# Multi-level Multi-criteria Analysis of Alternative Fuels for Waste Collection Vehicles in the United States

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## *Abstract*

Historically, the U.S. waste collection fleet was dominated by diesel-fueled waste collection vehicles (WCVs); the growing need for sustainable waste collection has urged decision makers to incorporate economically efficient alternative fuels, while mitigating environmental impacts. The pros and cons of alternative fuels complicate the decisions making process, calling for a comprehensive study that assesses the multiple factors involved. Multi-criteria decision analysis (MCDA) methods allow decision makers to select the best alternatives with respect to selection criteria. In this study, two MCDA methods, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Simple Additive Weighting (SAW), were used to rank fuel alternatives for the U.S. waste collection industry with respect to a multi-level environmental and financial decision matrix. The environmental criteria consisted of life-cycle emissions, tail-pipe emissions, water footprint (WFP), and power density, while the financial criteria comprised of vehicle cost, fuel price, fuel price stability, and fueling station availability. The overall analysis showed that conventional diesel is still the best option, followed by hydraulic-hybrid WCVs, landfill gas (LFG) sourced natural gas, fossil natural gas, and biodiesel. The elimination of the WFP and power density criteria from the environmental criteria ranked biodiesel 100 (BD100) as an environmentally better alternative compared to other fossil fuels (diesel and natural gas). This result showed that considering the WFP and power density as environmental criteria can make a difference in the decision process. The elimination of the fueling station and fuel price stability criteria from the decision matrix ranked fossil natural gas second after LFG-sourced natural gas.

This scenario was found to represent the status quo of the waste collection industry. A sensitivity analysis for the status quo scenario showed the overall ranking of diesel and fossil natural gas to be more sensitive to changing fuel prices as compared to other alternatives.

**Keywords:** alternative fuels, waste collection, decisions making, multi-criteria analysis

# 1. Introduction

## 1.1 Initial Position

The waste collection industry is driven by the need to reduce costs and emissions while increasing operation efficiency. These challenges encourage the collection industry to explore alternative fuel technologies including compressed natural gas (CNG); liquefied natural gas (LNG); biodiesel (B20, B100), and hydraulic-hybrid (an alternative to conventional diesel trucks, where trucks are able to recapture, store, and reuse braking energy, Bender et al., 2014).

Up to 2010, diesel-fueled waste collection vehicles (WCVs) were the backbone of the U.S. waste collection industry with less than one percent of WCVs using alternative fuel (Rogoff et al., 2010). The recent relatively low prices of natural gas compared to high diesel prices have incentivized the industry to consider natural gas as an alternative fuel for their fleets. In 2012, Waste Management Inc., based in Houston, Texas, and a leading provider of comprehensive waste management services in North America, operated the largest natural gas collection vehicles fleet in North America with nearly 1,700 CNG and LNG vehicles. In the next five years, it is anticipated that 80% of the Waste Management new trucks purchased will be fueled by natural gas. The company added 13 CNG fueling stations in the first-half of 2012, which brought their total to 31. Moreover, Waste Management planned to construct another 17 stations by the end of 2012 (Waste Management Inc., 2012). The second major waste hauler in the U.S., Republic Services, with currently more than 1,000 vehicles running on alternative fuels, plans to add 3,100 natural gas and other alternative-fueled WCVs by the end of 2015 (Republic Services, 2012). In 2012, WCV and transfer vehicles accounted for 11 percent of the total U.S. natural gas vehicles (NGVAMERICA, 2012). In contrast, diesel fuel purchases were estimated to consume 7.5% of the industry revenues in 2012 (Smith, 2012).

Undoubtedly, fuel cost has been the driving factor for the waste industry. A comprehensive decision matrix that considers other factors such as changing policies, future fuel prices, and uncertainty in fuel performance data, has not been developed. In the last three decades, the selection scheme for alternative fuels and energies has changed from a single-criterion cost-based assessment, to a multi-criteria analysis that considers environmental, social, operational, and even political factors (Pohekar and Ramachandran, 2004; Cavallaro, 2005; Wang et al., 2009; Linkov and Moberg , 2012; Read et al., 2013; Hadian and Madani, 2015). A multi-criteria analysis normally involve trade-offs among alternatives. Multi-criteria decision analysis (MCDA) methods allow stakeholders to select an optimal solution for complex problems involving such tradeoffs (Josimovic et al., 2015). The use of MCDA methods allows decision makers to systematically select the best alternative with respect to selection criteria, while understanding the tradeoffs that occur in selecting different alternatives (Linkov and Moberg, 2012).

