution control technology or reformulated diesel fuel. Ultra-low sulfur diesel (ULSD) is a fuel containing one-tenth the sulfur of standard diesel. The lower sulfur content is expected to result in lower particulate exhaust emissions. However, because of the extra processing energy, ULSD produces more greenhouse gases than standard diesel fuel over its life cycle. Diesel fuel faces significant fuel-quality and engine-emissions requirements. Current EPA regulations set a maximum "limit of 0.05% by weight on the sulfur content and a minimum cetane number of 40" for diesel fuel used in vehicles (Murphy *et al*., 2004:5). The cetane number measures the ignition quality of a diesel fuel.

2.4 Alternative Fuels

During the last two decades there has been a considerable worldwide effort to develop alternatives to gasoline and diesel fuel in the transportation industry. The primary motives for this effort have been two-fold: energy preservation and air pollutant reduction. While extensive research interest during the past decade concentrated on ethanol and methanol as alternative fuels, more recent research has emphasized the potential of agricultural oils as diesel fuel replacements. These non-petroleum, renewable substitutes can be obtained from oilseed crops such as soybean, sunflower, and rapeseed. Fuels produced through chemical and thermal processes are referred to as biodiesel fuels (Ahouissoussi and Wetzstein, 1997:3). Studies have shown that alternative-fueled engines consistently emit lower emissions of hydrocarbons, carbon monoxide, and particulate matter than diesel engines (Beer *et al*., 2001:51).

The EPAct defines alternative fuels as fuels that are substantially non-petroleum (maximum 15% petroleum) and yield energy security and environmental benefits (United States Congress, 1992:Sec 301). Under the EPAct, alternative fuels include ethanol, methanol, propane gas, natural gas, hydrogen and electricity. Biodiesel was added to the EPAct in 1998 as an alternative fuel when added to conventional diesel at blends of 20% or higher.

Alternative fuel vehicles are classified into three categories: flexible fuel vehicles, bi-fuel vehicles and dedicated fuel vehicles. A flexible fuel vehicle (FFV) is designed to run on more than one type of fuel or fuel mixture (Bechtold, 1997:174). Bi-fuel vehicles have two separate fuel systems. Most bi-fuel vehicles have one compressed natural gas tank and one petroleum derived fuel tank. Dedicated fuel vehicles are designed to fuel only one type of alternative fuel.

2.4.1 Compressed Natural Gas.

Natural gas is an alternative fuel that meets tighter vehicle-emission requirements. Natural gas is a non-renewable, indigenous fuel that could replace imported, expensive crude oil. However, supplies of natural gas are also limited. Natural gas is a fossil fuel extracted from underground reservoirs composed of methane and other hydrocarbons including ethane, propane, butane and inert gases such as carbon dioxide, nitrogen, and helium (Beer, 2001:47). Interest in using natural gas as a transportation fuel has increased in recent years, because it offers the potential for reducing exhaust emissions. There are two types of natural gas, compressed natural gas (CNG) and liquefied natural gas (LNG). CNG fueling stations are more prominent in the US and can be found in most major cities. Since it is derived from fossil fuels, CNG is considered an alternative fuel but not considered a renewable alternative fuel. In extenuating circumstances, CNG can be a renewable fuel because it can be purified from the biogas extracted from waste treatment facilities, landfills and anaerobic digesters.

CNG has advantages compared with diesel fuel. Noise levels from natural gas vehicles are less than those of diesel vehicles. Due to its compressed gaseous nature, the potential for water and soil pollution is effectively eliminated by the use of natural gas. CNG vehicles produce less air pollutants and greenhouse gases than diesel vehicles (Office of Technology Assessment, 1990:100). It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions. CNG also has nearly zero sulfur levels and, thus, negligible sulfate emissions. Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per unit of fuel and has very low particulate emissions compared to diesel fuel (Beer, 2001:51). CNG has low cold-start emissions due to its gaseous state and has extended flammability limits, allowing stable combustion at leaner mixtures. CNG also has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer. It is much lighter than air and it is safer than spilled diesel due to its gaseous state. Engines fueled with natural gas in heavy-duty vehicles offer more quiet operations than equivalent diesel engines, making them more attractive for use in urban areas.

CNG also has its disadvantages. CNG on board a vehicle takes 3 to 4.5 times more volume for storage than diesel and the extra weight of the fuel tank leads to higher fuel consumption or loss of payload (Office of Technology Assessment, 1990:97). It requires dedicated catalysts with high loading capability of active catalytic components to maximize methane oxidation. The composition can vary widely depending on the CNG source, which affects stoichiometric air/fuel ratios. Its driving range is limited because its energy content per volume is relatively low as a result of its gaseous state. CNG also requires special refueling stations. Exhaust emissions of methane, which is a greenhouse gas, are relatively high compared with low sulfur diesel (Beer, 2001:52). It can give rise to backfire in the inlet manifold if the ignition system is faulty or fails in use. Relatively small fugitive emissions of methane can have a significant effect on the greenhouse gas emissions.

2.4.2 Liquefied Petroleum Gas.

Liquefied petroleum gas (LPG) is a mixture of propane, butane and other hydrocarbons and is a byproduct of natural gas extraction and crude oil refining. As an automotive fuel, LPG is essentially propane and must be stored under modest pressures to keep it in liquid form. Propane has been used as a vehicle fuel for the past 60 years and in 1992 propane was the most popular alternative fuel in the US (Bechtold, 1997:24).

As a fuel, propane has several advantages. Disregarding infrastructure and conversion costs, like CNG, propane costs less than conventional fuels (Peil, 2001:171). Propane has no evaporative emissions associated with the fuel, has low carbon monoxide emissions, and low nitrogen oxide emissions (Bechtold, 1997:25). In the past, refueling emissions were quite high due to the trapped fuel located in the fueling mechanism. However, in 1998 the EPA regulated this amount to two cubic centimeters, equivalent to the amount released in gasoline refueling (Bechtold, 1997:25).

2.4.3 Ethanol.

Using ethanol to fuel vehicles is what Henry Ford intended for his first automobiles (Tiffany, 2002:7). Ford was a proponent of ethanol because of its good combustion properties and its potential effect on the agriculture market. In 2001, the United States domestically produced 1.77 billion gallons of ethanol from renewable sources and an estimated 5 billion gallons will be produced by 2012 (Andress, 2002:2). Ethanol is an alcohol and an oxygenated organic carbon compound. It is the intoxicating component of alcoholic beverages, and is also used as a solvent (Masters, 1998:377). Ethanol has also replaced methyl tertiary butyl ether (MTBE) in oxygenated fuels to reduce groundwater contamination because the use of MTBE is no longer permitted in some areas due to concerns with groundwater and drinking water contamination (He, *et al*., 2003:950).

Ethanol can be domestically produced from renewable resources such as corn, wheat, and wood and the non-renewable resource such as petroleum and natural gas. Ethanol can also be produced from other agricultural goods such as sugar cane (in Brazil) and grapes (in France) (Jones and Yu, 2004 :6). Ethanol can be manufactured from the fermentation of sugar derived from grain starches or sugar crops and the utilization of the non-sugar fractions of crops. Alcohols such as ethanol can be used in diesel and gasoline engines by either modifying the fuel or by extensive engine adaptations. Ethanol will easily blend with gasoline but not as easily with diesel. Hydrous ethanol production is a one-stage refining process, unlike the two-stage anhydrous ethanol process where water is removed (Wheals, *et al*., 1999:483). Hydrous ethanol can be used as an octane booster or as a blend with diesel fuel to form diesohol (15% ethanol, 85% diesel) (Beer, *et al*., 2001:337). Anhydrous ethanol can be used as a blend with gasoline to form E85 (85% ethanol, 15% gasoline).

As a renewable fuel, ethanol offers many advantages. Ethanol produces less CO_2 than conventional fuels. Limited tailpipe emissions data indicate that ethanol is likely to reduce benzene emissions compared with diesel fuel. Formaldehyde emissions would be similar, while acetaldehyde emissions would increase substantially. Ethanol in solution is hazardous, with high flammability, moderate toxicity, and is a moderate irritant (Beer, *et al*., 2001:37). Particulate emissions are lower with ethanol than with conventional fuels. For blends, benzene levels decrease as the ethanol concentration increases. A 10% blend of ethanol with conventional fuels lowers the carbon monoxide emissions by 30-40% (He, 3002:951). Ethanol also contains no sulfur unlike most other fuels. Ethanol also has a few disadvantages. The chemical emulsifiers and ignition improvers used to blend ethanol may contain harmful chemicals. There are higher emissions of formaldehyde and acetaldehyde from ethanol vehicles than from diesel vehicles and there may be an odor problem with the fuel (He, 2003:955).

2.4.4 Methanol.

Methanol is yet another alternative fuel produced from both fossil fuels and renewable domestic resources. Similar to biodiesel, methanol can be used in pure (100%) form or blended with petroleum diesel. In recent years, methanol was also used to produce the gasoline additive methyl tert-butyl ether (MTBE) to help reduce smog (National Energy Education Development Project, 2004:18). Methanol is the most preferred alcohol used in the transesterification process to produce biodiesel (Montgomery, 2004:16). In chemistry terms, methanol, also known as methyl alcohol or wood alcohol is the simplest alcohol (Bechtold, 1997:7). It is formed naturally from the metabolism of bacteria. It is oxidized to destruction by the help of sunlight and releases carbon dioxide and water. Currently, the majority of methanol produced in the US is from natural gas resources. Other sources for methanol production include coal, residual oil, and biomass. The conventional methanol production process using natural gas as a feedstock is also relatively costly, complex and potentially unsafe (Norbeck *et al.*, 1998:23). Extensive research is in place to produce methanol safely from carbon dioxide and other biomass feedstocks. Producing methanol from carbon dioxide will create a closed carbon fuel cycle process and in effect will significantly cut down on greenhouse gases (Azar, 2003:965). Carbon dioxide can be obtained from concentrated sources like flue gases of fossil-powered plants and cement factories, but it can also be obtained from the air.

2.4.5 Biodiesel.

Although extensive research interest during the past decade centered upon ethanol and methanol processing technologies, more recent research has emphasized the potential of plant oils as diesel fuel extenders or replacements. Fuels produced through chemical and thermal processes are referred to as biodiesel fuels (Ahouissoussi, 1997:2). Biodiesel can be produced from the reaction of oils from oilseed crops (such as soybean, sunflower, and rapeseed), used vegetable oils, or animal fats with an alcohol such as methanol or ethanol in the process called transesterification (Ma and Hanna, 1999:7). A catalyst such as sodium hydroxide or potassium hydroxide can be used to improve the reaction. Figure 2-1 shows the transesterification process.

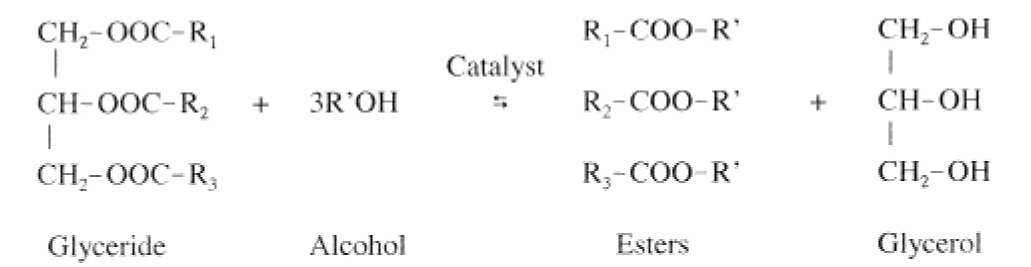

Figure 2-1. Biodiesel Transesterification Process

Biodiesel is similar to petroleum based diesel given that it operates in compression-ignition engines; however, biodiesel is a cleaner burning replacement fuel, non-toxic and biodegradable. On a life-cycle basis, biodiesel is more climate-friendly than diesel (Beer, *et al.*, 2001:30).

A blend of 20% biodiesel mixed with 80% petroleum diesel fuel (B20) can be used in nearly all diesel equipment without any engine modification requirements (Wardle, 2003:8). Higher percentage blends and pure biodiesel (100% biodiesel, or B100), can be used in many engines built in the past ten years with little or no modification (U. S. Department of Energy, 2004b). Contrary to the belief of some engine manufacturers, many road-test results found no difference in engine functionality between diesel and biodiesel (Bushanam and Edwards, 2004:12). Biodiesel is currently being used in over 100 major fleets to include trucking, school districts, public transit and military fleets (United States Department of Energy, 2001:6).

The use of biodiesel in diesel engines significantly reduces emissions of sulfates, hydrocarbons, carbon monoxide and particulate matter. The National Soydiesel Development Board reported that the use of B20 includes reductions of 31% in particulate matter, 21% in carbon monoxide, and 47% in total hydrocarbon emissions (Raneses, 1999:153; Beer, 2001:144). Biodiesel emissions from alternative-fueled engines consistently indicate lower emissions of reactive hydrocarbons, carbon monoxide, and particulate matter than diesel engines. The ratio of biodiesel to diesel is directly proportional to the emission reductions.

There appear to be no additional health risks of air toxic emissions from biodiesel with respect to mortality or toxicity. Compared with diesel, all air toxic emissions from biodiesel are lower in emissions except for acrolein (Beer, 2001:68). Though highly toxic, the slight increase in acrolein is offset by the decrease in the equally toxic aldehydes.

Biodiesel does have several disadvantages. One disadvantage of biodiesel includes the constraints on the availability of agricultural feedstock which imposes limits on the possible contribution of biodiesel as a fuel. Biodiesel is also more viscous than diesel fuel; this affects fuel atomization during injection and requires modified fuel injection systems for higher blends of biodiesel. Due to the high oxygen content, it produces relatively high NOx levels during combustion (Beer, 2001:31). Oxidation stability is lower than that of diesel so that under extended storage conditions it is possible to produce oxidation products that may be harmful to the vehicle components. Due to the absorbing characteristics of biodiesel, contact with humid air must be avoided. Production of biodiesel is not sufficiently standardized. Biodiesel that is outside of the American Society for Testing and Materials (ASTM) standards can cause corrosion, fuel system blockage, seal failures, filter clogging and deposits at injection pumps. Lastly, a modified refueling infrastructure is needed to handle biodiesels, which adds to their total cost.

2.4.6 Hydrogen.

Recent interest in hydrogen (H_2) as a substitute for gasoline and diesel in transportation markets is primarily due to two important realizations: (1) H_2 fuel is essentially limitless, as H_2 can be derived by electrolyzing water (ideally through the use of renewable energy technologies) and (2) H_2 fuel is clean burning, as the oxidation of hydrogen yields only water (Farrell *et al*., 2003:1357). For these reasons, H_2 is expected to meet a larger share of global energy needs in the coming decades. In the US and many other countries, the exclusive reliance on petroleum for transportation services has repeatedly raised concerns related to energy security, economic security and environmental quality; a H_2 fueled economy would reduce these concerns (Melaina, 2003:743).

Currently, H_2 is primarily produced from the steam reformation process (at very high temperatures) of natural gas or methane at a cost similar to gasoline (Bechtold, 1997:32). H_2 can be used to fuel vehicles directly in internal combustion engines or as a fuel cell. Because of their high efficiencies and near-zero emissions, fuel-cell vehicles (FCVs) are undergoing dynamic research and development efforts and could replace internal combustion engines (Farrell *et al*., 2003:1363). Important advantages of H_2 fuel cells are no air pollution or greenhouse gas emissions during operation, high energy efficiency and no soil or water contamination (Wang, 2002:307). The biggest disadvantage to using H_2 as a fuel is the low energy storage density compared with all other fuels (Bechtold, 1997:32). Another drawback to hydrogen fuel is capital cost of the vehicle and infrastructure. Due to complex fuel storage requirements, capital costs are expected to be significantly higher. The theoretical potential of hydrogen is there for great environmental benefits provided the technology can be implemented.

2.4.7 Other Alternative Fuels.

Another option of alternative fuels has recently been studied. Hythane also known as hydrogen and compressed natural gas (HCNG), a mixture of hydrogen gas and compressed natural gas is a clean burning fuel (Munshi, 2004:1). Relative to diesel, hythane reduces NO_x emissions by 95%. Compared with CNG, HCNG emissions of carbon dioxide decreased by 7%. Few modifications are needed to run hythane in internal combustion engines (Munshi, 2004:2). The transportation industry also sees hythane as a transition from liquid fuels to fuel cells as the fuel source for vehicles in the future.

Another fuel blend is O^2Diesel™ developed by AAE Technologies, Inc. O^2Diesel™ is a 7.7% blend of ethanol with 1% of O^2Diesel's proprietary fuel additive technology added to conventional or ultra low sulfur diesel (Nixon, 2003:2). A generic version of O^2Diesel™ is known as e-diesel or diesohol which blends up to 15% ethanol with conventional diesel fuel and an emulsifier (Beer, 2001:41). AAE Technologies' research claims that using e-diesel is safe and dramatically lowers vehicles emissions including particulate matter, carbon monoxide and NO_x without the loss of operational performance or the need for vehicle or infrastructure changes (Nixon, 2003:1). E-diesel can be used in diesel engines with no modifications and also offers enhanced fuel characteristics such as increased lubricity and anti-corrosion properties (Beer, 2001:44).

2.5 Net Energy Gain/Loss

Energy balance for alternative fuels is a controversial subject. Net energy gain is defined as the difference between the energy in the fuel product (output energy) and the energy needed to produce the product (input energy). Some studies concluded that the energy inputs for producing corn ethanol were greater than the energy contained in the ethanol product. Pimental (1991) calculated a net energy loss of 54,000 British Thermal Units (BTUs) for corn-derived ethanol. However, more recent studies from the USDA in 2002 indicate a net energy gain between 21 and 34 percent for corn derived ethanol (Andress, 2002:2). Wang (2002) estimates that further technological improvements in agriculture practices will increase the net energy gain to 47 percent for corn based ethanol. In comparison, biodiesel has a 220 percent net energy gain, while gasoline, diesel and methanol all have net energy losses (-20, -16 and -24 percent respectively (Andress, 2002:2; Sheehan *et al.*, 1998:33). Limited data shows that there is a net energy gain when producing methanol only through phytoplankton byproducts. The Center for Solar Energy and Hydrogen Research indicates methanol synthesis produced from natural gas carries a net energy loss of 68% compared to a net energy loss of 80% for gasoline (Specht *et al*., 1998:392).

Compared with alternative fuels, both gasoline and diesel yield much less than energy than they consume. A study co-sponsored by the DOE and the USDA shows a net energy loss of 19.5% for gasoline and 15.7% for diesel fuel.

According to research conducted by Robert Edwards for the European Commission Joint Research Center, energy balance is not an integral characteristic when comparing transportation fuels (Edwards, 2004). Edwards suggests that GHG balance and costs are the main issues of consideration when using a well to wheels analysis. Precise energy input data, transport distances, and fuel distribution are not of high importance when comparing fuels in a well to wheels analysis. Unlike GHG balance and cost considerations, energy balance does not take into account cost, efficiency use of the renewable resources and greenhouse gas emissions. The allocation of the byproducts is the main difference between energy and GHG balance. The energy balance formula considers merely the energy content used for a process while GHG balance takes into account how a byproduct of a fuel such as animal feed or household products are employed (Edwards, 2004).

2.6 Air Emission Models

The EPA uses modeling for estimating emissions from vehicles and fuels. Rather than testing and emitting air toxics, modeling allows the EPA to predict future emissions of various fuels. *MOVES*, Motor Vehicle Emission Simulator encompasses the criteria pollutants, air toxics and greenhouse gas emissions under various conditions (United

States Environmental Protection Agency, 2004:1). The US Department of Energy sponsors the *GREET* (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model that allows researchers and analysts to evaluate well to wheel emissions of various vehicle and fuel combinations (Wang, 2001:1). *GREET* was developed by the Argonne National Laboratory in 1995 and is considered the industry standard for measuring air emissions (Wang, 2002:308). It measures both greenhouse gases and criteria pollutants. *POLCAGE* (Possibilistic Life Cycle Analysis using *GREET* and Environmental Design of Industrial Products) is the latest emissions model that was developed to test ten different fuel options for the Philippine automotive transport sector (Tan, 2004:907). The most extensive emissions research accomplished for the Australian Greenhouse Office included fifteen different transport fuels (Beer *et al*., 2001:xv). Beer *et al*. (2001) provided literature, studied their emissions and modeled future air quality emissions on these fuels. All of these models are excellent tools in estimating air emissions; however, none of the models took cost, performance or any other fuel characteristics or values into consideration.

2.7 Decision Analysis Models

There are two primary methods of thinking about decisions: alternative-focused thinking and value-focused thinking. Alternative-focused thinking (AFT) considers the alternatives and compares them to each other, while value-focused thinking (VFT) compares alternatives to organizational values (Keeney, 1992:3). AFT focuses on the actual alternatives, even though the choices do not reflect the fundamental objectives. VFT promotes the development of better alternatives that reflect what the decision maker values. Value-focused thinking implies that one determines what is important and subsequently measures these objectives (Keeney, 1992:6). VFT models should also be mutually exclusive and collectively exhaustive. Value and measure definitions should not overlap and all values and measures important to the decision maker must be present in the model. VFT models are best suited for structured decisions. Kirkwood (1997) states that completeness, non-redundancy, independence, operability and small size are keys to constructing a hierarchy (Kirkwood, 1997:16). VFT also provides insight to the decision. The following is the VFT 10-step Process developed for the Air Force Institute of Technology (Shoviak, 2001:63). This methodology will be described in more detail in Chapter 3 of this research.

Step 1: Problem Identification
Step 2: Create the Value Hierarchy
Step 3: Develop Evaluation Measures
Step 4: Create Value Functions
Step 5: Weight the Value Hierarchy
Step 6: Alternative Generation
Step 7: Alternative Scoring
Step 8: Deterministic Analysis
Step 9: Sensitivity Analysis
Step 10: Conclusions and Recommendations

2.8 Other Multiple-Objective Decision Analysis Tools

Similar to VFT, the Analytic Hierarchy Process (AHP) is a multiple-objective decision analysis tool developed by Dr. Tom Satty in the early 1970s (Winebrake and Creswick, 2003:360). AHP aids the decision maker in a future decision and always utilizes a top-down approach. The AHP has steps that are both similar and different than VFT. The following are the steps for AHP.

1. State the objective
2. Identifying the elements of the problem.
3. Select the alternatives.
4. Decompose the problem into a hierarchy.
5. Weight the hierarchy elements using pairwise comparisons.
6. Synthesize the priorities to create an evaluation of alternatives.
7. Arrange sets in different levels of relevance.
8. Conduct a sensitivity analysis on the results.

Once all criteria for the stated problem/goal are determined, they are grouped into homogenous sets. In each individual set, the criteria are sorted by means of a system called pairwise comparisons. This allows the decision maker to concentrate on two measures at a time. The measures are weighted on a 1 to 9 scale, 1 being equal importance and 9 being extremely more important. All criteria are weighted and scaled. The scores are analyzed using sensitivity analysis and scenarios. AHP is a solid decision analysis tool that applies to future decisions with limited research on current issues. AHP was not used in this research because all our criteria are certain and the research is used for a prompt decision. (Winebrake and Creswick, 2003:359). Poh and Ang (1999) used the AHP process while researching transportation fuels for Singapore. They used an iterative forward and backward approach unlike the top to bottom approach used in VFT (Weir, 2004). Unlike VFT, which only weights the hierarchy once, the AHP methodology can manipulate the scoring and become subjective with respect to the decision maker. Another difference between VFT and AHP is the order of the steps. Generating alternatives is the third step in AHP and the sixth step in VFT.

Life cycle assessment (LCA) is one of the most popular analysis tools for a product. The main purpose of LCA is to identify the environmental impacts of goods or services from the cradle to grave of that product or service (Goralczyk, 2003:205).

Lynch and Eliason (1997) developed a model that compared the following five performance categories: reliability, energy consumption, operating costs, capital costs and air pollution emissions and was evaluated at nine different geographical locations. (Lynch and Eliason, 1997:33). This model used the best available data for mass transit systems; however, the comparison used equal weightings across all measures.

The EPA used the Multi-Criteria Integrated Resource Assessment (MIRA) to improve research results relating to environmental issues (Stahl, *et al*., 2002:1). MIRA uses a mixture of societal values and environmental policy to help exacerbate environmental problems. MIRA may be one of the better multiple objective decision analysis tools for environmental issues. The weighting is the biggest downfall of MIRA. The weightings are equal across the board unlike VFT.

Hackney and deNeufville (1999) considered a life cycle model that compared emissions and energy efficiency trade-offs of alternative fuels on a level playing field by eliminating tax incentives. Their study was an improvement over previous models but was limited to alternative fuels by disregarding more efficient fuel blends such as B20 and E85. This model compared cost and emissions; however, another limitation of this study is that it did not give an all-inclusive comparison that included all measure evaluators.

2.9 Summary

Chapter 2 provided background on the history of the automotive fuel industry and how the automotive industry has affected the environment through air pollution and the near exhaustion of petroleum. To ease the air pollution and oil shortage problems, non-renewable alternative fuels and renewable alternative fuels can and should replace petroleum based fuels for automotive use. The chapter thoroughly explains advantages and disadvantages of renewable alternative fuels compared to petroleum based fuels. Chapter 2 also introduced emission models used in previous research, the VFT process and an additional multiple-objective decision analysis tools such as AHP and MIRA. The chapter finally explained why VFT is the most appropriate technique to use in this research effort.

Chapter 3: Methodology

This chapter describes how Value-Focused Thinking (VFT) was applied to the decision of choosing alternative fuels for Government Owned Vehicles (GOVs). In a broad sense, Value-Focused Thinking consists of deciding what you want and figuring out how to get it (Keeney, 1994:4). In the decision making process, values are more fundamental than the solution alternatives. Shoviak (2001) established a ten-step process that thoroughly covers the entire framework of Value-Focused Thinking. The 10-step process will be divided through three different chapters. Steps 1 through 6 are included in this chapter. Steps 7-9 are included in the results, Chapter 4. Step 10 will cover the conclusion and recommendations in Chapter 5.

3.2 Step 1: Problem Identification

The utilization of alternative fuels, predominantly in the transportation sector, is necessary in order to decrease the consumption of petroleum and dependence on petroleum imports. Government agencies have a responsibility to reduce petroleum utilization, not only because of Presidential Executive Orders, but also for good stewardship for the world according to the Kyoto Protocol (Clinton, 1999; Maples *et al*., 1996:2). Although alternative fuels are used at many Air Force installations, as of September 2004, only six Air Force installations were in full compliance of Executive Order 13149 and the EPAct (Parker, 2004:23). The Air Force Center for Environmental Excellence (AFCEE) sponsored this research as an effort to increase Air Force wide knowledge and implementation of alternative fuels.

This VFT model was designed to assist military installation decision makers in selecting renewable alternative fuels for government owned vehicles. Using this model, decision makers may save money, reduce their dependence on imported petroleum, reduce greenhouse gas emissions and criteria air pollutant emissions without compromising the performance of the automobile. The model was flexibly built so that new alternatives for fuels can easily be implemented and scored. VFT allows for the development of newer technologies and options to be easily added to the model without having to reconstruct a new model for each modification (Keeney, 1992:38-39).

3.3 Step 2: Create the Value Hierarchy

Once the overarching problem of the model was identified, the first tier of values was constructed. Values are principles used to evaluate the potential consequences of proposed alternatives. The value hierarchy is an organized representation of what is important to the decision-maker with respect to the overall problem. Kirkwood (1997) identifies the top-down method and the bottom-up method as approaches to develop this hierarchy (Kirkwood, 1997:19-23). The top-down method begins by deciding what first tier value is most important (*Environmental Issues* or *Resources*). Through discussions with the decision maker, AFCEE, the first tier was built. The first tier value hierarchy is shown in Figure 3-1. The overarching decision is displayed in red and the first tier values are displayed in pink.

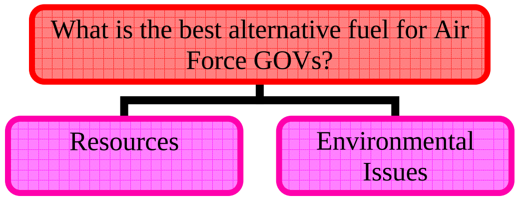

Figure 3-1. First Tier Values

After the first tier categories were identified, they were broken down into more distinct second tier values. The *Resources* value is shown in Figure 3-2. The second tier of the value hierarchy contains the measures upon which the entire decision is based. The first tier value is shown in red and the second tier values are displayed in pink.

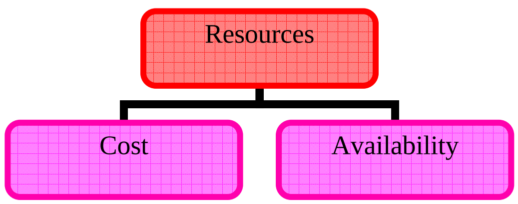

Figure 3-2. *Resources* Value

3.3.1 Resources.

The *Resources* value includes all *Costs* and *Availability*. In order to capture the primary costs associated with fuels, it was necessary to consider initial as well as future financial requirements. Two measures were used as contributors to the cost value. These measures include *Life Cycle Cost* and *Fuel Credits*. Executive Order 13123 mandated the utilization of life cycle costs when considering alternative fuel options (Clinton, 1999). *Life Cycle Cost* includes base price, conversion cost (engine modifications), infrastructure cost, fueling costs, and maintenance costs. Fuel credits are used as incentives to use certain alternative fuels. Alternative fuel vehicles defined by the US Department of

Energy (DOE) receive fuel credits. This model assumed that fuels used in alternative fuel vehicles receive fuel credits. B20 is not defined as an alternative fuel but receives a fuel credit for every 2,250 gallons of B20 used. Figure 3-3 displays the second tier *Cost* value as it appears in the hierarchy. All measures are more thoroughly described in Appendix A.

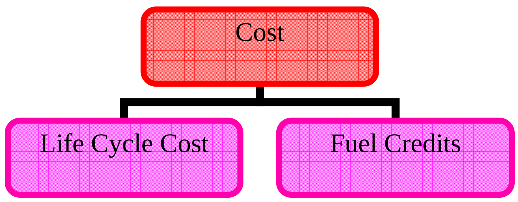

Figure 3-3. *Cost* Value

The next second tier value underneath *Resources* is *Availability*. *Availability* is important because the fuel should be easily accessible for fueling and must sufficiently supply the demand. *Availability* is measured by *Distance to Fueling Station* and *Supply* and is shown in Figure 3-4. McChord Air Force Base switched from CNG to E85 because the CNG fueling station was located too far from base and the E85 fueling station was built on base (United States Government Accounting Office, 2003:6).

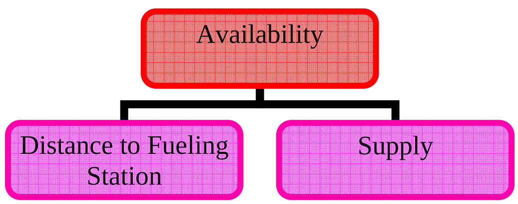

Figure 3-4. *Availability* Value

3.3.2 Environmental Issues.

Environmental Issues refer to the environmental friendliness of the alternative. The benefits of using an environmentally friendly alternative fuel are smaller impact on the environment, improved public image and the meeting of government milestones that require the use of alternative fuels. As shown in Figure 3-5, *Environmental Issues* are measured through *Air Emissions*, *Safety* and *Fuel Source*. Air emissions measured are *Greenhouse Gases*, *Nitrogen Oxides*, *Volatile Organic Compounds*, *Carbon Monoxide*, *Sulfur Dioxide* and *Particulate Matter*. Figure 3-6 displays the *Air Emissions* second value tier with its associated measures. The data for *Air Emissions* came from the GREET model as discussed in chapter 2. Also stated in chapter 2 was the importance of air pollution from automobiles.

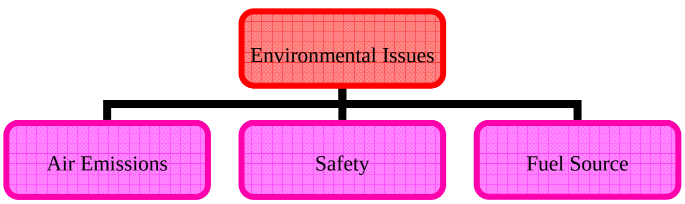

Figure 3-5. *Environmental Issues* First Tier Value

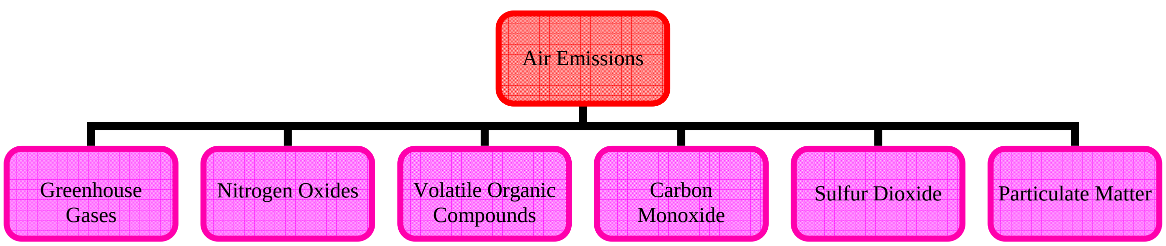

Figure 3-6. *Air Emissions* Second Tier Value

Fuels safety for the decision maker's purposes included handling, storage, dispensing and utilization of fuels. Figure 3-7 displays the *Safety* value which is measured by the *Flash Point* and whether or not the alternative is a *Ground or Water Contaminant*.

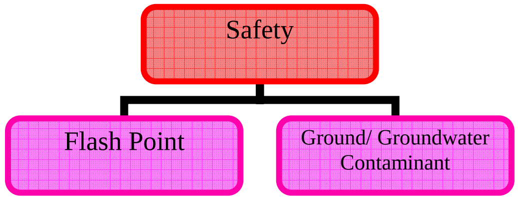

Figure 3-7. *Safety* Second Tier Value

The *Fuel Source* is measured by the type of fuel identified by the alternative. The alternatives can be greater than or equal to 85% renewable, alternative, less than 85% renewable blended with petroleum, or 100% petroleum. *Fuel Source* is highly regarded due to the role of renewable feedstocks in sustainable development and domestic energy security. The *Fuel Source* second tier value is displayed in Figure 3-8.

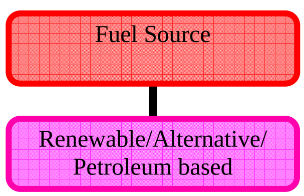

Figure 3-8. *Fuel Source* Second Tier Value

After analysis and consultation with subject matter experts and the decision-maker, the current model now characterizes the "fundamentally important problem areas" being addressed (Keeney, 1992:98). Figure 3-11 shows the entire VFT hierarchy.

3.4 Step 3: Develop Evaluation Measures

Once the construction of the model hierarchy was complete, the next step was to develop evaluation measures. These evaluation methods were created to define how each measure was assessed and scored. According to Kirkwood, evaluation measure scales are classified as either “natural or constructed, and either direct or proxy” (Kirkwood, 1997:24). In this context, natural is defined as a scale that is interpreted the same by everyone. Natural scales are easily quantified, such as cost measured in dollars. From this model, measurement of grams of carbon monoxide emitted is an example of a measure with a natural scale. A constructed scale is used when a natural scale does not exist to evaluate a measure. An example of a constructed scale from this model is *Fuel Credits*. One fuel credit is equal to 450 gallons of B100 or 2,250 gallons of B20.

A direct scale “measures the degree of attainment” of the objective while a proxy scale “reflects the measurement of its associated objective,” but does not directly measure it (Kirkwood, 1997:24). Profit in dollars is measured on a direct scale. Gross national product is measured on a proxy scale because it measures the economy of a country.

Each measure has a set upper and lower boundary. The upper boundary identifies the most preferred level of a measure, while the lower boundary identifies the least preferred level of a measure. Table 3-1 lists all measures, the measure type, boundaries and the units of each measure.

Table 3-1. Model Measures.

2nd Tier Value	Measure	Measure Type	Lower Bound	Upper Bound	Units
Cost	Life Cycle Cost	Natural Proxy	$0.30	$0.20	dollars/gallon
	Fuel Credit	Constructed Proxy	0	10	credits/1000 gallons
Availability	Distance to Fueling Station	Constructed Proxy	>5	On base	miles
	Supply	Natural Direct	0	100	million gallons/day
Air Emissions	Greenhouse gases	Natural Direct	1000	0	grams/mile
	NOx	Natural Direct	5	0	grams/mile
	SOx	Natural Direct	5	0	grams/mile
	PM	Natural Direct	5	0	grams/mile
	CO	Natural Direct	7	0	grams/mile
Safety	Flash Point	Natural Direct	-300	175	degrees Fahrenheit
	Ground/ Water contaminant	Constructed Direct	No	Yes	none
Fuel Source	Renewable/ Alternative	Constructed Proxy	Petroleum based	$\geq$ 85% Renewable	fuel type

3.5 Step 4: Create Single Dimension Value Functions

Single dimension value functions (SDVFs) are used to standardize each measure in the hierarchy. Kirkwood employs two procedures called piecewise linear and exponential (Kirkwood, 1997:61). Piecewise linear SDVFs can be used when the scoring has discrete or categorical options such as low/medium/high or yes/no. Exponential SDVFs have equations of a particular form which depend on the extreme high and low values of the measure. In the majority of situations, the exponential SDVF is used. Equation 3-1 shows the exponential SDVF for a monotonically increasing exponential evaluation measure (Kirkwood 1997:65; Duke, 2004):

$$V(x) = \frac{1 - \exp[-(x - Low)/\rho]}{1 - \exp[-(High - Low)/\rho]} \qquad (3\text{-}1)$$

where

x = the scored amount of the alternative in that measure

High = the upper extreme of the measure

Low = the lower extreme of the measure

ρ = strength value that is set by the decision-maker that changes the shape of the value function (ρ can not equal infinity)

The Logical Decisions software uses the exponential SDVF equation. The decision maker adjusts the "ρ" value as well as the "High" and "Low" values. For all exponential SDVFs, the (linear, concave or convex and positive or negative) relationship between the value and the score of the measure is more important than the actual shape of the function. Linear functions represent constant returns to scale, concave functions represent decreasing returns to scale and convex functions represent increasing returns to scale. A value function with a positive slope signifies a measure that increases in value as the function reaches the "High" value. In contrast, a value function with a negative slope represents a measure that decreases in value as the function reaches the "High" value. Figure 3-9 shows an example of a piecewise linear SDVF in this model.

Figure 3-9. *Ground or Water Contaminant* SDVF

The *Ground or Water Contaminant* measure scores whether or not an alternative is a contaminant. It is scored as either a 1 or 0. The *Particulate Matter* measure is an example of a convex, decreasing exponential SDVF as displayed in Figure 3-10. The SDVFs for remaining measures in this model can be found in Appendix A.

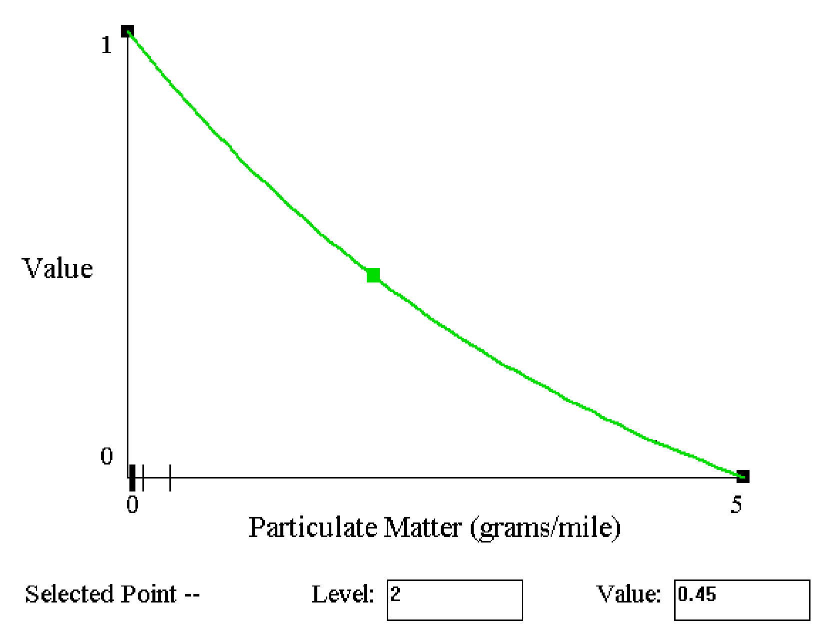

Figure 3-10. *Particulate Matter* SDVF

3.6 Step 5: Weight the Value Hierarchy

The hierarchy was weighted using a top down approach and was validated by the subject matter experts at the Air Force Center for Environmental Excellence (AFCEE). The top down weighting approach required that the weights of each value be assigned in relation to other values in that tier. The second tier is weighted by assigning a value in relation to other values in that tier within that first tier value. The measures are assigned weightings in relation to other measures under the same second tier.

The first tier values of *Resources* and *Environmental Issues* are the first values to be weighted under the top-down approach. *Environmental Issues* was weighted using a direct assessment approach. The decision maker gave *Environmental Issues* a weighting with a ratio of 13:7 compared to *Resources*. Therefore, *Environmental Issues* received a weighting of 65% and resources received a weighting of 35%. The sum of these values adds up to 100%. Equation 3-2a and b show the calculations for finding the weight of *Environmental Issues* and *Resources*.

$$W_{\text{Environmental Issues}} = 13/20 = 65\% \qquad (3\text{-}2a)$$

$$W_{\text{Resources}} = 7/20 = 35\% \qquad (3\text{-}2b)$$

Underneath the *Resources* first value tier are the second tier values of *Cost* and *Availability*. Using the direct assessment approach, the decision maker assigned *Cost* a weighting of 60% and *Availability* 40%. Multiplying the *Cost* weighting by the weighting of *Resources* gives us the global weighting of *Cost*. The same was done for *Availability*. Cost has a global weighting of 33.3% and *Availability* 11.1%.