### 1.2 Goal and Objectives

The goal of this paper is to determine if the waste collection industry is moving in the right direction toward a more environmental-friendly alternative at a reasonable financial cost. This is done through application of MCDA methods to select the best alternative fuel for the waste collection industry, and to determine trade-offs among environmental and economic aspects of alternatives fuels. MCDA methods have been used to rank alternative fueled buses for public transportation (Tzeng et al., 2005), alternative transportation fuels (Mohamadabadi et al., 2009), electricity generation alternatives (Cristóbal, 2011), municipal solid waste management alternatives (Herva and Roca, 2013), and landfill sites (Şener et al., 2006).

In this study, MCDA methods were used to rank alternative fuels for WCVs using a multi-level multi-criteria decision analysis framework (Read et al., 2013) that incorporates environmental and financial criteria, providing insights for better decision-making by the waste industry. Sensitivity analysis will be performed to determine the robustness of fuel rankings to changing policies, selection criteria, and fuel performance data. This will help determine the long-term consequences of selecting a certain fuel for the industry. The initial positon of the waste collection industry will be compared to the results of this study.

The rest of the paper is outlined as follows. Section 2 presents the MCDA methods and data used to rank alternative fuels. Section 3 ranks alternative fuels for waste collection vehicles. Finally, Section 4 presents the conclusions make recommendations the waste collection industry.

## 2. Methods

Alternative fuels were identified based on a literature review. Fuel selection criteria that consider environmental and financial factors were established. The fuel performance data (a quantitative measure of the fuel performance with respect to each selection criteria) were obtained from the literature. Finally, two MCDA methods, Simple Additive Weighting (SAW) (Churchman and Ackoff, 1954) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981), were used to rank fuel alternatives for the waste collection industry using the multi-level environmental and multi-criteria approach (Read et al., 2013). The selection of these two methods was based on their ability to handle multi-attribute decision making problems. The following sections provide more details about the decision analysis process.

### 2.1 Fuel Alternatives for Waste Collection Vehicles

Nine different fuels could be considered for WCVs; gasoline, diesel, natural gas (Gordon et al., 2003), biodiesel (López et al., 2009), liquefied petroleum gas, hydraulic-hybrid (a hydraulic hybrid WCV consists of a typical diesel-fueled WCV components - a diesel engine, a clutch, a transmission system, a differential, and wheels, combined with the hydraulic system elements - an axial piston pump, a clutch, a simple transmission system, used to recapture, store, and reuse braking energy (Bender et al.,2013; Bender et al., 2014;. de Oliveira et al., 2014), hybrid diesel-electric (transfers conventional chassis WCVs into dual power options specifically designed for collection and transportation of the waste, thus reduces tailpipe emissions within cities and neighborhoods, FAUN, 2015), hydrogen gas (FAUN, 2011), ethanol E85, and dimethyl ether (DME) (Tsuchiya and Sato, 2006). Only four fuel technologies were commercially available for WCVs - diesel, natural gas, biodiesel, and hydraulic-hybrid. Diesel-fueled WCVs can operate on fossil diesel or biodiesel (BD) blends (BD20 and BD 100), but may require engine modifications when using biodiesel blends (U.S. EIA, 2015). BD100 is made of 100% biodiesel, while BD20 is a blend of 20% biodiesel and 80% fossil diesel (U.S. EIA, 2015a). In the U.S., biodiesel is produced from a diverse biomass feedstock, led by soybean oil which accounted for more than 50% in 2013 (U.S. EIA, 2015b). In this study, two sources of biodiesel were investigated; soybean as a primary source of biodiesel in the US, and algaculture as an alternative future source. Natural gas WCVs can operate either using CNG or LNG, which can be obtained from a fossil or biogenic source. In this study, fossil sources were categorized as North American or Non-North-American. Landfill gas (LFG) sourced natural gas was the only biogenic natural gas source considered in this study. LFG is comprised of mainly methane (50-60%) and carbon dioxide (40-40%) (Shin et al., 2005; U.S. EPA, 2012). It also consists of hundreds of other compounds at lower concentrations such as oxygen, nitrogen, sulfur compounds, water vapor and organic compounds (U.S. EPA, 2000; Shin et al., 2005). In order to use LFG as an alternative vehicular fuel, LFG should be converted to pipeline quality natural gas with high BTU content, through the separation of methane from carbon dioxide and other constituents (Hesson, 2008; U.S. EPA, 2000).