Air Emissions, *Safety* and *Fuel Source* are second tier values that fall under the *Environmental Issues* first value tier. *Air Emissions*, *Safety* and *Fuel Source* are weighted in relation to each other because they are under the *Environmental Issues* first tier. Therefore, *Life Cycle Cost* and *Fuel Credits* are assigned weights compared to each other because they are both located under the cost second tier. Figure 3-11 displays the entire hierarchy with local weightings. The sum of each separate tier within a branch equals 100%. The sum of *Environmental Issues* and *Resources* equals 100%. The sum of *Cost* and *Availability* equals 100% and the sum of *Air Emissions*, *Safety* and *Fuel Source* equals 100%. For the measures, the sum of *Life Cycle Cost* and *Fuel Credits* equals 100%. This method of displaying local weights is the same for all measures with each respective second tier value. The overarching problem is shown in red, the first tier values in pink, second tier values in green, and measures in blue.

A complete table of global weights for all measures is included in Table A-1. The global weightings show the comparison of the weights for all of the measures in the hierarchy. The global weightings of all measures in terms of percentages equal 100%.

Step 6: Generate Alternatives

All of the alternatives for this model were chosen from the existing literature review. In a study for the Australian Greenhouse Office, the life cycle emissions of fifteen different fuels in heavy duty vehicles were evaluated (Beer *et al*., 2001). These fuels included compressed natural gas, liquefied natural gas, three types of unleaded gasoline blends, six diesel fuel blends, two biodiesel fuel blends, ethanol and hydrogen. Ahouissoussi and Wetzstein (1997) studied the comparative cost analysis of biodiesel, compressed natural gas, methanol and diesel for transit bus systems. The most comprehensive study to date was accomplished by Hackney and de Neufville (2001). Their work included the emissions, energy and cost trade-offs of eleven different fuel sources.

This model incorporates transportation fuels that are easily procured in the United States. The alternatives were also chosen such that it best achieves the values specified in the model. The alternatives are biodiesel (B100 and B20), ethanol (E85), methanol (M85), e-diesel, CNG, propane, gasoline and diesel fuel. Gasoline and diesel fuel are not considered alternative fuels. However, running these alternatives in the model will give the decision maker a better understanding of how these conventional fuels compare to alternative fuels with the established values and measures.

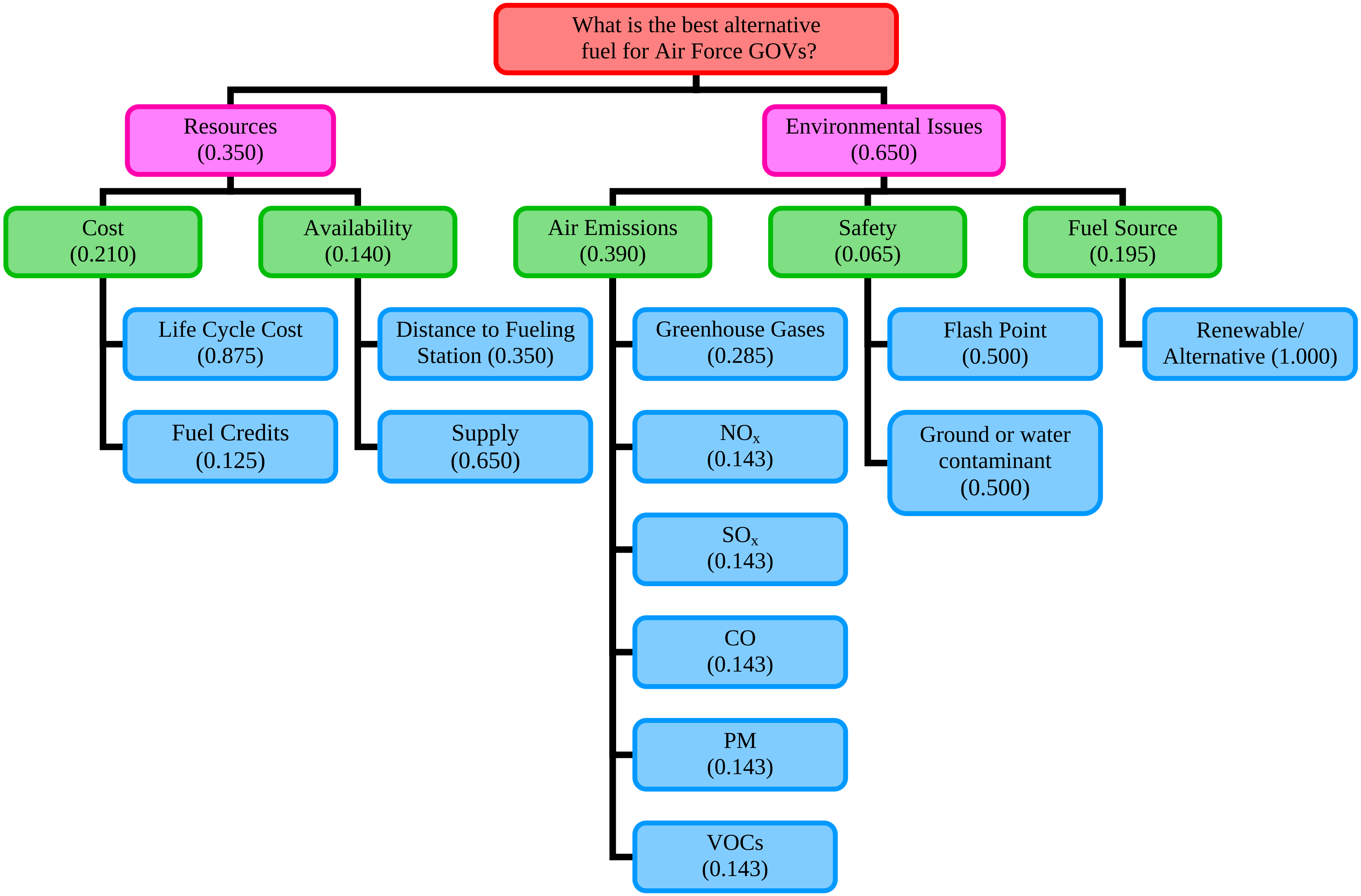

Figure 3-11. Complete Value Hierarchy with Local Weightings

Chapter 4: Results

This chapter presents results obtained through the application of the VFT model to the AFCEE in San Antonio, Texas. The results include the scoring and rankings of the alternatives and sensitivity analysis of the developed model. The model was run using data from three unnamed Air Force Bases at various geographic locations to determine if the rankings of alternatives would change at these differing locations. A minimum amount of sensitivity analysis on the three other geographic locations was performed. The data for *Life Cycle Cost, Distance to Fueling Station* and *Availability* measures were the only affected attributes for those three model runs. The assumption was made that all other data remained constant. The physical characteristics of the fuels such as air emissions and flash point do not change with a change in geographic locations.

As mentioned in the previous chapter, the results are a combination of steps 7 through 9 (alternative scoring, deterministic analysis and sensitivity analysis) of the model. Some of the data for scoring the alternatives was provided by the *Alternative Fuels Handbook* (Bechtold, 1997). All air emission data came from testing results using the *GREET* model (Wang, 2001). Deterministic and sensitivity analysis was completed using the *Logical Decisions* program (Logical Decisions, 2001).

4.1 Step 7: Alternative Scoring

Tables 4-1 and 4-2 show the scoring of each alternative within each measure. Alternatives are scored one measure at a time. The tables are broken up into the respective first tier values. Table 4-1 shows the actual scoring of the measures in the

Resources first tier value for the AFCEE model. These values are input into a *Logical Decisions* matrix and scored based on the SDVFs of each measure.

Table 4-1. Alternative Scoring for *Resources* Value

Alternative	Life Cycle Cost (US $/mile)	Fuel Credits (credit per 1000 gallons)	Distance to Fueling Station	Production (million gallons/year)
B100	0.2687	10	< 5 miles	> 100
B20	0.2244	2	On base	> 100
E-Diesel	0.2221	0	< 5 miles	> 100
Diesel Fuel	0.2164	0	On base	> 100
E85	0.2787	10	< 5 miles	> 100
M85	0.2708	10	> 5 miles	> 100
CNG	0.2419	10	On base	> 100
Gasoline	0.2200	0	On base	> 100
Propane	0.2677	10	< 5 miles	> 100

Table 4-2 shows the actual scoring of the measures in the *Environmental Issues* first Tier value. All air emissions data was output from the *GREET 1.6 model* (Wang, 2001). Many assumptions were made when inputting data into *GREET*. The scenario and fuel pathway selections, pathway options, fuel production, feedstock, fuel transportation and vehicle operation were all characteristics of the model that must be chosen by the user or a default characteristic was used. The only changes made for the air emissions output were the percentage of renewable feedstock used for the fuels. B100, B20, M85, and E85 were all fuel blends that were changed in the *GREET* model specifically for utilization in this VFT model. Once all fuel and vehicle assumptions were made, the *GREET* program output a Microsoft Excel spreadsheet of air emissions. The flash point temperatures were taken from the *Alternative Fuels Guidebook* (Bechtold, 1997). All of the data from Table 4-2 was input into a *Logical Decision* matrix and scored against individual SDVFs.

Table 4-2. Alternative Scoring for *Environmental Issues* Value

Alternative	GHGs (grams/ mile)	NO_x (grams)	SO_x	PM-10	Carbon Monoxide (grams)	VOCs	Flash Point (degrees Fahrenheit)	Fuel Source
B100	203	0.843	0.128	0.056	3.182	0.745	175	≥ 85% renewable
B20	321	0.312	0.086	0.043	2.876	0.202	170	< 85% renewable
E-Diesel	416	0.7	0.15	0.13	1.12	0.11	55	< 85% renewable
Diesel Fuel	416	0.758	0.17	0.132	1.125	0.114	165	Petroleum
E85	398	0.926	0.439	0.352	4.413	0.472	55	≥ 85% renewable
M85	494	0.454	0.066	0.037	4.232	0.231	52	≥ 85% renewable
CNG	465	0.563	0.101	0.03	4.555	0.125	-300	Alternative
Gasoline	506	0.492	0.232	0.053	5.595	0.293	-45	Petroleum
Propane	445	0.441	0.093	0.033	4.148	0.087	-156	Alternative

4.2 Step 8: Deterministic Analysis

After each alternative was scored within each measure, the y-axis values of each alternative were multiplied by the weighting of each measure and then summed across all measures for each alternative. The computation of each alternative's total value score uses the value function as shown in Equation 4-1 (Kirkwood, 1997; 61). *Logical Decisions* does not output the total value score of an alternative nor does it output the corresponding score for an alternative within a measure.

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (4\text{-}1)$$

where,

$v(x)$ = The total value score of alternative x.

$v_i(x_i)$ = The single dimension value function for measure i

x_i = The score for alternative x on measure i

w_i = The weight for measure i

n = total number of measures

$$\sum_{i=1}^{n} w_i = 1.0$$

The alternatives are then ranked in descending order according to their total score. Examining how each alternative received its value provides insight to the decision maker to see where each alternative scored within each value or measure.

4.2.1 Deterministic Analysis for AFCEE Model.

Figure 4-1 displays the ranking of alternatives with respect to all model measures. This gives the decision maker an overall vision of the problem with respect to the measures. B100 ranked as the most preferred alternative and E85 (ethanol) ranked second. Unsurprisingly, diesel and gasoline ranked as the lowest two alternatives in this model. From Figure 4-1, it is evident that B100, E85 and M85 (methanol) scored high in the *Renewable/Alternative Fuel* measure compared with other fuels. B100 also scored highest in the *Greenhouse Gases* measure, while all fuels appeared to score equally in the *Supply* measure. Although diesel and gasoline scored lowest overall, they both scored relatively high in *Life Cycle Cost*. M85 scored lowest in *Distance to Fueling Station*, but compensated with a high *Flash Point* score. B100, E85, CNG (compressed natural gas), M85 and propane all received high *Fuel Credits* scores, and propane, B100, E85, and CNG scored high in the *Ground or Water Contaminant* measure. The disadvantage of grouping all measures in the ranking of alternatives is difficulty in seeing the value of measures with smaller weightings such as *Nitrogen Oxides*, *Sulfur Oxides*, *Volatile Organic Compounds* and *Carbon Monoxide*. In order to gain more insight on the ranking of alternatives, bar graphs of rankings within each value tier need to be examined.

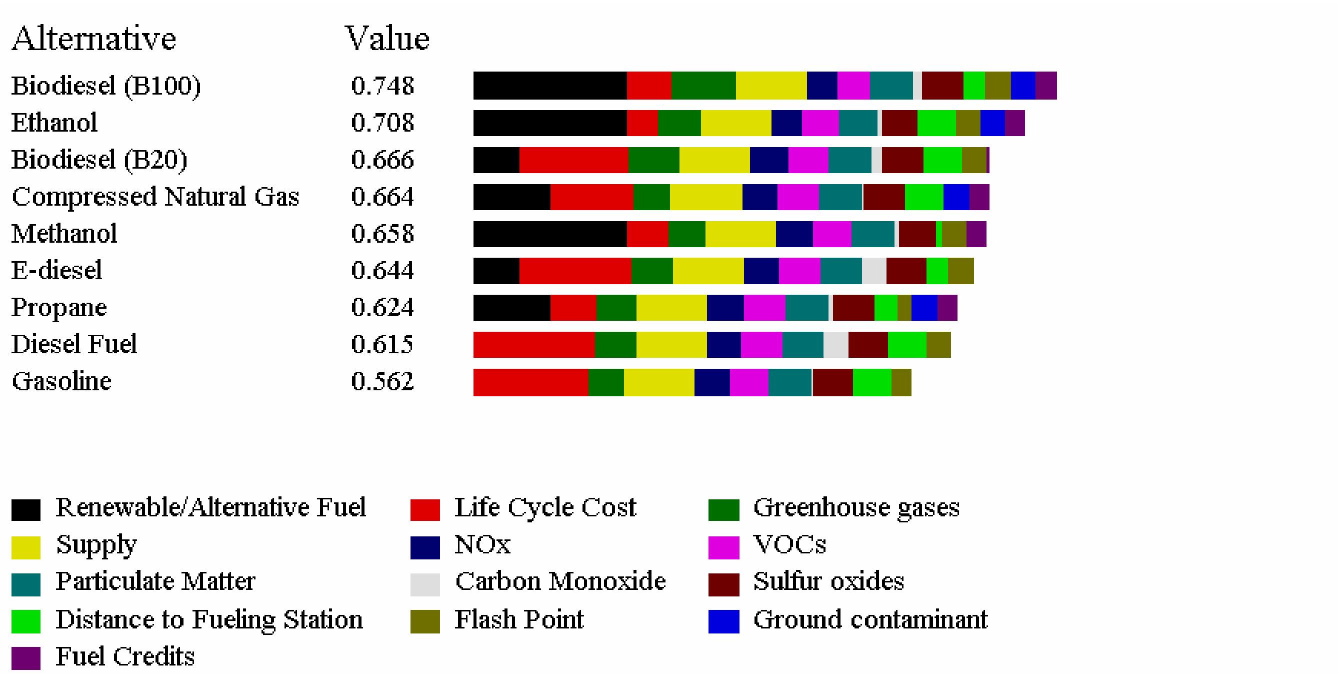

Figure 4-1. Overall Ranking with Respect to Measures

Looking at the ranking of alternatives with respect to the first tier value gives the decision maker a bigger picture of the two most important values according to the hierarchy for this model. The ranked alternatives with respect to the first tier values are shown in Figure 4-2. The bar chart shows the alternative name and the total score on the left of the bar graph. The different colors in the bar graph represent the scoring of the alternatives with respect to the first tier values. The results show that B100 is the best alternative followed by E85. The black portions of the bars illustrate the scoring with respect to *Environmental Issues* and the red portions of the bars represent the scoring with respect to the *Resources* first tier value as shown in the legend underneath the bar charts. From Figure 4-2, it is evident that B100 and E85 (E85) scored highest with respect to *Environmental Issues*, while gasoline and diesel scored lowest with respect to *Environmental Issues*. It is also easy to see that methanol (M85) scored lowest in the *Resources* value.

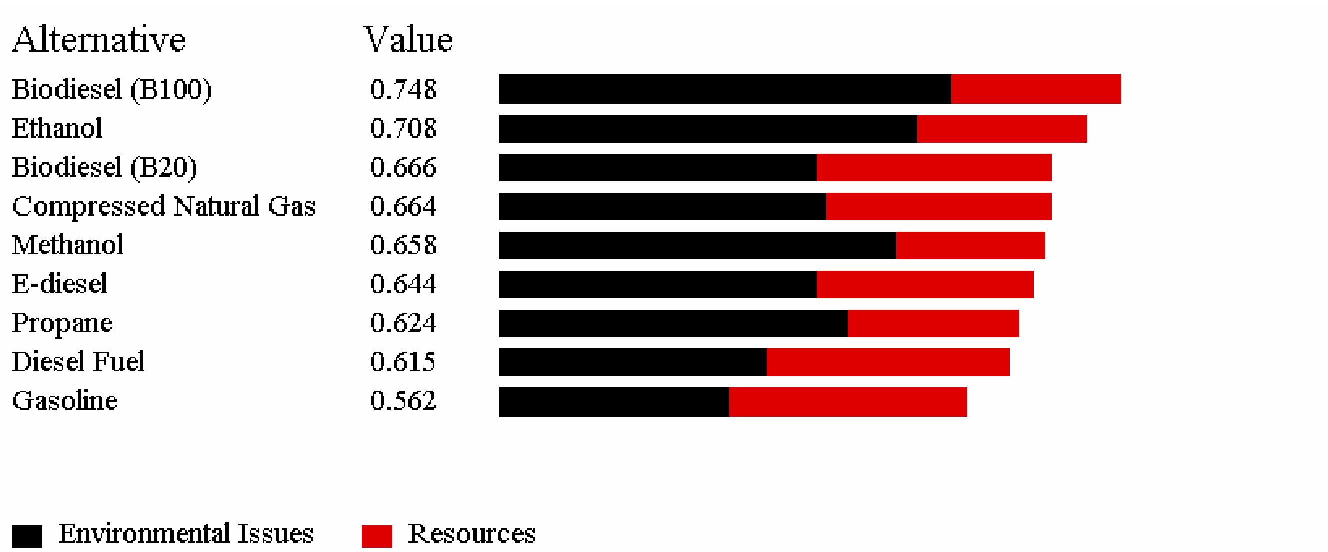

Figure 4-2. Overall Ranking with Respect to First Tier Values

It is also important to see how the alternatives scored within the first tier values. Figure 4-3 shows the breakout of the total value for each alternative within the *Resources* first tier value. The legend underneath the bar graph shows the two different colors representing the two second tier values, *Cost* and *Availability*, which fall underneath *Resources* in the model hierarchy. The figure shows a clear distinction in cost among fuels. The top five fuels (diesel, gasoline, B20, CNG and e-diesel) cost significantly less; therefore, scoring higher than the last four fuels (propane, E85, B100 and M85). The red bars show the scoring of the alternatives with respect to the *Availability* second tier value. It is difficult to see how each alternative scored under this value. Further analysis indicates that all fuels scored the same under the *Supply* measure of the *Availability* value. The actual scoring for the *Supply* measure is shown in Table 4-1. Breaking the rankings down into measures within the *Availability* value will also provide insight.

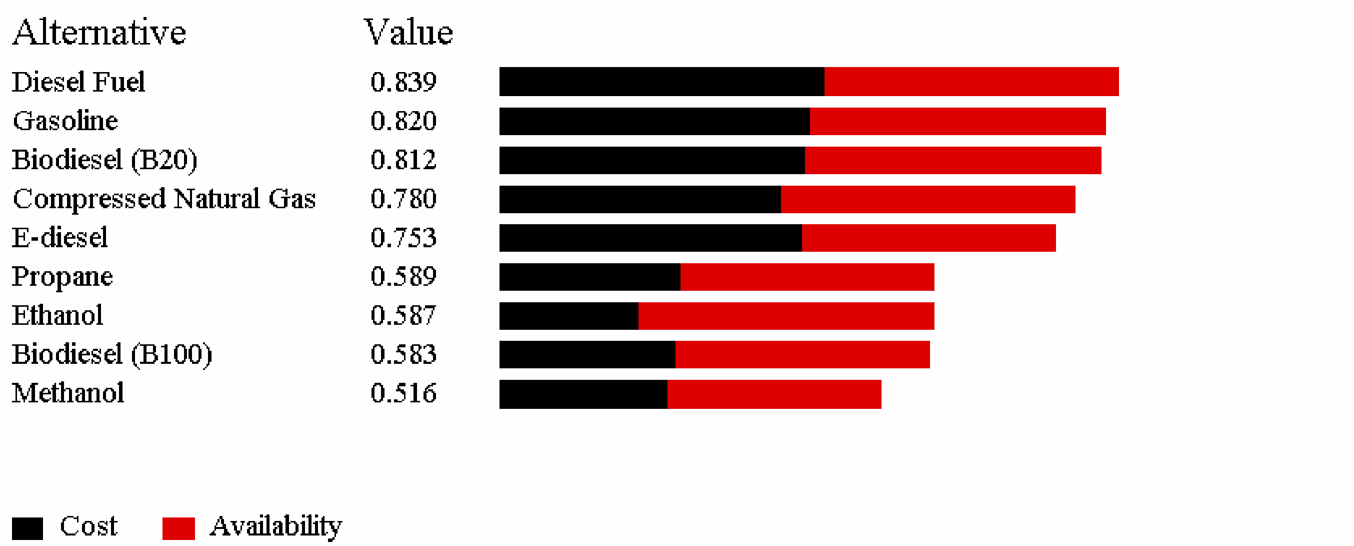

Figure 4-3. *Resources* Ranking and Scores

Figure 4-4 shows the scoring for the two measures under the *Availability* second tier value. This bar chart clearly shows that all fuels scored equally under *Supply* because all fuels meet the overall fuel demands with respect to the overall supply of the fuel. M85 scored the lowest under the *Distance to Fueling Station* measure due to its increased distance from the decision maker compared to all other fuels. B100, e-diesel and propane are all located within five miles of the base leading to a lower score compared to B20, CNG, E85 and gasoline, which are all located on base.

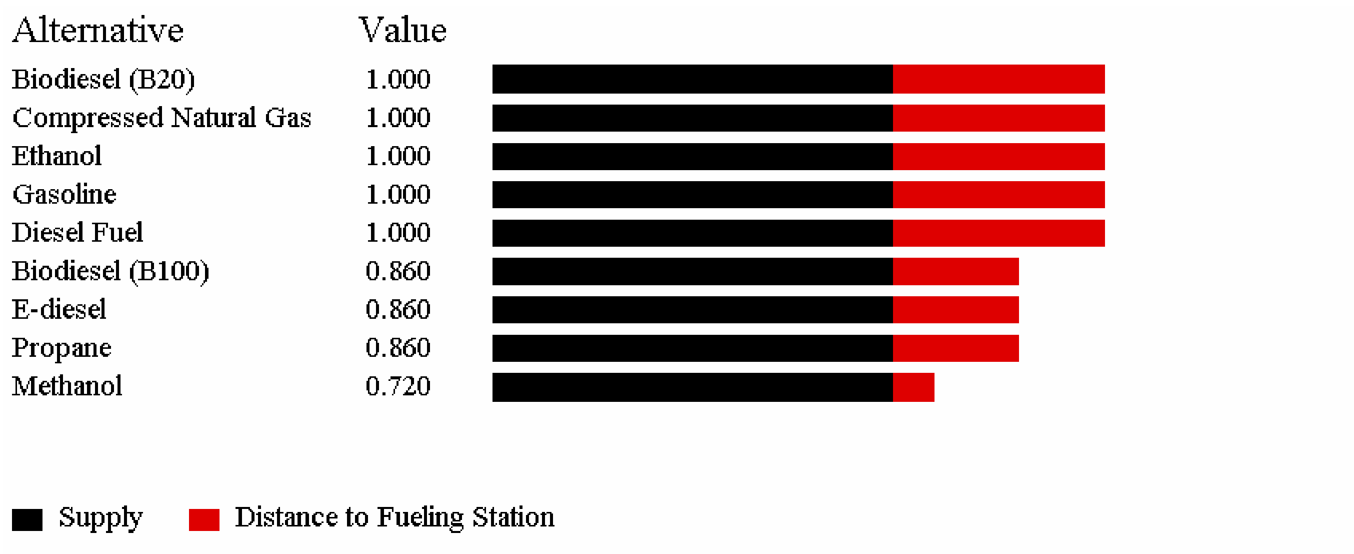

Figure 4-4. *Availability* Ranking and Scores

Besides *Availability*, the other second tier value under *Resources* is *Cost*. Figure 4-5 shows the rankings and total value of the fuels with respect to *Cost*. Diesel ranked highest even though it received no score within the *Fuel Credits* measure. Although CNG, propane, B100, M85 and E85 all scored highest within the *Fuel Credits*, they all scored lowest under the *Cost* value. This indicates that *Life Cycle Cost* has a much higher weighting than *Fuel Credits*. The chart shows that diesel scored highest with gasoline and e-diesel following closely behind under the *Life Cycle Cost* measure.

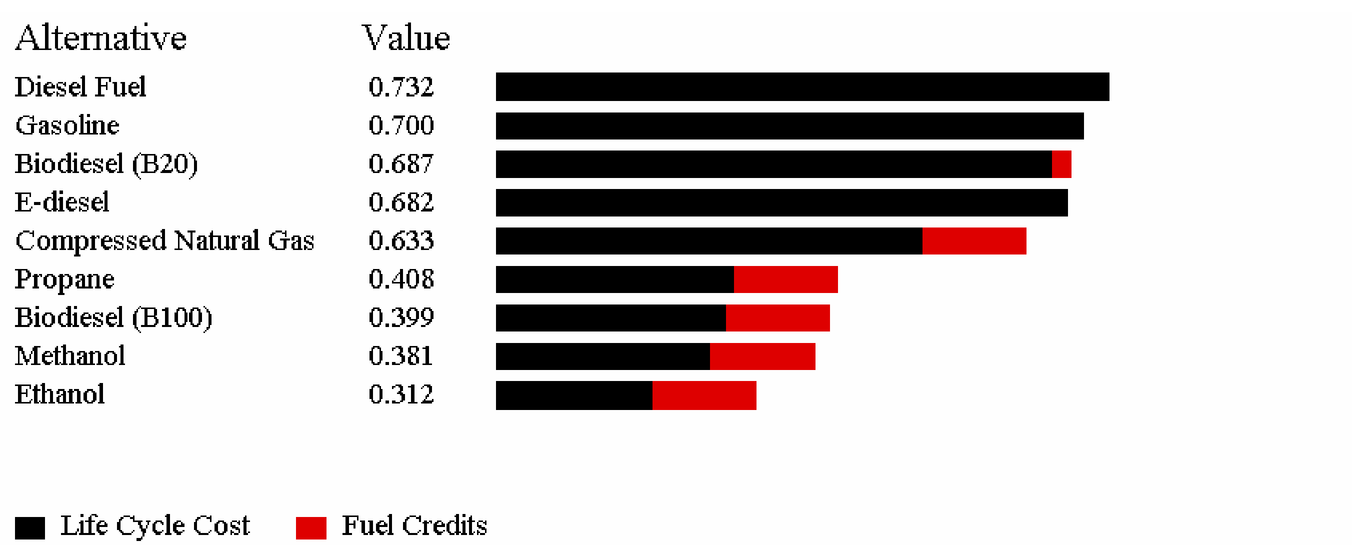

Figure 4-5. *Cost* Ranking and Scores

After looking at the rankings of the *Resources* first value tier, it is important to see how the alternatives ranked with respect to the *Environmental Issues* first value tier. At first glance, it seems that all fuels scored similarly regarding the *Air Emissions* second tier value. Fuels that scored high under *Fuel Source* indicated a direct relationship to the *Environmental Issues* overall ranking. B100, E85 and M85 all scored highest under the *Fuel Source*; therefore, also ranking highest in *Environmental Issues*. *Safety* played a less significant role as indicated by the green bars; however, it played a decisive role between the rankings of M85 and E85.

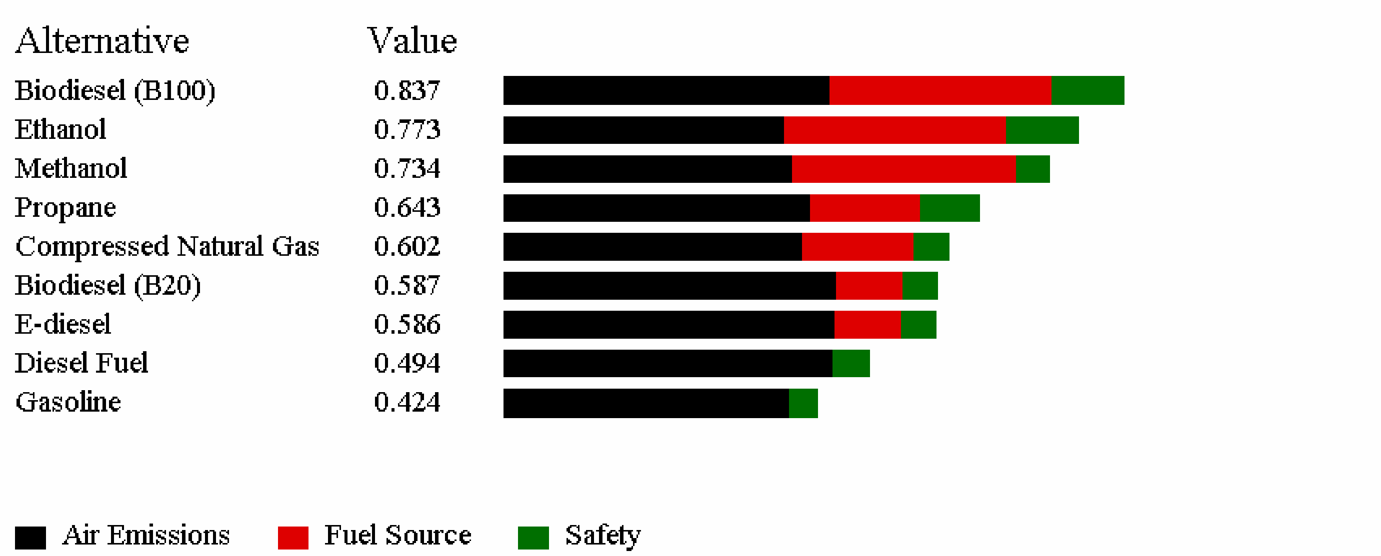

Figure 4-6. *Environmental Issues* Ranking and Scores

Air Emissions, *Fuel Source* and *Safety* rankings and scores will provide further insight about the overall decision. Figure 4-7 shows the rankings and scores for the *Safety* second tier value. B100 received a perfect score under the *Safety* value due to its high flash point temperature and non-contaminating characteristics. E85 and propane also scored high under this second tier value. All other fuels either received a score of zero for the *Flash Point* or *Ground or Water Contaminant* measure. CNG received a zero for *Flash Point* and B20, diesel, e-diesel, M85 and gasoline all received a zero for the *Ground or Water Contaminant* measure.

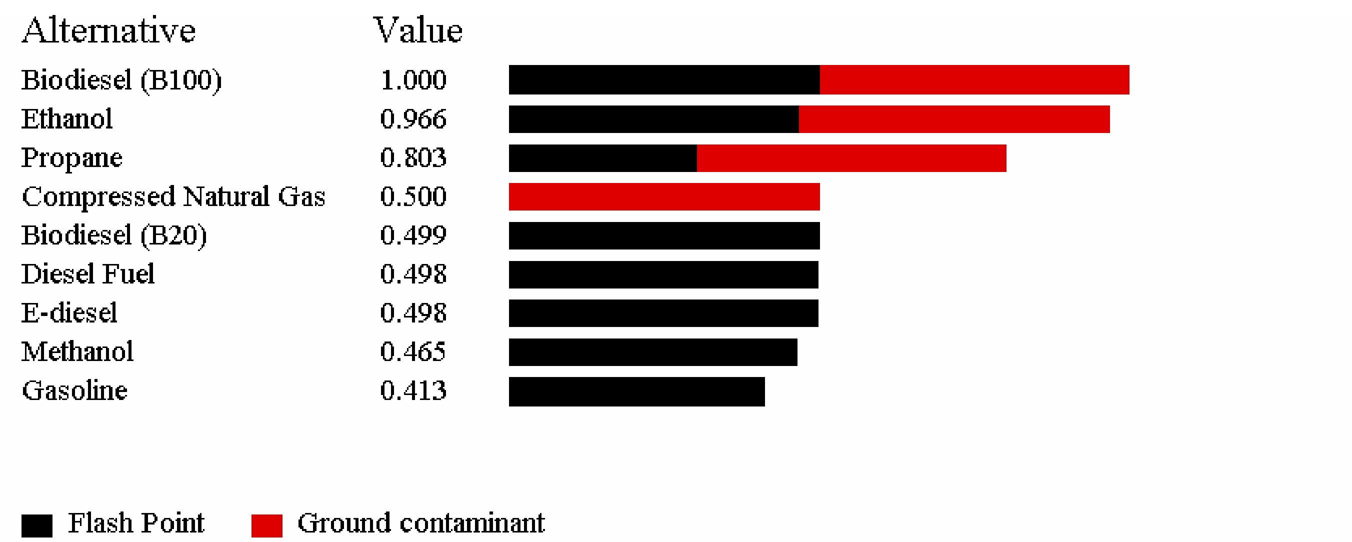

Figure 4-7. Safety Ranking and Scores

The *Fuel Source* played a decisive role in the overall scoring and alternative rankings. It accounts for 19.5% of the overall weighting in this analysis. Figure 4-8 shows the rankings of the fuels under the *Fuel Source* second tier value. Only one measure exists under this value. The *Renewable/Alternative Fuel* measure is categorical and each fuel had the same score as at least one other fuel. B100, E85 and M85 each had perfect scores in this measure and gasoline and diesel both scored zero. CNG and propane each received a value of 0.500 because they are both considered non-renewable alternative fuels. B20 and e-diesel were compensated with a value of 0.300 under the *Fuel Source* value because they are considered renewable blends.

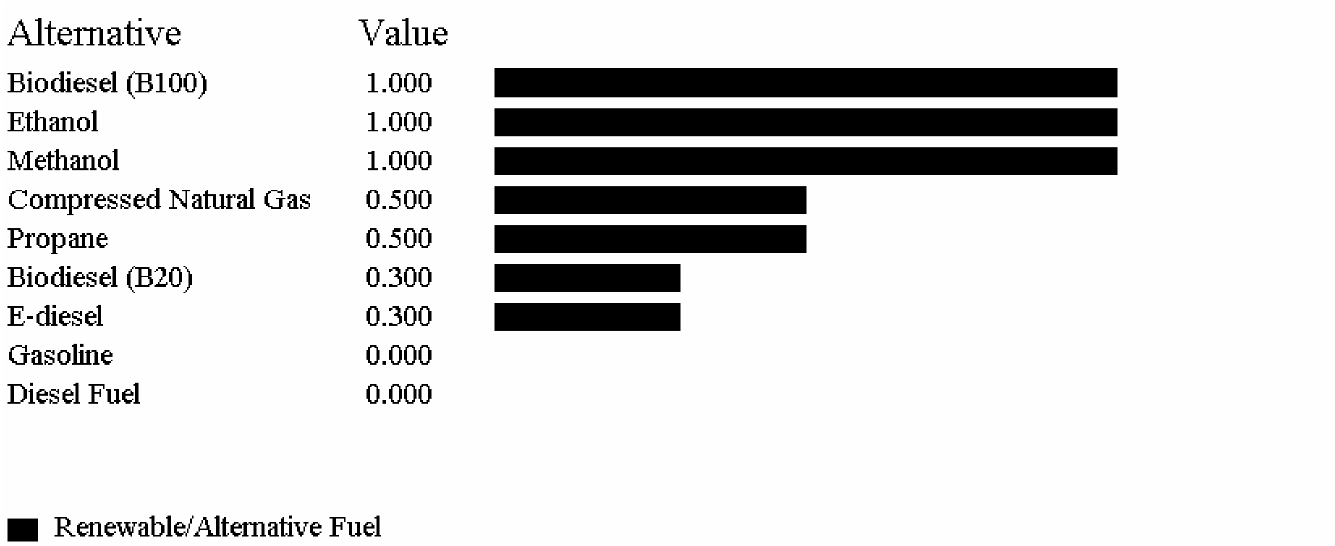

Figure 4-8. *Fuel Source* Ranking and Scores

Figure 4-9 displays the ranking of the fuels respective to *Air Emissions*. Surprisingly, B20 is ranked atop the *Air Emissions* tier due to low emissions of NO_x and SO_x as shown in Table 4-2 and E85 is ranked lowest due to high SO_x and carbon dioxide emissions. B100 scored highest in *Greenhouse Gases* but relatively low in *Carbon Monoxide*. However, if the values to the left of the colored bars were not displayed in Figure 4-9, it would be difficult to see the differences in the fuels with respect to *Air Emissions*. In order to gain more insight into this decision, further analysis must be accomplished through sensitivity analysis in step 9.

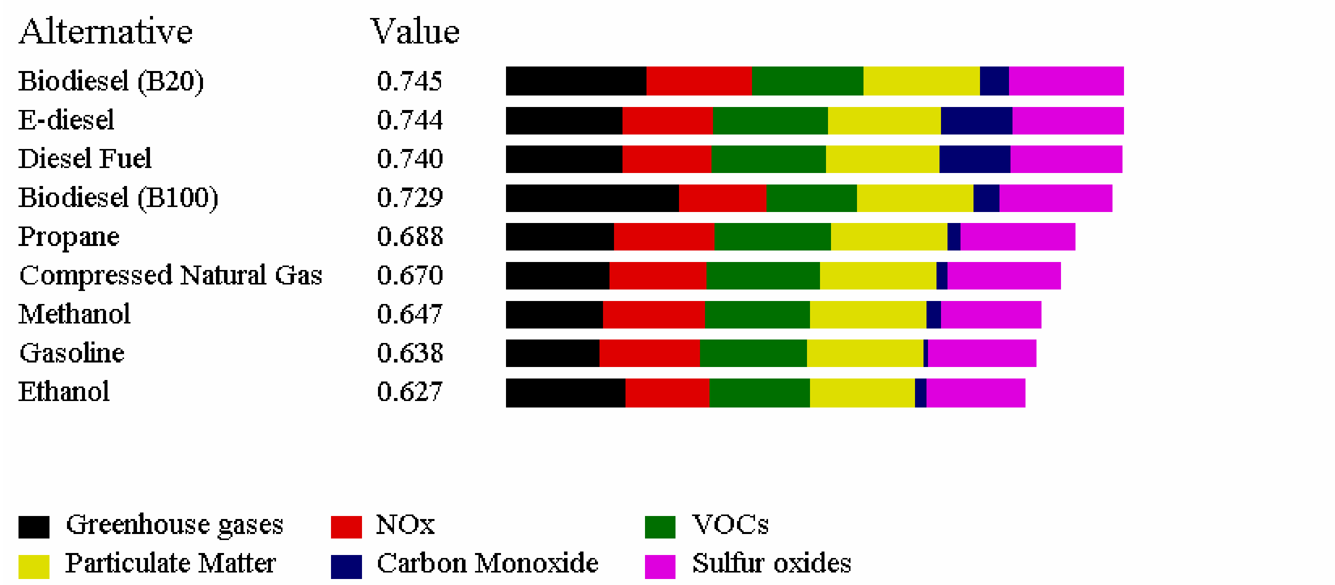

Figure 4-9. Air Emissions Ranking and Scores

4.2.2 Deterministic Analysis for Other Geographic Locations Models.

Table 4-3 displays the *Life Cycle Cost* for each of the nine fuels at four different geographic locations. Table 4-4 shows the categorical values for the *Distance to Fueling Station* measure at the four same locations. The equations and SDVFs utilized for this analysis are equal to the equations and SDVFs employed for the AFCEE model. The *Supply* measure was also considered as a changing parameter for this analysis; however, the actual supply numbers were no different for this analysis.

Table 4-3. Alternative Scoring for *Life Cycle Cost* Measure at All Locations

Geographic Location	Gasoline	CNG	LPG	M85	E85	B20	B100	Diesel	E-diesel
Gulf Coast	$ 0.2200	$ 0.2419	$ 0.2677	$ 0.2708	$ 0.2787	$ 0.2244	$ 0.2687	$ 0.2164	$ 0.2221
Lower Atlantic	$ 0.2226	$ 0.2515	$ 0.2765	$ 0.2786	$ 0.2541	$ 0.2215	$ 0.2650	$ 0.2181	$ 0.2239
Midwest	$ 0.2203	$ 0.2274	$ 0.2780	$ 0.2747	$ 0.2465	$ 0.2204	$ 0.2636	$ 0.2178	$ 0.2236
West Coast	$ 0.2341	$ 0.2633	$ 0.2853	$ 0.2941	$ 0.2639	$ 0.2258	$ 0.2706	$ 0.2239	$ 0.2300

Table 4-4. Alternative Scoring for *Distance to Fueling Station* at All Locations

Geographic Location	Gasoline	CNG	LPG	M85	E85	B20	B100	Diesel	E-diesel
Gulf Coast	On base	On base	< 5 miles	> 5 miles	< 5 miles	> 5 miles	< 5 miles	On base	< 5 miles
Lower Atlantic	On base	On base	On base	> 5 miles	> 5 miles	< 5 miles	> 5 miles	On base	> 5 miles
Midwest	On base	< 5 miles	< 5 miles	> 5 miles	On base	On base	< 5 miles	On base	< 5 miles
West Coast	On base	On base	On base	> 5 miles	< 5 miles	< 5 miles	> 5 miles	On base	< 5 miles

Table 4-5 displays the results of the rankings and scores for all four geographic locations. B100 ranked first in three out of four locations, E85 ranked first in one location and second in three locations, and B20 ranked third in three locations. Gasoline and diesel ranked as the worst two, in three out of four locations.