Accordingly, twelve alternative fuels or fuel blends were considered for the WCVs in the U.S. based on fuel type and source; (1) diesel, (2) CNG (North American), (3) CNG (Non-North American), (4) LNG (North American), (5) LNG (Non-North American), (6) hydraulic-hybrid, (7) CNG (LFG sourced), (8) LNG (LFG sourced), (9) BD20 (Algaculture), (10) BD20 (soybean), (11) BD100 (Algaculture), and (12) BD100 (soybean).

### 2.2 Fuel Evaluation Criteria

First, a multi-level fuel selection criteria matrix that considers environmental and financial factors was established (Figure 1). The upper level criteria were then broken down into sub-criterion categories, e.g. tail-pipe emissions (second level environmental criterion) of WCVs were evaluated based on carbon monoxide, carbon dioxide, nitrogen oxides, particulate matters, and total hydrocarbons emissions. Fuel performance data were collected for each alternative with respect to the sub-criterion category, e.g., fuel performance data were used for carbon monoxide, carbon dioxide, nitrogen oxides, particulate matters, and total hydrocarbons emissions (level 3).

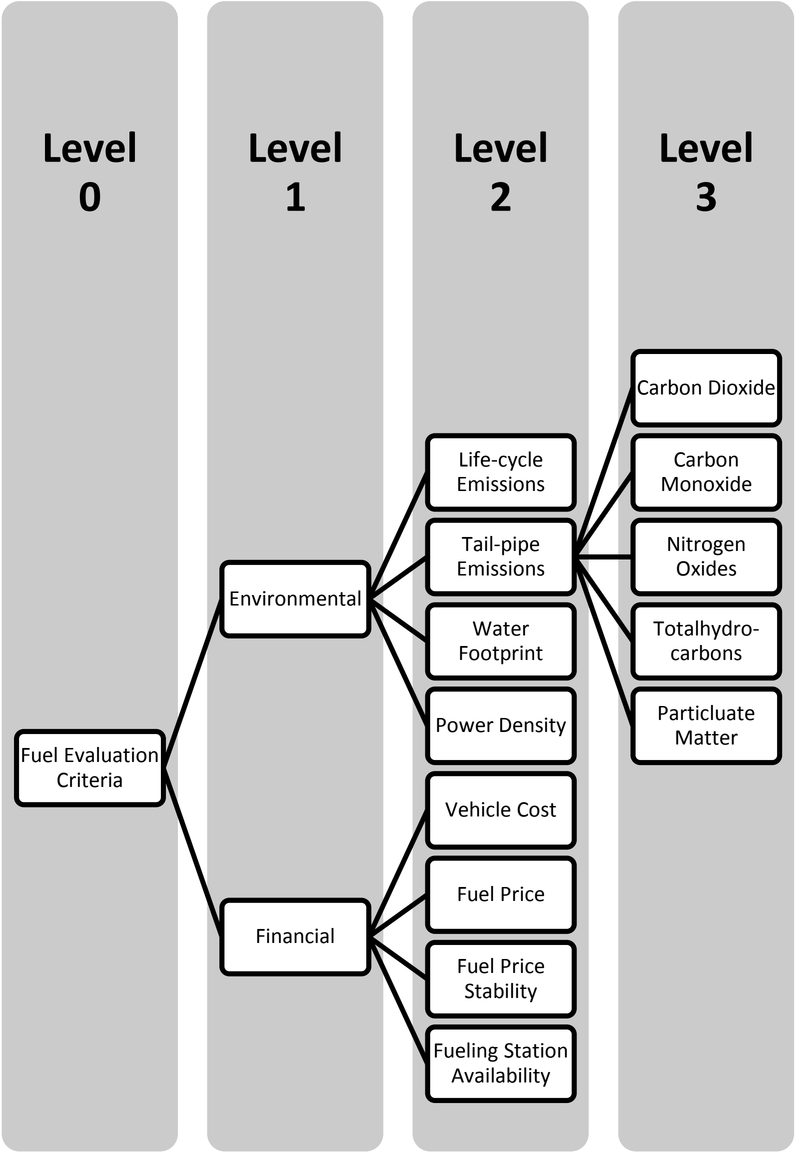

Figure 1: Multi-level multi-criteria decision making matrix.

### 2.2.1 Environmental Criteria

Four environmental criteria were considered in this study: life-cycle emissions of alternative fuels and fuel blends, tail-pipe emissions of alternative fuel WCVs, water footprint (WFP), and power density of alternative fuel and fuel blends.

#### 2.2.1.1 Life-cycle Emissions of Alternative Fuels

Life-cycle emissions of alternative fuels and fuel blends had been calculated by Maimoun et al. (2013) using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model provided by Argonne National Laboratory (U.S. DOE, 2012a). Life-cycle emissions of alternative fuels and blends represent the total equivalent of greenhouse gas emissions produced during the entire life-cycle of the fuel (fuel production emissions, fuel transportation emissions and tail-pipe emissions at the point of use). The life-cycle emissions associated with diesel, CNG (North American), CNG (Non-North American), LNG (North American), LNG (Non-North American), hydraulic-hybrid, LNG (LFG sourced), CNG (LFG sourced), BD100 (Algaculture), BD20 (Algaculture), BD100 (soybean), and BD20 (soybean) were estimated at 2.85, 3.01, 3.27, 3.14, 3.39, 2.33, 0.62, 0.5, 1.4, 2.52, 0.71 and 2.38 kg $CO_{2eq}$ per collection vehicle kilometer travel (CVkmT), respectively (Maimoun et al., 2013). It should be noted that the fuel