Table 4-5. Rankings and Scores for Different Geographic Locations

Rank	Gulf Coast	Total Value	Lower Atlantic	Total Value	Midwest	Total Value	West Coast	Total Value
1	B100	0.748	B100	0.736	E85	0.767	B100	0.725
2	E85	0.708	E85	0.714	B100	0.758	E85	0.715
3	B20	0.666	M85	0.652	B20	0.673	B20	0.663
4	CNG	0.664	B20	0.651	CNG	0.672	E-Diesel	0.63
5	M85	0.658	CNG	0.647	M85	0.659	CNG	0.625
6	E-Diesel	0.644	Propane	0.627	E-Diesel	0.622	M85	0.623
7	Propane	0.624	E-Diesel	0.622	Diesel	0.612	Propane	0.611
8	Diesel	0.615	Diesel	0.611	Propane	0.605	Diesel	0.601
9	Gasoline	0.562	Gasoline	0.558	Gasoline	0.562	Gasoline	0.537

In contrast to the other geographic locations, the Midwest location displayed a change in the top ranking. Figure 4-10 shows the overall ranking and score with respect to all measures at the Midwest location. E85 received a higher score in *Life Cycle Cost* and *Distance to Fuel Station*. Compared to the AFCEE model, diesel and propane also traded rankings. Compared with propane, diesel scored higher in *Life Cycle Cost* and also higher in *Distance to Fueling Station* in the Midwest location. This is also shown in Tables 4-4 and 4-5.

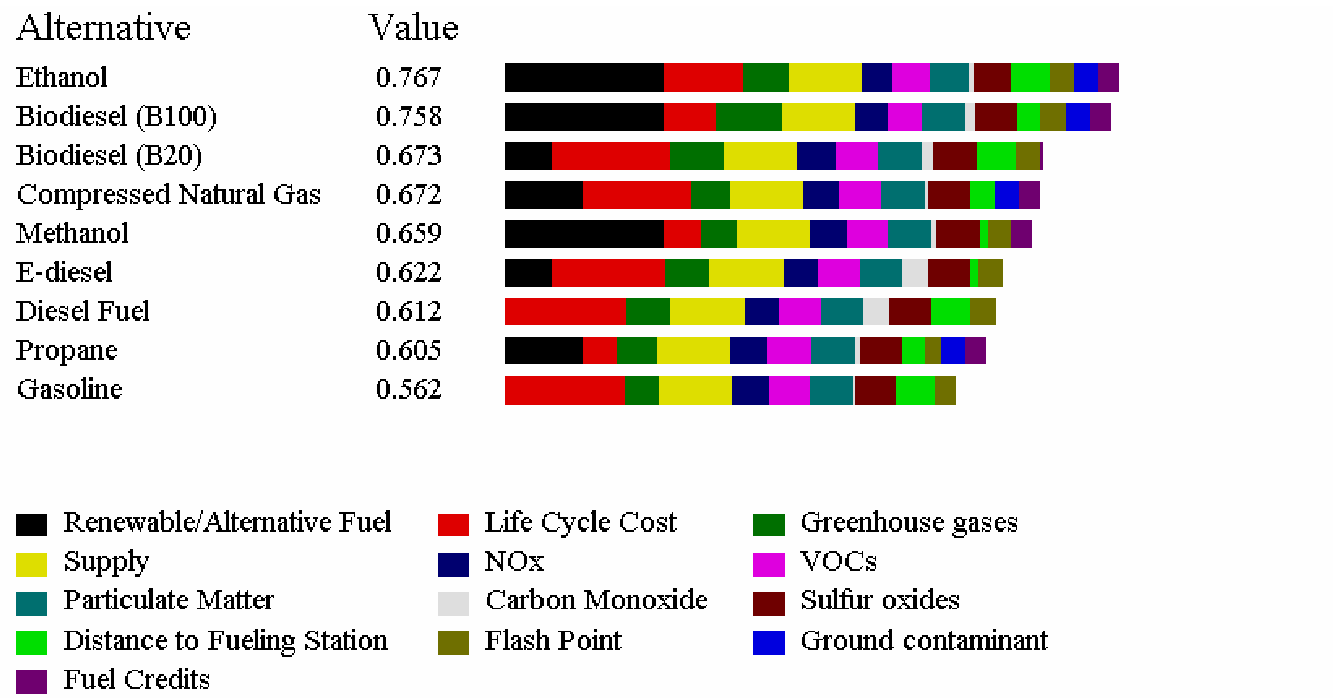

Figure 4-10. Overall Ranking with Respect to Measures at Midwest Location

4.3 Step 9: Sensitivity Analysis

Sensitivity analysis can give the decision maker additional insight to determine if changes in the model could impact the current ranking of alternatives. Applying sensitivity analysis to the weighting can show the relative importance of each value or measure (Kirkwood, 1997:82). It is important to note that changing the weights in the first value tier of the hierarchy also affects the weights of the second tier values and the measures associated with the first tier value.

4.3.1 Sensitivity Analysis for AFCEE Model.

The sensitivity graph for *Resources* is shown in Figure 4-11. The *Resources* value is currently weighted at 35% as indicated by the vertical line on the x-axis. Each colored line represents an alternative as shown in the legend on the right of each sensitivity graph. Starting from the top, left side of the graph, the black diagonal line indicates B100 as seen in the legend to the right. The top ranking alternative will always be the highest diagonal line that crosses the vertical line at the value's or measure's global weight. The ranking of each alternative could change as the weighting for the value or measure changes. If the vertical line moved to approximately 53%, (indicated on the x-axis) the highest diagonal line crossing the vertical line would be the green diagonal line, B20 as indicated in the legend. This would mean that for an increase in weighting for the Resources value from 35 to 53%, B20 would be the highest ranking alternative in the model. If the vertical line moved even further right towards approximately 77%, diesel fuel, indicated by a gray line, would be the most preferred alterative in this model. Changing the weight of *Resources* to 77% is highly unlikely. This would make the ratio of importance 3:1 in favor of *Resources* over *Environmental Issues*. Lowering the weight of the *Resources* value would not change the ranking of B100 from the most preferred alternative. This is identified by finding the intersection of the vertical line with B100 and following the B100 line all the way to the left of the graph. The left end of the graph signifies a weighting of zero. B100 is the highest diagonal line from the zero point to the vertical line with no other lines intersecting along the way. Currently, the lowest ranking alternative is identified where the vertical line intersects with the lowest diagonal line. In Figure 4-11, this line is identified as gasoline. At the lowest ranks, a change in weighting from 35% to approximately 60% would make propane the lowest ranking alternative instead of gasoline.

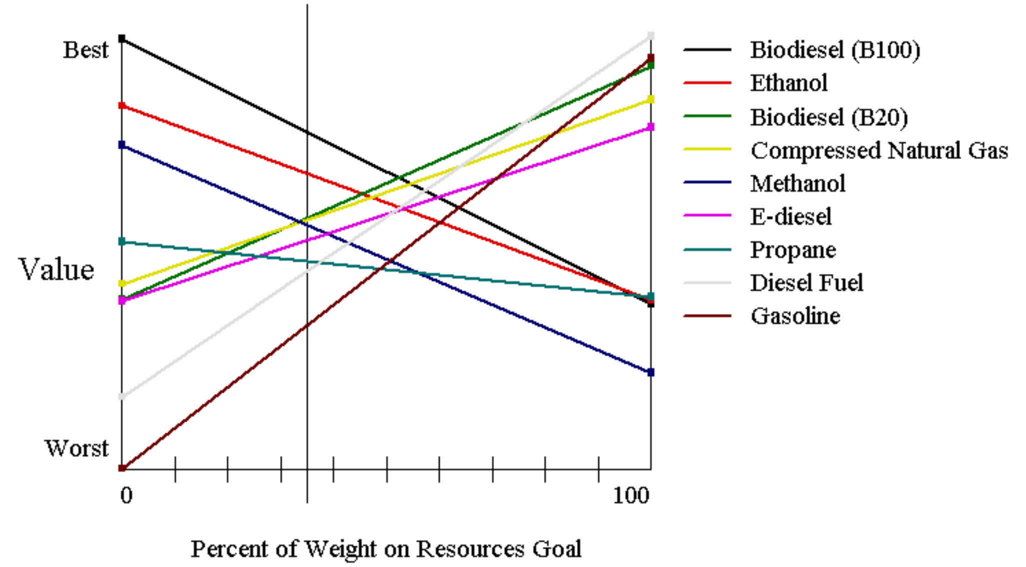

Figure 4-11. Sensitivity Analysis of *Resources* First Tier Value

The sensitivity analysis can be further broken down by looking at the second tier *Cost* value. The same process used to analyze the sensitivity analysis of the *Resources* value is used for all other sensitivity analysis graphs. Figure 4-12 shows the sensitivity graph of the *Cost* value. B100 scored the highest in this model; therefore, in all sensitivity graphs for this model, B100 will be the most preferred alternative as long as the weightings stay unchanged. As identified by the vertical line, the weighting for the *Cost* value is 21%. Changing the weight to approximately 39% would change the highest ranking alternative to B20. The ranking of alternatives is fairly sensitive to the current weight of the *Cost* value if the decision maker believes the weight of Cost could change from 21% to 39%. Changing the global weight of *Cost* to 65% would make diesel the preferred alternative. This change in weight of 43 percentage points is unlikely. The analysis can now be broken down to the most detailed element of the model, the measure.

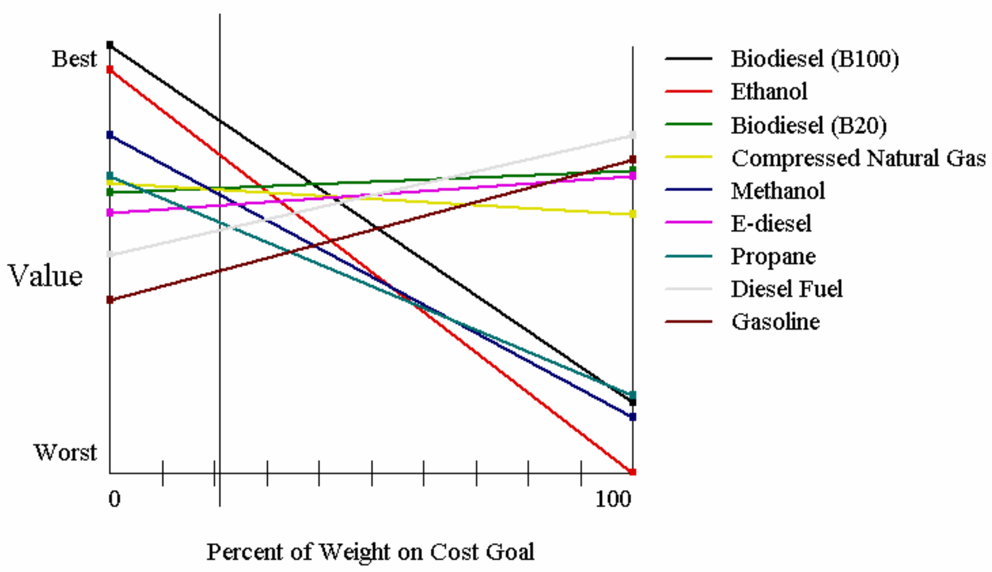

Figure 4-12. Sensitivity Analysis of *Cost* Value

After analyzing the *Resources* first value tier and the *Cost* second value tier, the Life Cycle Cost and Fuel Credits measures can be examined for further insight. Figure 4-13 presents the sensitivity graph of the *Life Cycle Cost* measure. The sensitivity graph of *Life Cycle Cost* looks very similar to the *Cost* value sensitivity analysis. The current weight of the *Life Cycle Cost* measure is 18.4%. Increasing the weight of *Life Cycle Cost* to approximately 31% would make B20 the most preferred alternative. Making *Life Cycle Cost* one-third of the global weight is doubtful unless the *Resources* weighting also changed. The top ranking alternatives are not sensitive to the change in weighting for the *Life Cycle Cost* measure. Looking at another measure under the *Cost* value may be more valuable.

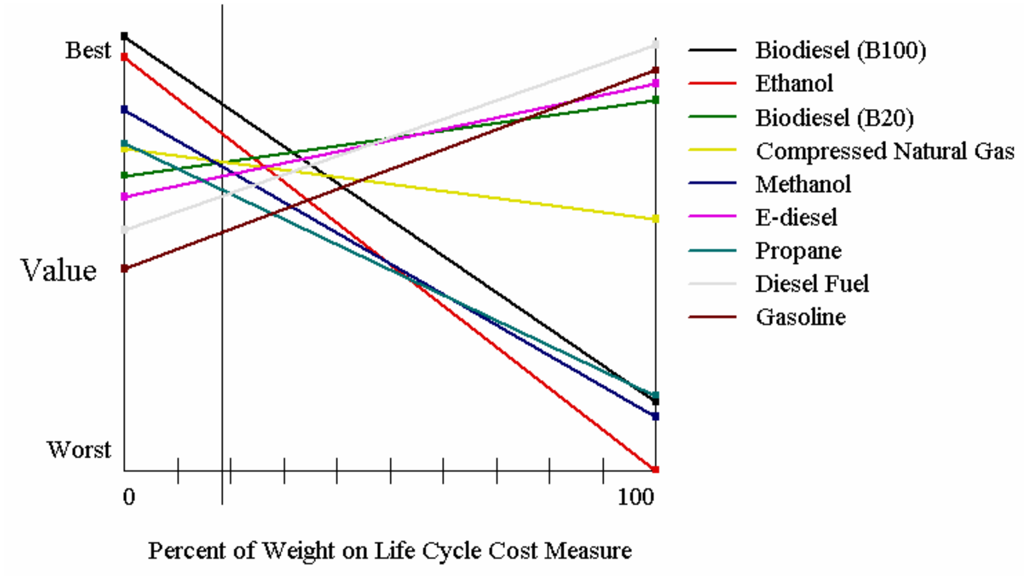

Figure 4-13. Sensitivity Analysis of *Life Cycle Cost* Measure

Figure 4-14 shows the sensitivity graph of the *Fuel Credits* measure. B100 is the most preferred alternative unless *Fuel Credits* was the sole measure in this model. This is shown by having no colored, diagonal lines crossing B100 until the x-axis reaches 100% where five alternatives meet at one point. This signifies that if *Fuel Credits* incurred a weighting of 100%, five fuels would all be the top alternative. This is improbable; therefore, the *Fuel Credits* measure is not sensitive to change for the top alternative. B100, E85, CNG, propane and M85 all have positive slopes in the *Fuel Credits* sensitivity analysis graph. This signifies that as the weighting of the *Fuel Credits* measure increases, the overall value of these fuels also increases. In contrast, the B20, e-diesel, diesel and gasoline functions all have negative slopes; therefore, as the weight on *Fuel Credits* increases, the overall value of these fuels decreases. All other sensitivity analysis graphs that do not show significance to the change in rankings of fuels will be included in Table B-3 in Appendix B.

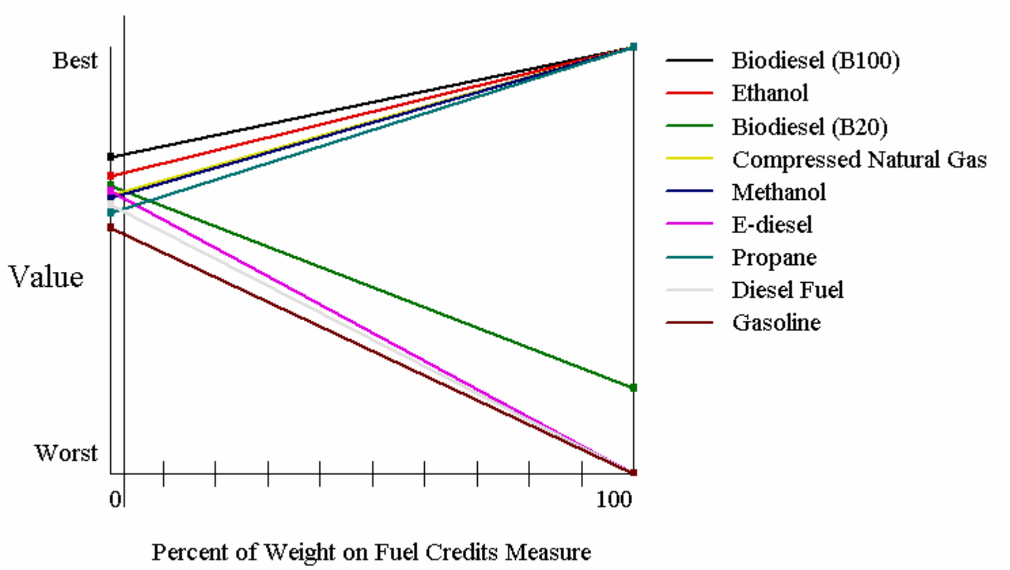

Figure 4-14. Sensitivity Analysis of *Fuel Credits* Measure

After the sensitivity of *Cost* value is examined, the *Availability* value is analyzed. The weight of the *Availability* value must increase to 32% for the top alternative to change from B100 to E85 according to Figure 4-15. An increase of 18 percentage points is unlikely because it would double the weight of *Availability*. The *Availability* value is not sensitive to change for the top alternative. All fuels have a positive slope within this value. This infers that as the weight of *Availability* increases, the value of all fuels increases as well.

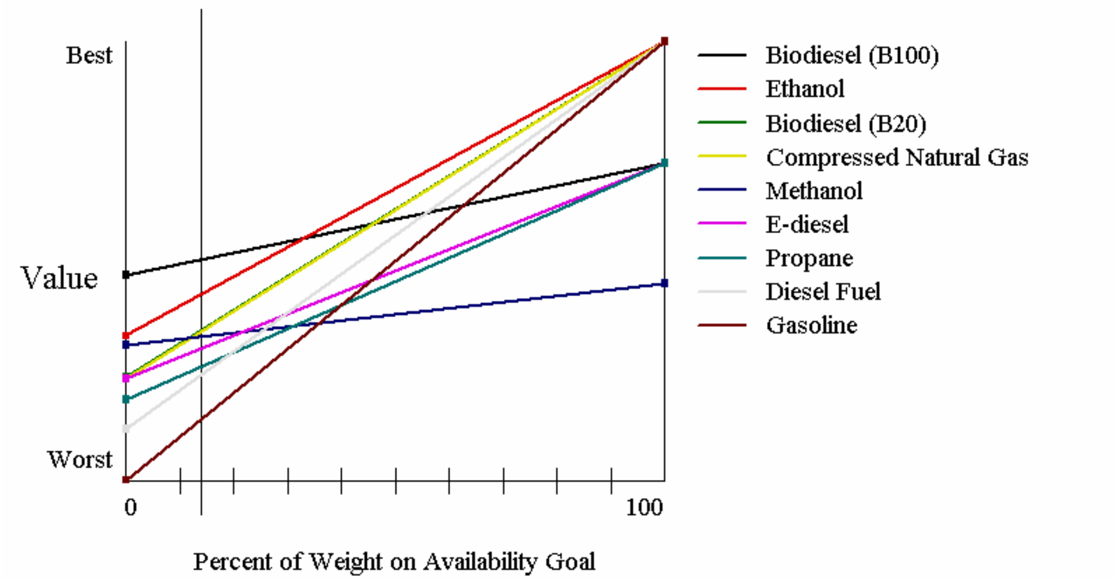

Figure 4-15. Sensitivity Analysis of *Availability* Value

Figure 4-16 displays the *Distance to Fuel Station* measure. The current weight of this measure is 4.9%. Changing the weight of the *Distance to Fuel Station* measure to approximately 8% would change the ranking alternative from B100 to E85. An increase in weighting of 3.1 percentage points is probable. The top alternatives are sensitive to the weight changes of this measure. The lowest ranking alternatives are also sensitive to the weight changes of the *Distance to Fueling Station* measure. Changing the weight to 9% would turn M85 into the lowest ranking alternative instead of gasoline.

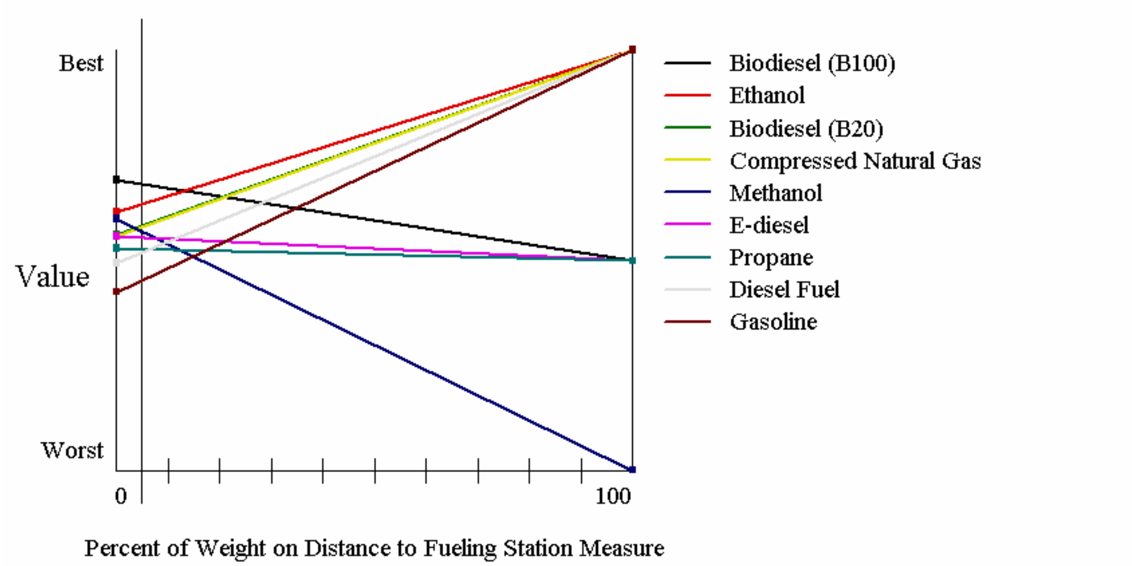

Figure 4-16. Sensitivity Analysis of *Distance to Fueling Station* Measure

The global weighting of the *Environmental Issues* value is 65%. According to Figure 4-17, an increase in the weighting will not change the ranking of alternatives. B100 would be the highest ranking alternative if Environmental Issues was weighted anywhere from 48 to 100%. However, if the weight of this first tier value was less than 48%, the rankings would be sensitive to the change in weighting. B20, indicated by a green diagonal line with negative slope would become the most preferred alternative if Environmental Issues was weighted between 22-48%. All intersections between colored lines show potential rank changes. The rank change occurs at the corresponding x-axis weighting value of the intersection. For example, propane and gasoline intersect at an x-axis weight value of approximately 51%. If the percent of weight on the Environmental Issues value changed to below 51%, propane would become the lowest ranking fuel instead of gasoline.

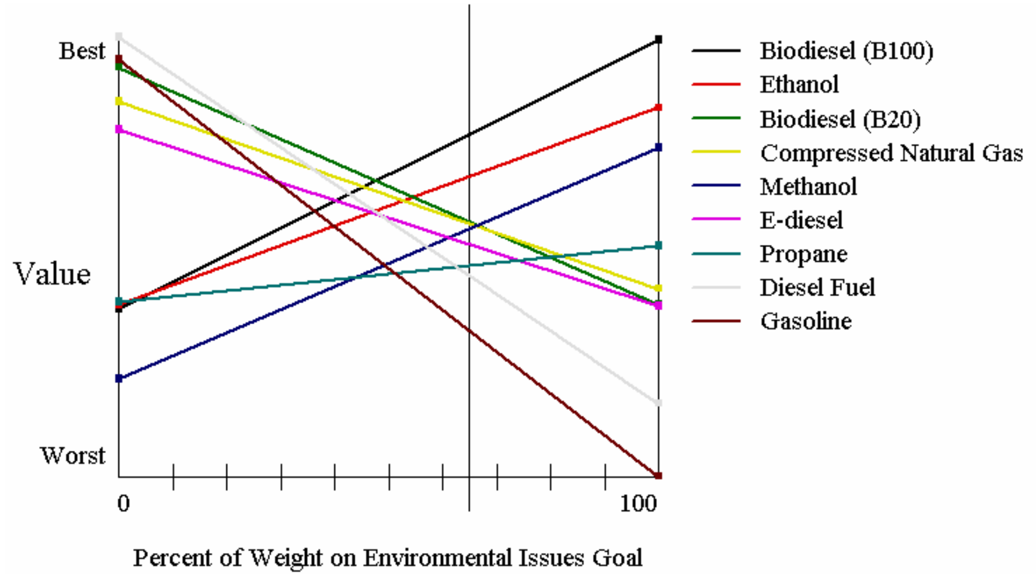

Figure 4-17. Sensitivity Analysis of *Environmental Issues* First Tier Value

The majority of the measures under the *Environmental Issues* first tier value were not sensitive to changes for the top alternatives. The *Carbon Dioxide* measure was one of the few sensitivity analysis graphs that showed potential significance. Figure 4-18 shows the current weighting of *Carbon Monoxide* at 5.6%. A change from 5.6% to 14% can be annotated as an increase of 8.4 percentage points. This is calculated by subtracting 5.6% from 14%. A weight change of 8.4 percentage points appears to show sensitivity; however, two items must be considered. First, the weight of the *Carbon Dioxide* measure is proportionate to five other *Air Emission* objectives. In order to accurately consider other *Air Emission* objectives, the *Greenhouse Gases*, *Nitrogen Oxides*, *Sulfur Oxides*, *Particulate Matter* and *Volatile Organic Compounds* measures must also increase in weighting. An increase of 8.4 percentage points must be multiplied by five equaling a 42 percentage point change in *Air Emissions* which is improbable. Next, an increase in the weighting from 5.6% to 14% is almost a 200% increase in the weighting change. This is calculated by dividing 14% by 5.6% and multiplying by 100%. This shows that the weighting of the *Carbon Monoxide* measure would have to more than double in order to change the top ranking alternative from B100 to e-diesel as indicated by the intersection of the black diagonal line and the pink diagonal line.

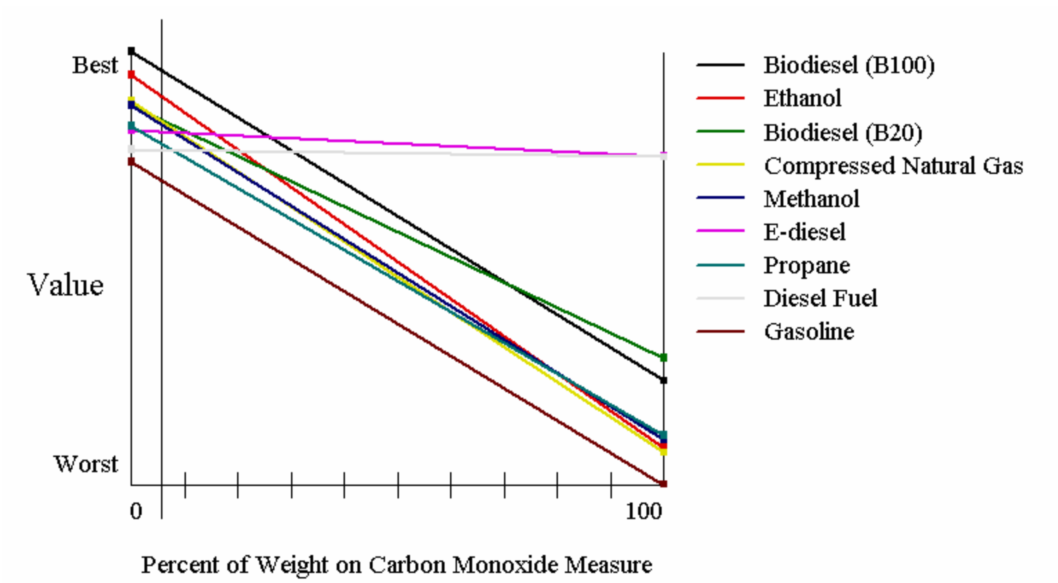

Figure 4-18. Sensitivity Analysis of *Carbon Monoxide* Measure

The weighting of the *Renewable/Alternative Fuel* measure is equal to the weighting of the *Fuel Source* second tier value. This measure is the only objective evaluated under the *Fuel Source* value. Figure 4-19 shows the sensitivity analysis graph of the *Renewable/Alternative Fuel* measure. The current weighting of this measure is 19.5%. An increasing change in the weight of this measure will not affect the top ranking alternative. However, a decreasing change in the weighting from 19.5% to approximately 5% will change the ranking alternative from B100 to B20.

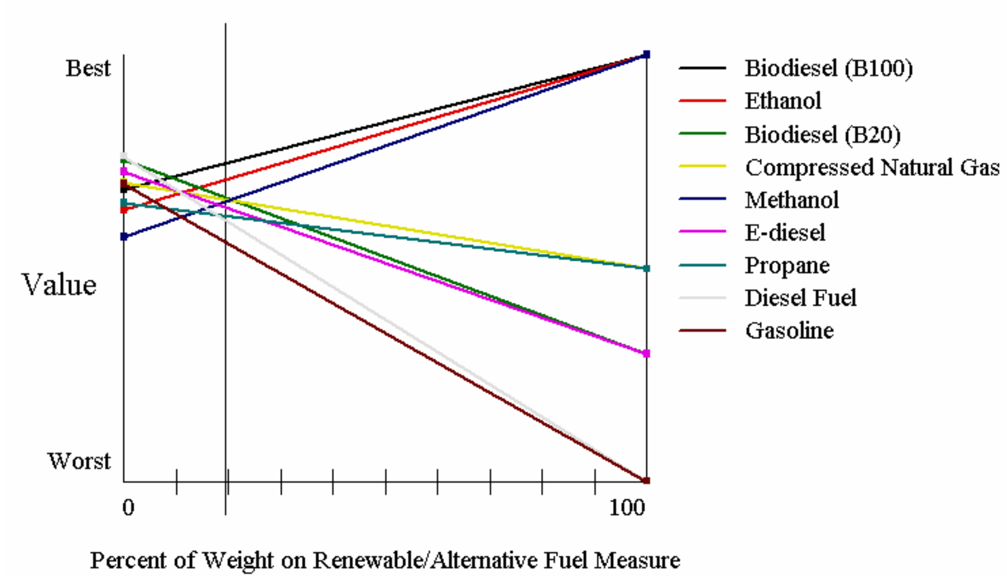

Figure 4-19. Sensitivity Analysis of *Renewable/Alternative Fuel* Measure

4.3.2 Sensitivity Analysis for Other Geographic Locations.

Unlike the AFCEE model, the Midwest geographic location model scored E85 as the top alternative. Analysis of the Midwest model shows that the top alternatives are sensitive to changes in weighting of the *Resources* and first tier value. Figure 4-19 shows that the vertical line represents the current weighting of the *Resources* value. The current ranking is 35%. A slight decrease in the weighting changes the most preferred alternative from E85, indicated by the black diagonal line, to B100, distinguished by the red diagonal line.

Figure 4-20 shows the sensitivity analysis graph for *Environmental Issues* for the Midwest model. This graph is a mirror image of the *Resources* sensitivity analysis graph for the same model. The changing of weights for the *Resources* value will inversely affect the changing of weights for the *Environmental Issues* value.

Table 4-5 shows a sensitivity table of the Midwest model with respect to the *Resources* value. At the current weight of 35% for *Resources*, E85 is the highest ranking alternative in the Midwest model. However, if the weight of Resources decreased to 30%, B100 would be the most preferred alternative. The numbers for Table 4-5 were taken from Sensitivity Tables output by *Logical Decisions*.

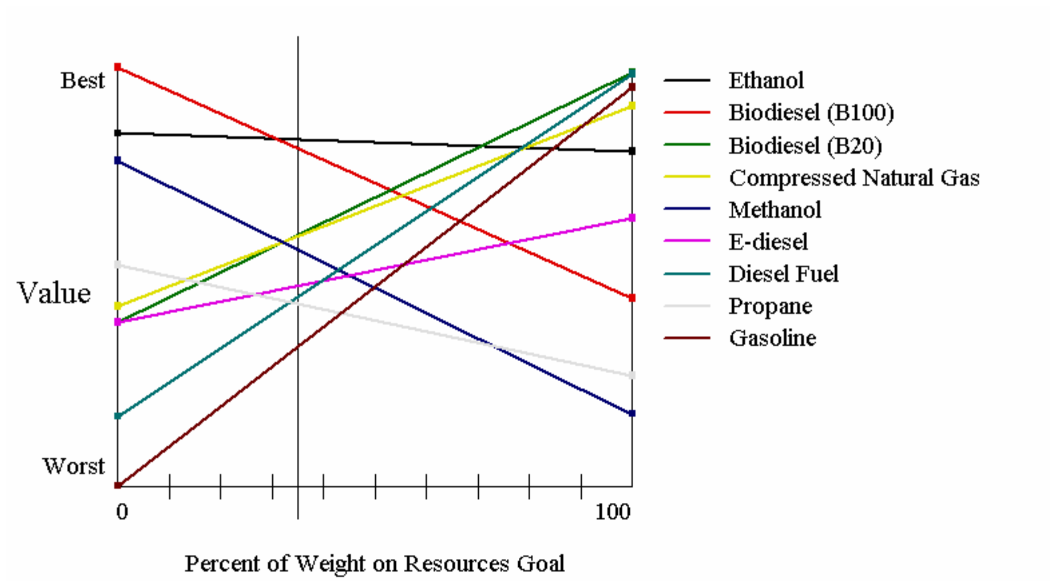

Figure 4-20. Sensitivity Analysis of *Resources* First Tier Value for Midwest Location

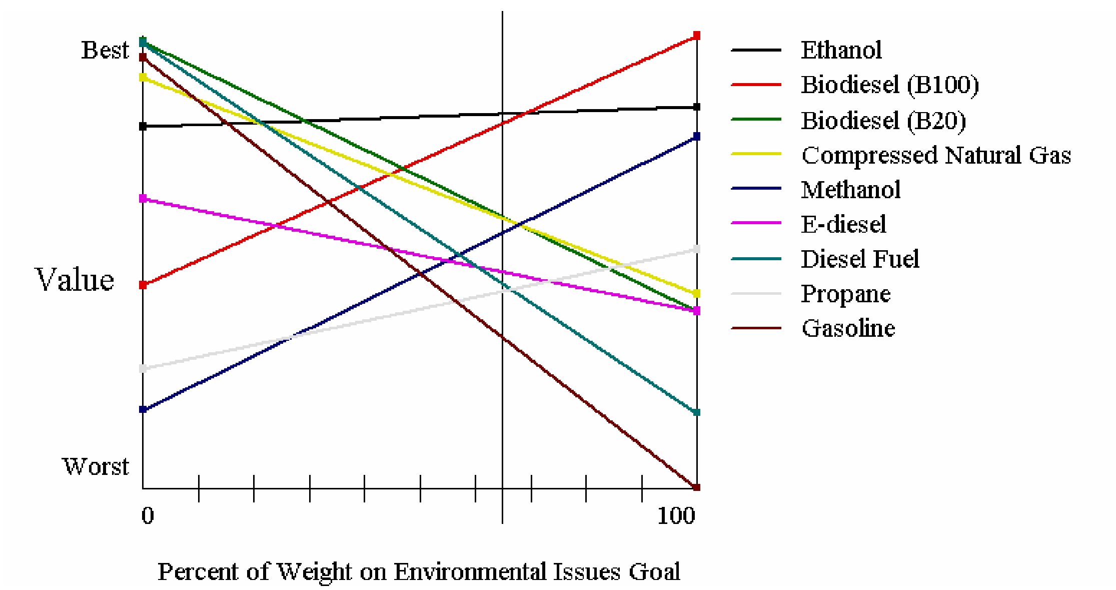

Figure 4-21. Sensitivity Analysis of *Environmental Issues* First Tier Value for Midwest Location

Table 4-6. Sensitivity Table of *Resources* First Tier Value for Midwest Location

Alternative	Value at Current Weight of 35%	Alternative	Value at Adjusted Weight of 30%
E85	0.767	B100	0.769
B100	0.758	E85	0.768
B20	0.673	M85	0.671
CNG	0.672	CNG	0.662
M85	0.659	B20	0.661
E-Diesel	0.622	E-Diesel	0.617
Diesel	0.612	Propane	0.610
Propane	0.605	Diesel	0.595
Gasoline	0.562	Gasoline	0.542

4.4 Results Summary

Chapter 4 analyzed the results of scoring nine different fuels at four different locations in this VFT model. The deterministic analysis showed that B100 offers the greatest value to the decision maker at the AFCEE. Based on this model, the analysis also proved that B100 is not always the most preferred fuel at every location. The ranking of alternatives with respect to the model values and measures provided some insight to the decision maker on how each alternative scored. Finally, sensitivity analysis provided further insight on how the ranking of alternatives could potentially vary with a change in value and measure weights.

Chapter 5: Conclusions and Recommendations

The purpose of this research was to comparatively evaluate the resources and environmental issues of renewable alternative fuels and their blends (B100, E85, M85, B20, and e-diesel) compared to non-renewable alternative fuels (CNG and propane) and conventional fuels (gasoline and diesel) using the decision analysis approach of Value-Focused Thinking. Step 10 of the VFT process provides conclusions and recommendations for this thesis research effort. This effort provides a tool for installation commanders, environmental managers, or transportation personnel to select renewable alternative fuels for their vehicles. By systematically acquiring the best possible alternative, a decision maker can now support his/her argument for use of renewable alternative fuels.

5.1 Overview

In addition to providing recommendations and conclusions for this VFT model, this chapter will also discuss limitations of this model, answer research questions suggested by the literature reviewed and make recommendations for future research in this field of study. Three main focus areas and associated questions were suggested by the literature reviewed.

(1) Are renewable alternative fuels justified when compared to gasoline, diesel fuel and non-renewable alternative fuels according to the VFT model? What are the environmental benefits of using renewable alternative fuels? Is there a net energy gain in the production process of alternative fuels?

(2) Is it more cost effective to use renewable alternative fuels in different regions of the United States? Which renewable alternative fuels are more suited for certain regions of the United States? What agencies/organizations are involved in providing guidance and making the decision to use renewable alternative fuels on each Air Force installation?

(3) What methodologies are available for analyzing the selection of renewable alternative fuels? What are the steps involved to employ each methodology? What are the appropriate measures that comprise a model to select renewable alternative fuels in the Department of Defense? How do changes in the model parameters affect the outcome of the model?

5.2 Step 10: Recommendations

This research identified many different fuels that educational institutions, private businesses and government agencies have tested as possible solutions to alleviate the current air pollution problems and impending petroleum shortage. From these fuels, nine were used as alternatives in this comparative analysis. According to the VFT model created in this research, B100 scored the highest overall and E85 scored a close second. In the Lower Atlantic, Gulf Coast and West geographic locations, B100 is the recommended alternative in this research. At the Air Force installation located in the Midwest location, however, E85 is the recommended alternative. Thus, the most preferred fuel can change with location.

5.3 Research Answers

Overall, B100, E85 and B20 scored higher than all other fuels, and alternative fuels scored higher than conventional fuels. For the AFCEE model, which uses data from the Gulf Coast location, air emissions varied among fuels. The effects of changes in the model are all analyzed using sensitivity analysis. According to the sensitivity analysis, the *Air Emissions* objective for the AFCEE model was not sensitive to the change for the highest ranking alternative except at extreme conditions. However, the *Air Emissions* objective for the Midwest model was sensitive to change for the highest ranking alternative. *Life Cycle Cost* and *Fuel Source* comprised nearly 38% of the weighting for the alternatives, while air emissions contained 39% of the overall weighting for this model. In the Midwest model, the ranking of top alternatives were sensitive to the change in weighting for the *Life Cycle Cost* measure, but only the middle alternatives were sensitive to the change in weighting for the *Fuel Source* goal. Overall, CNG scored higher than both M85 and e-diesel. As an alternative fuel, M85 scored low due to its high *Life Cycle Cost*, and low *Safety* score. This VFT model scores not only by means of cost and other resources, but also with environmental considerations. All renewable blends and alternative fuels are justified for utilization over conventional fuels at Air Force installations located in the all of the regions evaluated in this research.

The main environmental benefits of using renewable alternative fuels are lower emissions overall compared to conventional fuels and the conservation of non-renewable resources. Generally, renewable fuels are also safer. Andress (2002) consolidated the net energy balance studies for corn derived ethanol. According to the latest studies, corn derived ethanol has net energy gains between 21% and 47% while gasoline has net energy losses between -33% and -19% (Andress, 2002:3). According to a joint study between the USDA and the DOE, biodiesel "yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle" (Sheehan *et al*., 1998:v).

According to the Defense Energy Support Center (DESC), any military organization can submit fuel requirements to the Service Energy Offices. This document must include the military installation location, a point of contact, projected annual fuel usage, storage capabilities, preferred method of delivery and frequency of deliveries (Defense Energy Support Center, 2004). The DESC takes care of the solicitation, logistics and quality requirements and ensures delivery of the fuel. Also, the Warner Robins Air Logistics Center Support Equipment and Vehicles Directorate (formerly the Alternative Fuel Vehicles Directorate) leads the Air Force in testing alternative fuel vehicles for potential utilization.

VFT, AHP, LCA, MIRA and efficiency versus cost are all popular decision making methods used to select renewable alternative fuels (Keeney, 1992; Stahl, 2002). Most multiple objective decision analysis models have the same basic steps. These steps are identifying the problem, identify the fundamental objectives of the problem, structure the objectives, measure the objectives, quantify the objectives, create alternatives, score the alternatives and provide insight (Keeney, 1992). The GREET, MOVES and POLCAGE are industry standard models that measure life cycle emissions of different fuels (Wang, 2001; United States Environmental Protection Agency, 2004; Tan, *et al*., 2004). These models are integral in predicting future emissions of various fuels.

5.4 Model Strengths

The VFT process provides the decision maker with priceless information regarding what is important about the issue at hand. In this case, commanders can decide what fuels would best suit their mission at a specific location while complying with environmental regulations and keeping costs to a minimum. This benefits their organization by providing maximum value to the analysis. This research is also a milestone regarding the comparison of alternative fuels. Other models include merely a tailpipe emissions or fueling cost analysis. Other models disregard well to wheel emissions, life cycle cost, availability, and safety issues—important goals which embrace the entirety of this decision and were analyzed in this research. This model also allows for scoring flexibility. With technological advances in the fuel production process, cost and emissions data could change. Any other data changes regarding any alternatives can easily be changed in the *Logical Decisions* program as well. Principally, this model provides valuable insight with respect to the objectives and measures that influence the scoring of the alternatives.