consumption and associated emissions are expected to vary significantly depending on vehicle age, driving cycle, weather conditions, traffic pattern, terrain, and other factors. For the purpose of this analysis, average literature values were assumed to be sufficient to conduct the analysis. Moreover, changes in driving cycle and other factors were assumed to the have the same influence on all alternative fuels.

#### 2.2.1.2 Tail-pipe Emissions of Alternative Fuel WCVs

Tail-pipe emissions of WCVs include carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), total hydrocarbons (THC) and particulate matter (PM). Tail-pipe emissions for conventional diesel-fueled WCVs were measured by Farzaneh et al. (2009) using two portable emissions measurement systems (PEMS). Emissions from conventional diesel-fueled WCVs were investigated under four different operation modes including (1) urban driving, (2) trash collection, (3) freeway driving, and (4) landfill activities (Farzaneh et al., 2009). For this study, a weighted average was calculated for each pollutant using the average emission factor associated with each driving mode and the fraction of the driving mode with respect to the overall route. The average tail-pipe emissions from conventional diesel-fueled WCVs were estimated to be 2.8 kg/km, 17.1 g/km, 17.1 g/km, 0.6 g/km, and 0.06 g/km for $CO_2$, CO, $NO_x$, THC, and PM, respectively.

A study by Texas Transportation Institute (2009) compared the tail-pipe emissions of CNG fueled WCVs relative to conventional diesel vehicle, e.g. the tail-pipe NOx emissions of CNG vehicles were found to be 96% less than conventional diesel WCVs (Table 1). Tail-pipe emissions for LNG were assumed to be equal to CNG based on their identical chemical properties. According to the U.S. Environmental Protection Agency (EPA), the use of hydraulic-hybrid diesel WCVs has a potential fuel savings of up to 30%. Therefore, tail-pipe emissions from hydraulic-hybrid WCVs were assumed to be 30% less than conventional diesel-fueled WCVs (Hall, 2010). de Oliveira et al. (2014) also reported 15 to 25% improvement in fuel economy of heavy-duty hydraulic-hybrid WCV compared to conventional diesel-fueled WCVs. Tail-pipe emissions for buses running on BD20 and BD100 showed lower emissions compared to diesel buses, except for $NO_X$ emissions (U.S. EPA, 2002). Relative emissions values shown in Table 1 were applied to the weighted average of the conventional diesel tail-pipe emissions to estimate alternative-fueled WCVs tail-pipe emissions.