5.5 Model Limitations

The VFT model was designed to provide insight to the decision maker and assist in the decision making process. However, the model is not perfect and has limitations. The data gathered for this research was somewhat inconsistent. In the literature review and data gathering process, data for individual measures were found from different sources. Not all sources included data for each fuel used in the model. The DOE and the *Alternative Fuels Guidebook* provided sufficient data for fuel characteristics and specifications; however, most indirect fuel costs were spread out over different sources or were outdated. Fueling prices fluctuate daily. This could easily change the ranking of alternatives if fuel data was not averaged over time and location. Assumptions were also made on the *Distance to Fueling Station* measure. Some fuels had unfair advantages at certain locations with alternative fueling stations already located on base.

With regard to the model, a complete VFT model should be mutually exclusive and collectively exhaustive. Initially, *Performance* was included as a first tier value with the *Engine Modifications* and *Energy Content* as measures. *Engine Modifications* was initially measured by time, rather than cost. This measure was taken out and included as a cost under *Life Cycle Cost*. Some experts may argue that engine modifications should be measured by cost as a labor rate in addition to materials cost. This model measured engine modifications merely as a capital cost. Energy content relates to energy ratio and fuel efficiency. The decision maker did not want to consider any performance characteristics other than fuel efficiency. The fueling costs were calculated based on the fuel efficiency. Fuel efficiency is measured more as a characteristic of the engine and not of the fuel. This assumption also could have changed the alternative rankings through indirect costs. Although this research is the most comprehensive analysis of most alternative fuels to date, the fuel efficiency could have been calculated more accurately. Cetane and octane number are two measures not used in this model that also affect fuel efficiency. It is difficult to measure cetane and octane number when comparing different fuels. Cetane number is used to determine the ignition quality of a diesel engine and octane rating measures the resistance of a fuel to combustion knocking for gasoline and alcohol fuels (Bechtold, 1997:177). Like many decision analysis models or databases, the model or database is only as good as the data that is input.

The alternatives used in the model were based on a literature review and on the *GREET* model. Additional alternatives such as Fisher-Tropsch diesel, ultra-low sulfur diesel and reformulated gasoline could have been added as alternatives; however, these fuels do not help secure domestic energy security. Different percentages of renewable blends with petroleum could have been added as alternatives; nevertheless, most fueling stations carry renewable blends in standard percentages such as E10, E85, M85, B20 and B100.

Another weakness of this model is the ability to enter data from non-liquid or non-gaseous fuels. Although electric vehicle data is limited, the model does not directly support the measurement units used to analyze electric vehicles. With H_2 becoming the most researched fuel for the future, it would be difficult to analyze the data for H_2 as a fuel cell along with all other newly developed fuel cells.

As with any flammable liquid, safety was a value of concern in this model. Safety was measured by flash point and whether or not a fuel was a ground or water contaminant. According to subject matter experts, safety is not too high of a concern with fuels due to the common fueling techniques used at service stations nationwide. However, the handling and storage of fuels are of some concern. Production was thought to be a major concern with certain fuels; however, the literature review suggests that all alternative fuels can sufficiently supply any demands. The distance of the fuel stations from individual Air Force bases was also of concern due to security reasons and time demands. However, subject matter experts agreed that new infrastructure would be built on base for any fuels used in all government vehicles.

5.6 Recommendations for Future Research

This model focuses on renewable alternative fuels as energy replacements for conventional petroleum based fuels on Air Force installations. A more comprehensive analysis of current and future alternative fuels and different blend mixtures with petroleum based fuels through the use of a VFT model would further help decision makers and would also help reduce the impending world energy crisis. Additional testing and data gathering concerning these fuels will be an integral of future research. The publication of this information will also help advertise the use of renewable fuels world-wide. Moreover, along with tax incentives, the added production of these fuels will lower costs for consumers and producers. If simply 20% of the Federal fleet were converted to domestically produce alternative and renewable fuels, approximately 54 million gallons of gasoline and diesel fuel could be saved each year (National Renewable Energy Laboratory, 2003:2).

5.7 Final Thoughts

The security of our nation is highly dependent on our ability to secure our energy sources. The United States must immensely decrease our foreign dependence on petroleum for transportation fuels. This research provides new insights on the use of renewable fuels. The use of these fuels could lead to the decline in air pollution, creation of a more stable economy and enhance the security and self-sufficiency of this nation.

Appendix A: Measures

Life Cycle Cost

The *Resources* value includes *Costs* and *Availability*. In order to capture the primary costs associated with fuels, it was necessary to consider initial as well as future financial requirements. Executive Order 13123 states that renewable energy must be evaluated through life cycle costs (Clinton, 1999). Life cycle cost includes the base cost of the vehicle used, the conversion cost of the fuel, cost of the fuel per gallon, and the maintenance cost. This cost analysis is similar to the St. Louis Regional Clean Cities Program alternative fuels analysis. Vehicle cost, engine modifications cost, and maintenance cost data were taken from the St. Louis study (East-West Gateway Coordinating Council, 1994:4-6). The cost per gallon data was taken from the Clean Cities Alternative Fuel Price Report (United States Department of Energy, 2004a:1-4). Energy content, taken from the *Alternative Fuels Guidebook* was also used to calculate the fuel efficiency of each fuel (Bechtold, 1997). This differs from the St. Louis study, where fuel efficiency was assumed. Figure A-1 shows the SDVF for Life Cycle Cost. The figure shows that as Life Cycle cost increases, the value decreases linearly.

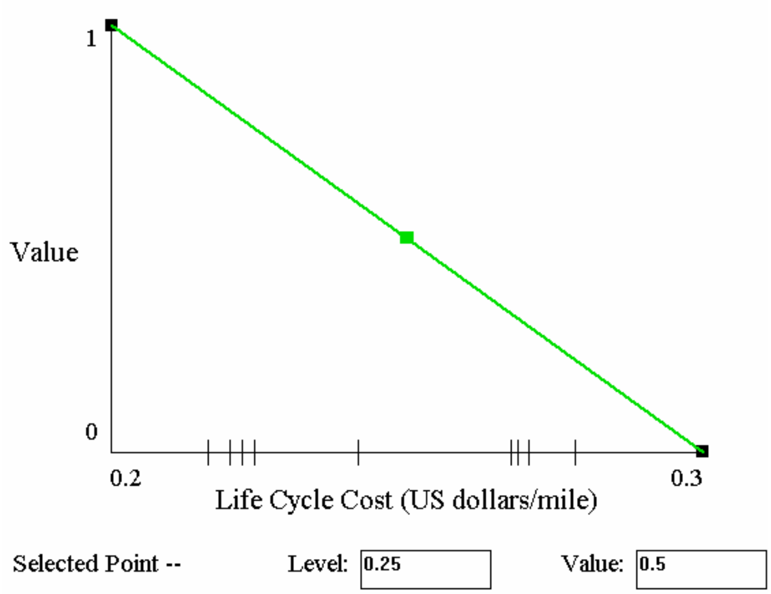

Figure A-1. *Life Cycle Cost* SDVF

Fuel Credits

Fuel credits are used as incentives to use certain alternative fuels. Credits can be earned at the rate of one credit per alternative fuel vehicle. Biodiesel can also earn fuel credits. One credit can be earned for the use of 450 gallons of B100 or 2,250 gallons of B20. This measure assumed that alternative fuels defined by EPAct also earned one credit (United States Congress, 1992:Sec. 508). For the *Fuel Credits* SVDF, credits were measured per 4,500 gallons as displayed in Figure A-2. The SDVF for fuel credits is also linear. As the number of fuel credits per 4,500 gallons of fuel increases, the value also increases. 4,500 gallons was used because it is a common denominator of 450 and 100 gallons.

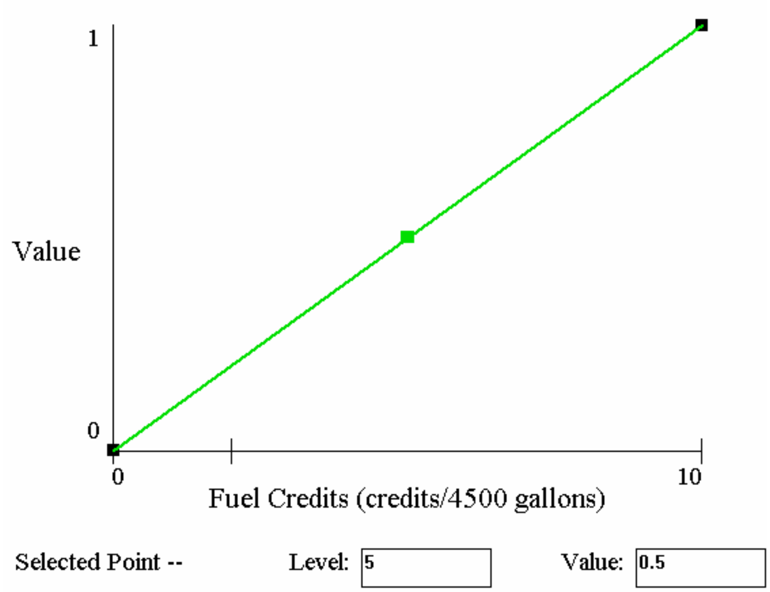

Figure A-2. *Fuel Credits* SDVF

Distance to Fueling Station

The distance to the fueling station is important for government vehicles. Not only does a short travel distance save time and money, but it decreases the vulnerability of government vehicles to attacks. On base fueling stations are most preferred. Fuel efficiency loses its value when trips to the fueling station waste time and money as evidenced at McChord Air Force Base (AFB). McChord AFB switched from CNG to E85 because the CNG fueling station was located five miles from base. Driving to and from the CNG station wasted nearly "half a tank" of fuel (Federal Vehicle Policy Division, 2003:6). The *Distance to Fueling Station* measure was evaluated through a piecewise linear SDVF. Under normal circumstances, distance is measured in miles; however, this model assumes that a fuel station located between zero and five miles off base receives the same value (0.6). The decision maker decided that five miles was a reasonable distance to travel if the fueling station was located off base. The decision maker also gave any distance over five miles a low value of "0.200." Figure A-3 shows the *Distance to Fueling Station* SDVF. For all locations, the distance of a fuel from the base was identified using the "Alternative Fuel Station Locator" program developed by the DOE or it was assumed (United States Department of Energy, 2004b).

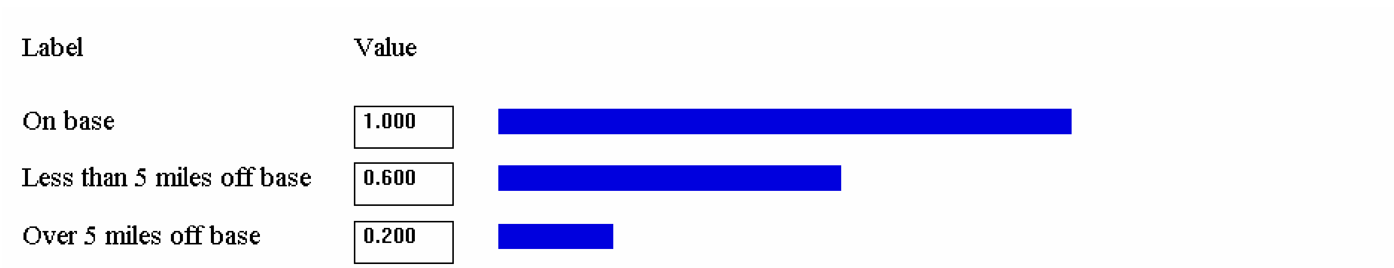

Figure A-3. *Distance to Fueling Station* SDVF

Supply

Supply assigns value to alternatives that can meet the consumer demand for the fuel. Further research indicated that the supply of alternative fuels have either met the demand for that product or produced over 100 million gallons of fuel per year. For example, in 1991, the US produced 875 million gallons of ethanol and 50 million gallons were exported due to low domestic demand (Bechtold, 1997:16). Although gasoline and diesel supply is expected to decrease in the coming years, the demand is currently being met through imported petroleum. The decision maker used literature from the *Alternative Fuels Guidebook* to decide the boundaries for the *Supply* measure (Bechtold, 1997:1-39). The *Supply* SDVF shown in Figure A-4 indicates a linear function. The value of the alternative is directly proportional to the amount supplied.

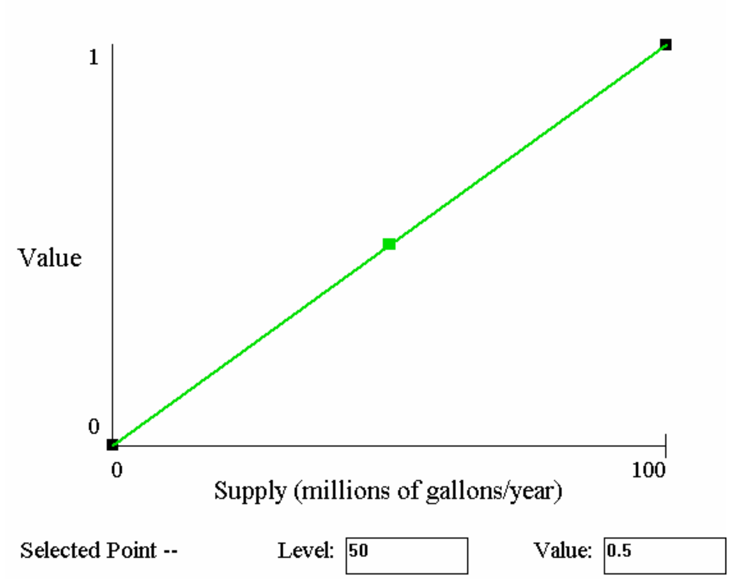

Figure A-4. Supply *SDVF*

Air Emissions

Each air emission measured in this model is described in Chapter 2. All air pollutants in this model (CO, NO_x, SO_x, GHGs, VOCs and PM) are measured in units of grams/mile. All *Air Emissions* measures were scaled on exponential SDVFs. These value functions were based on dose-response assessments that show a relationship between a toxic chemical and human exposure (Masters, 1998:136). Figure A-5 shows dose-response curves for carcinogens and non-carcinogens. None of the *Air Emissions* measured in this model are characterized as cancer causing agents; thus, all SDVFs are slightly exponential. It is important to note that the key to any air emissions measure is the negative relationship between the value and the amount of pollutant emitted, and not the actual shape of each function. Initially, the decision maker looked at EPA Tier 2 Standards while choosing boundaries for all *Air Emissions* SDVFs Environmental Protection Agency, 1999). However, Tier 2 Standards are based on tail-pipe emissions. All air pollutants are based on life cycle measurements; therefore, the decision maker raised the boundaries for all Air Emissions measures. Figures A-6 through A-11 display the *Air Emissions* SDVFs.

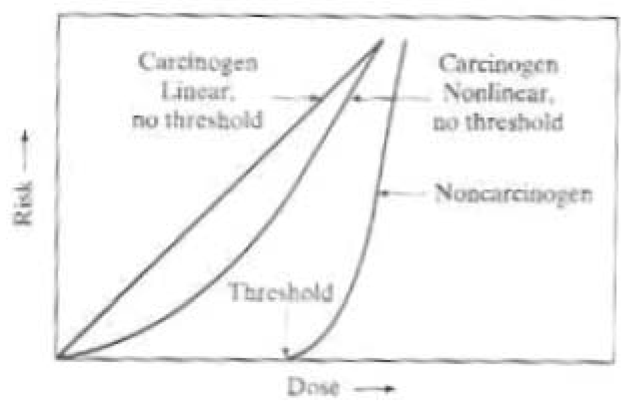

Figure A-5. Dose-Response Curves (Masters, 1998:137)

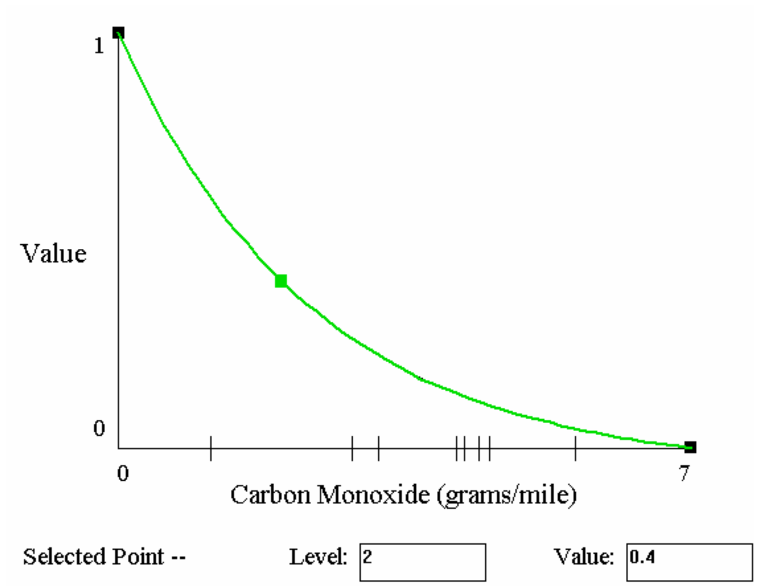

Figure A-6. *Carbon Monoxide* SDVF

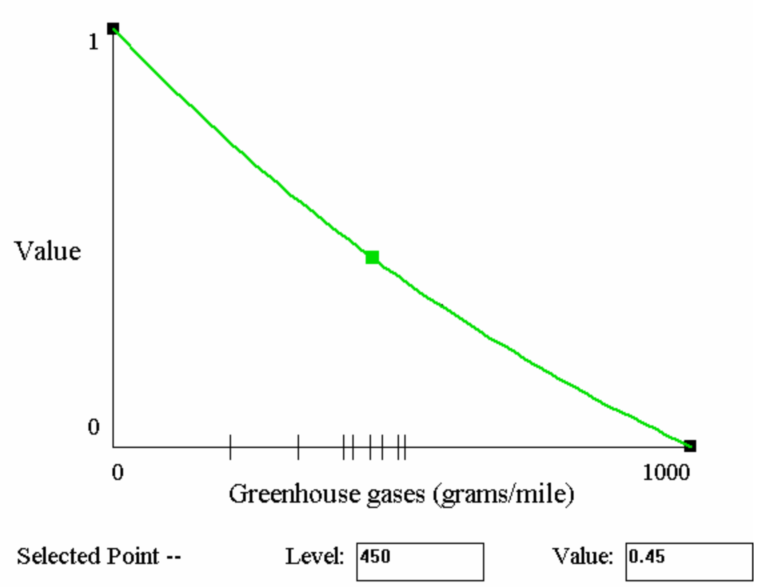

Figure A-7. *Greenhouse Gases* SDVF

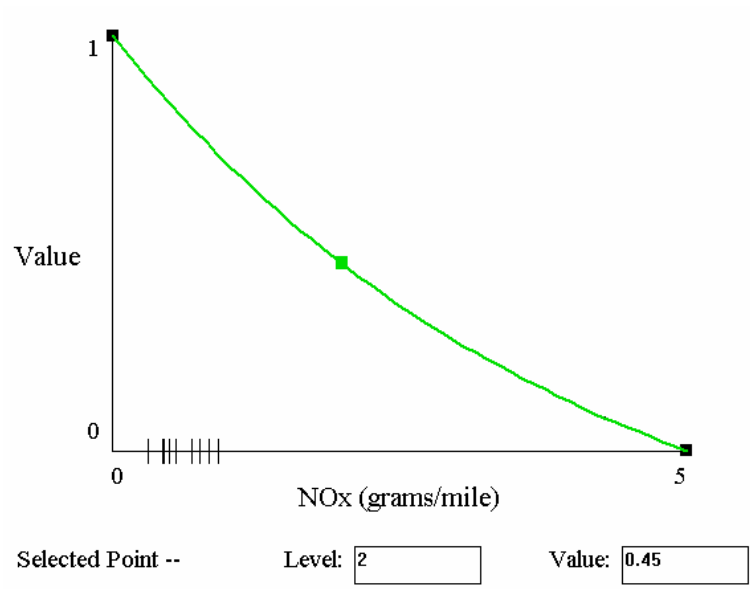

Figure A-8. NO_x SDVF

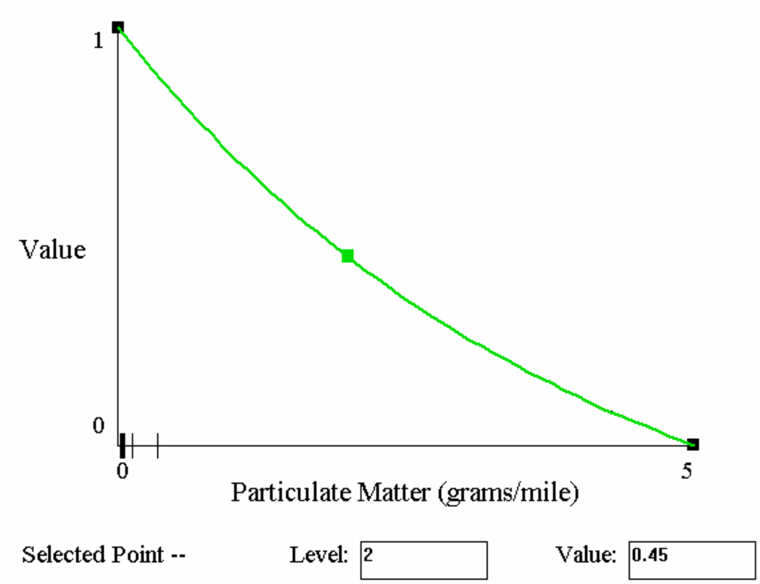

Figure A-9. *Particulate Matter* SDVF

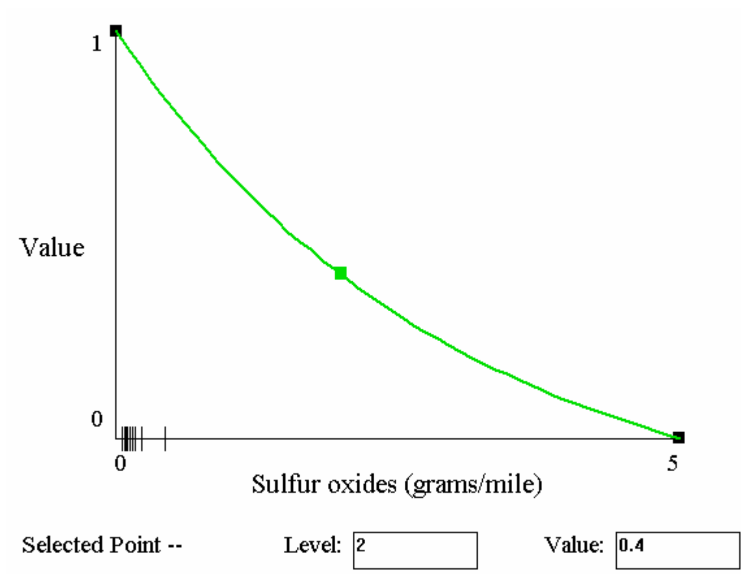

Figure A-10. *Sulfur Oxides* SDVF

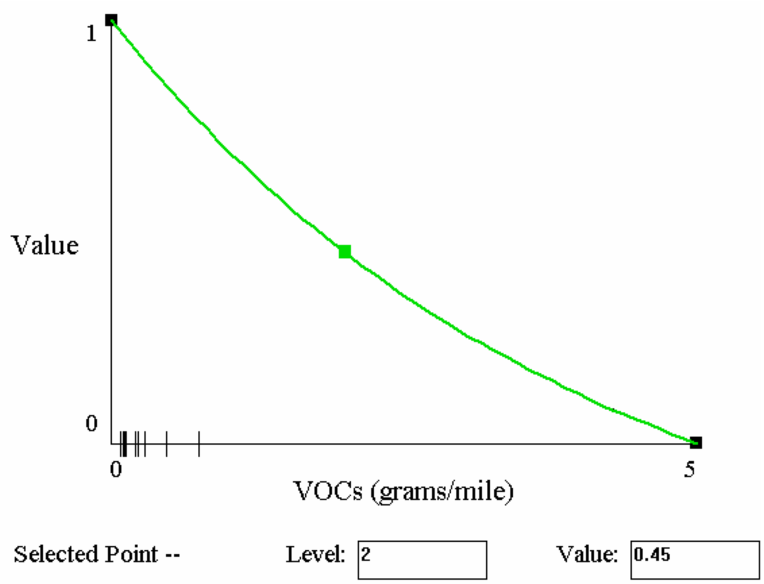

Figure A-11. *VOCs* SDVF

Flash Point

Flash point measures the temperature at which the alternative becomes ignitable when mixed with air. This is important especially during storage of the fuel in tanks. The flash point is a characteristic that make most fuels a hazardous substance. The *Flash* Point SDVF is a positive exponential function. As the temperature increases, the value of that alternative for the *Flash Point* measure also increases. Notice in Figure A-12 that flash point temperatures can be below 0 degrees Fahrenheit. This SDVF shows that a fuel with a flash point above approximately 140 degrees receives a relatively high score. A substance with a flash point less than 140 degrees Fahrenheit is considered a hazardous material (Code of Federal Regulations Title 40, 1999:261.21). On the other hand, a fuel with a flash point below 0 degrees Fahrenheit receives a value of under 0.5. The upper and lower boundaries were based on flash point temperature figures from the *Alternative Fuels Guidebook* (Bechtold, 1997:43-75).

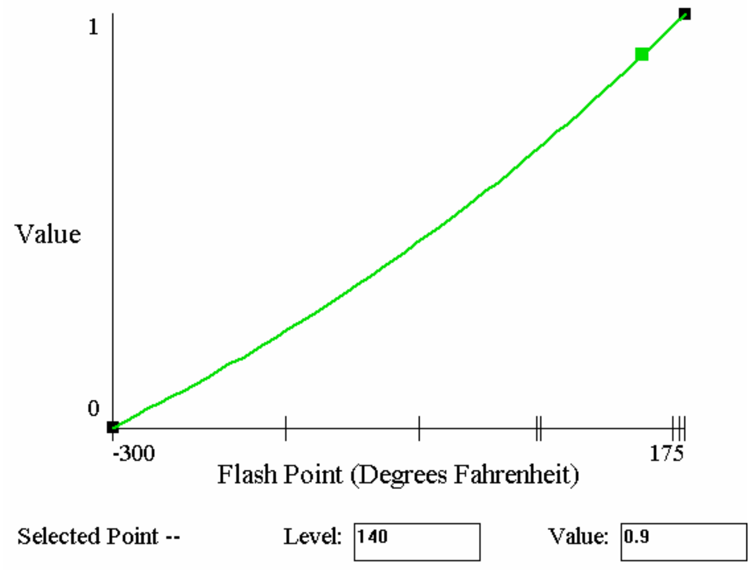

Figure A-12. *Flash Point* SDVF

Ground or Water Contaminant

Groundwater supplies 1/3 of the US's drinking water (Masters, 1998:220). Most spilled fuels can contaminate the ground, groundwater and surface water. Although most spills today are accidental and contained quickly, the Resource Conservation and Recovery Act controls which hazardous substances must be cleaned. The *Ground or Water Contaminant* SDVF is discrete. This measure is scored as a 1 for "no" or 0 for "yes" indicating whether the fuel can contaminate the ground or water as shown in Figure A-13.

Figure A-13. *Ground or Water Contaminant* SDVF

Fuel Source

The *Fuel Source* captures the value received when a fuel is biobased or defined as an alternative fuel by EPAct (United States Congress, 1992:Sec 508). Initially, this SDVF was exponential. This penalized EPAct alternative fuels that were not alcohol or biobased. Although fuels such as CNG and propane are not renewable, the decision maker felt that non-renewable alternative fuels have some value. Therefore, a piece-wise linear SDVF was developed to capture any alternative and score them accurately. Fuels that are 85% renewable or higher received the highest value. Fuels that are 85% renewable are considered alternative fuels, whereas, fuels that are not at least 85% biobased or alcohol based are not considered alternative fuels according to the EPAct (United States Congress, 1992). Fuels that are less than 85% renewable received the same value. Studies have shown that biodiesel is most effective at 20% and 100% blends while ethanol is most effective at 10% and 85% blends (He, 2003:950). Both the biodiesel and ethanol industries try to regulate the mixtures of their respective renewable blends to keep production constant. Figure A-14 shows the value function for the *Renewable/Alternative* measure.

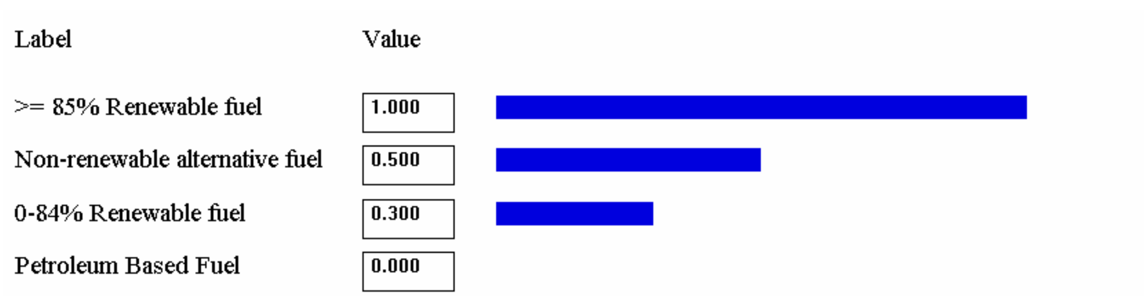

Figure A-14. *Renewable/Alternative* SDVF

Global Weighting

Viewing the global weights of the measures enables an assessment of the measures compared within in different second tier values. Table A-1 displays the global weights of all measures. The cumulative weight of the measures is also calculated to provide insight onto the weighting. Nearly 60% of the decision is based on the *Life Cycle Cost*, *Supply*, *Greenhouse Gases* and *Renewable/Alternative Fuel* measures.

Table A-1. Global Weights

Measure	Global Weight	Cumulative Weight
Renewable Alternative	19.500%	19.500%
Life Cycle Cost	18.375%	37.875%
Greenhouse Gases	11.143%	49.018%
Supply	9.100%	58.118%
Nitrogen Oxide	5.571%	63.689%
Sulfur Oxide	5.571%	69.261%
Particulate Matter	5.571%	74.832%
Carbon Monoxide	5.571%	80.404%
Volatile Organic Compounds	5.571%	85.975%
Distance to Fuel Station	4.900%	90.875%
Flash Point	3.250%	94.125%
Ground or Water Contaminant	3.250%	97.375%
Fuel Credits	2.625%	100.000%

Appendix B: Sensitivity Analysis

Figure B-1 shows the sensitivity analysis graph for the *Greenhouse Gases* measure. This graph is an example of a measure that is not sensitive to change for the top or bottom alternative. The top alternative is identified by the colored, diagonal line that has the highest intersection (with respect to the y-axis) with the vertical line. For the *Greenhouse Gases* measure, this line is identified as B100 as shown in the legend to the right. On the contrary, the lowest ranking alternative is identified by the colored, diagonal line that has the lowest intersecting point with the vertical line. For the *Greenhouse Gases* measure, the lowest ranking alternative is identified as gasoline. The top alternative is not sensitive to the change in weights because no colored lines intersect with B100. The same can be said for the lowest alternative. The lowest alternative is not sensitive to the change in weights because no colored lines intersect with gasoline. Table B-1 identifies two objectives that share this characteristic, the *Greenhouse Gases* measure and the *Safety* second tier value. The highest ranking and lowest ranking alternative of the sensitivity analysis graph for the *Safety* second tier value is similar to the sensitivity analysis of the *Greenhouse Gases* measure as displayed in Figure B-2.

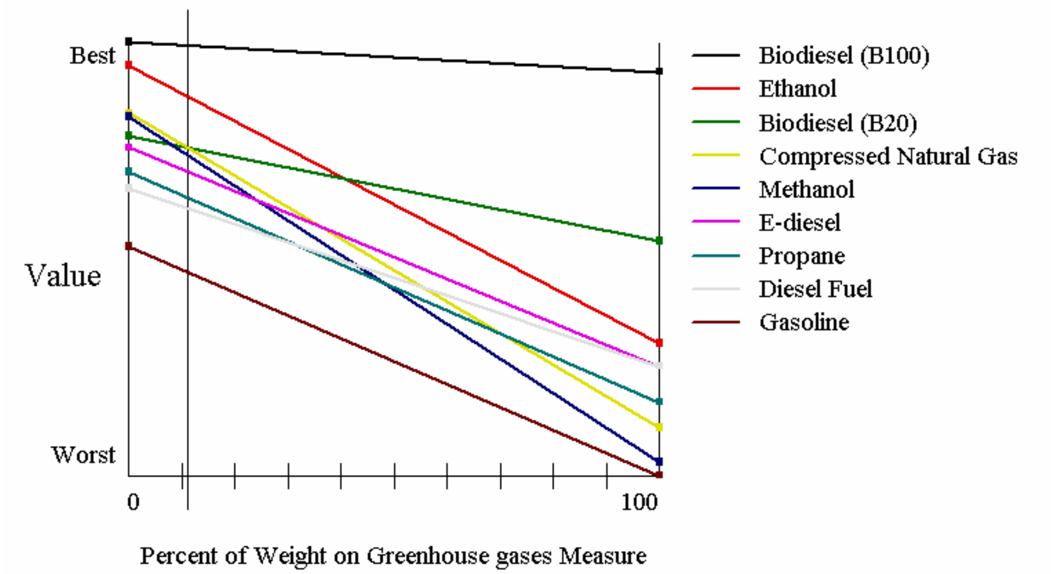

Figure B-1. Sensitivity Analysis of *Greenhouse Gases* Measure

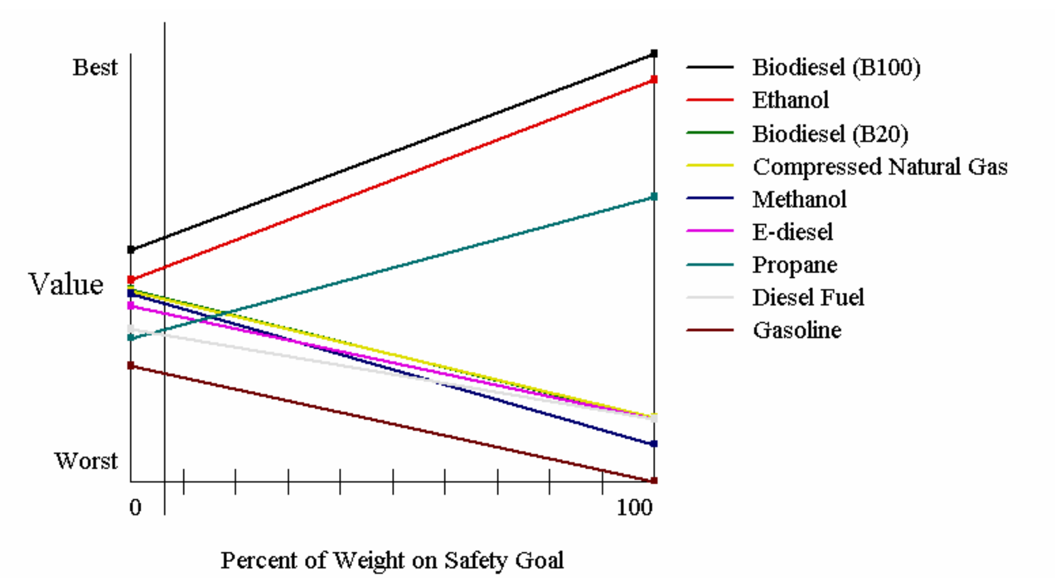

Figure B-2. Sensitivity Analysis of *Safety* Second Tier Value

Table B-1. Values/Measures Not Sensitive to Change for the Top and Bottom Alternative

Value/Measure	Percent Change in Terms of Current Weight Needed to Change Ranking of Top Alternative	Percent Change in Terms of Current Weight Needed to Change Ranking of Bottom Alternative
Supply Measure	1099.0%	1099%
Air Emissions Value	228%	244%
Greenhouse Gases Measure	0*	0**
Nitrogen Oxides Measure	682%	736%
Particulate Matter Measure	1579%	1077%
Sulfur Oxides Measure	1525%	1221%
Volatile Organic Compounds Measure	664%	1077%
Safety Value	0*	0**
Flash Point Measure	3077%	46%
Ground Contaminant Measure	3077%	3077%
* The top ranking alternative of the Greenhouse Gases measure and Safety value will not change regardless of weight		
** The bottom ranking alternative of the Greenhouse Gases measure and Safety value will not change regardless of weight		

Figure B-3 shows the sensitivity analysis of the *Nitrogen Oxides* measure. At first glance, it appears that this measure may be sensitive to changes in alternative rankings. There are two reasons why this is false. The *Nitrogen Oxides* measure is one of six objectives under *Air Emissions*. The weight of the *Nitrogen Oxides* measure is proportionate to five other *Air Emissions* objectives. In order to accurately consider other *Air Emissions* objectives, the *Greenhouse Gases*, *Carbon Monoxide*, *Sulfur Oxides*, *Particulate Matter* and *Volatile Organic Compounds* measures must also increase in weighting. A change from 5.6% to 38% can be annotated as an increase of 32.4 percentage points. This is calculated by subtracting 5.6% from 38%. A weight change of 32.4 percentage points appears to show sensitivity; however, an increase of 32.4 percentage points must be multiplied by five equaling a 162 percentage point change in *Air Emissions* which is impossible. Next, an increase in the weighting from 5.6% to 38%

is around a 680% increase in the weighting change. This is calculated by dividing 38% by 5.6% and multiplying by 100%. This shows that the weighting of the *Carbon Monoxide* measure would have to more than sextuple in order to change the top ranking alternative from B100 to B-20 as indicated by the intersection of the black diagonal line and the green diagonal line in Figure B-3. Table B-1 shows eight other objectives that share the same characteristic as the *Nitrogen Oxides* measure sensitivity analysis graphs. The table shows the percent change in terms of the current weight needed to change both the highest and lowest ranking alternative for the *Supply*, *Nitrogen Oxides*, *Particulate Matter*, *Sulfur Oxides*, *Volatile Organic Compounds*, *Flash Point*, *Ground and Water Contaminant* measures and the *Air Emissions* second tier value. Due to the similarities in sensitivity analysis graphs, the lack of insight they provide and the production of Table B-1, the sensitivity graphs for *Supply*, *Nitrogen Oxides*, *Particulate Matter*, *Sulfur Oxides*, *Volatile Organic Compounds*, *Flash Point*, *Ground and Water Contaminant* measures and the *Air Emissions* second tier value are not instructive in this research.

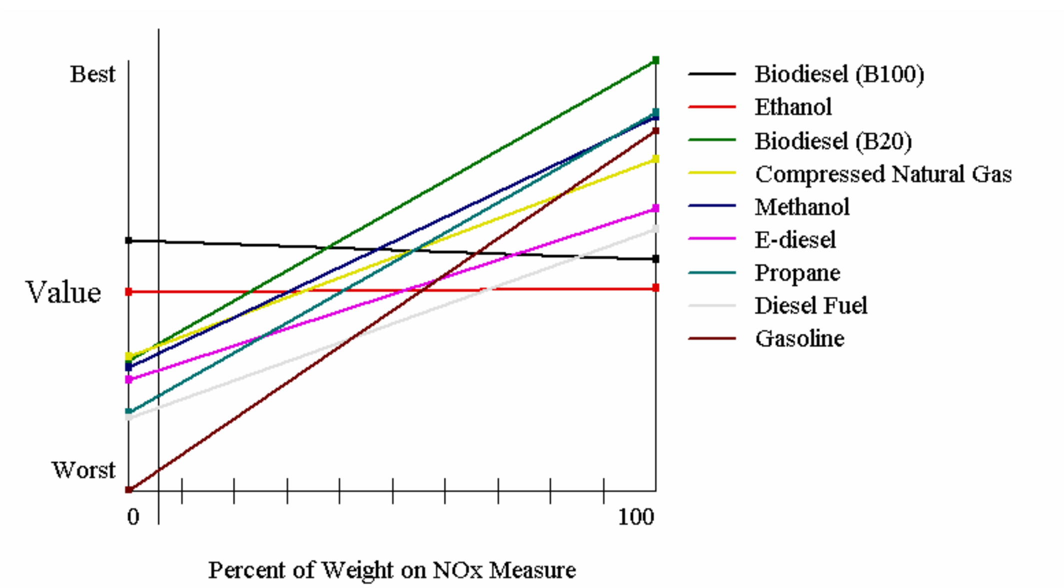

Figure B-3. Sensitivity Analysis of *Nitrogen Oxides* Measure

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14. ABSTRACT

The United States relies on imported oil as a result of domestic petroleum consumption rates greatly exceeding production rates. Alternative fuels are a major force in the effort to reduce petroleum consumption in the transportation industry. The transportation industry also accounts for 1/3 of all greenhouse gas emissions and nearly half of all cancers attributed to outdoor sources of pollutants.

The purpose of this research was to evaluate the economic and environmental feasibility of renewable alternative fuels and associated blends (ethanol, methanol, 100% biodiesel (B100), 20% biodiesel (B20) and e-diesel) compared to non-renewable alternative fuels (compressed natural gas and propane) and conventional fuels (gasoline and diesel) using the decision analysis approach of Value-Focused Thinking (VFT.) Specifically, this thesis sought to answer three sets of research questions addressing the appropriate methodology for selecting renewable alternative fuels, the justification for using renewable alternative fuels and the suitability of using the developed model at differing geographic locations.

The research questions were answered through a comprehensive literature review, and the development and utilization of the model. The culmination of this effort was the development of a complete and non-redundant VFT model that can be used by installation commanders, environmental managers, or transportation officers to select renewable alternative fuels for their government vehicles. Recommendations to utilize renewable alternative fuels through this decision analysis tool are also discussed.

15. SUBJECT TERMS

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