Table 1: Alternative-fueled waste collection vehicle (WCV) tail-pipe emissions relative to diesel-fueled vehicles.

| Fuel Category | $CO_2$ | CO | $NO_x$ | THC | PM | Source | Assumption |
|---|---|---|---|---|---|---|---|
| CNG (Source: American, non-American, LFG) | -27% | +1,200% | -96% | 5,700% | -- | Texas Transportation Institute (2009) | |
| LNG (Source: American, non-American, LFG) | -27% | +1200% | -96% | 5,700% | -- | Texas Transportation Institute (2009) | Tail-pipe emissions from LNG are equal to CNG |
| hydraulic-hybrid | -30% | -30% | -30% | -30% | -30% | Hall (2010) | Hybrid waste collection vehicles with 30% fuel saving will have 30% less tail-pipe emissions |
| BD20 (Source: Algaculture, soybean) | -- | -11% | +2% | -21% | -10% | U.S. EPA (2002) | Waste collection vehicles and heavy-duty vehicles are similar. |
| BD100 (Source: Algaculture, soybean) | -- | -47% | +10% | -68% | -45% | | |

#### 2.2.1.3 Water Footprint (WFP) of Alternative Fuels and Fuel Blends

The WFP is a measure of both the direct and indirect use of fresh water over the entire process life cycle (Hoekstra et al., 2009). It consists of three components; blue, accounting for the consumption of surface and groundwater resources; green, referring to consumption of rainwater stored in the soil as soil moisture, normally lost through evapotranspiration; and grey, relating to water pollution and defined as the volume of freshwater that is required to dilute pollutants to meet existing water quality standards. The total WFP of any process, product, or energy source is the summation of the blue, green and grey WPFs. The total WFP associated with alternative fuels was obtained from the literature (Gerbens-Leenes et al., 2008; Singh et al., 2011), except for LFG. The WFP of LFG source vehicular fuel was not evaluated previously, so the WFP of LFG conversion to vehicular fuel was calculated and is presented in this section.

Currently, commercial methods available to purify LFG include: (1) physical and chemical sorption of carbon dioxide to materials and solvents, (2) gas cooling separation, and (3) membrane separation (Läntelä et al., 2012). In this study, the WFP of LFG conversion to vehicular fuel was calculated for a water scrubber with water recycling to remove carbon dioxide, as it is considered the most cost effective and widely use technology for upgrading LFG to vehicular fuel, particularly when wastewater is reused as an absorbent (Hunter and Oyama, 2000; Rasi at al., 2008). The process consists of absorption, desorption, pumps, compressor, and drying (Läntelä et al., 2012).

In order to calculate the WFP of LFG conversion, it was important to set the system boundaries of the process (Madani and Khatami, 2015). The function of any landfill is the disposal of municipal solid waste and LFG is a byproduct of waste landfilling. According to the U.S. EPA (2012), large landfills are required to collect LFG for beneficial use or flaring. As a result, the system boundaries for calculating the WFP of LFG conversion to vehicular fuel excluded landfill construction and operation, LFG collection, and any condensate generated in the process, and only includes (1) water evaporated during the process and need to be replaced, (2) electricity consumption WFP, and (3) the WFP offsets as a result of energy recovered. The functional unit used was cubic meters of water per GJ of vehicular fuel produced.

The energy content of methane is 37,700 KJ/Nm$^3$. Therefore, the energy recovered in converting a standard cubic meter of LFG, assuming that 100% of the methane in LFG is recovered, is equal to 18,900-22,600 KJ per Nm$^3$ of LFG. The WFP of fossil natural gas is 110 L per GJ (Gerbens-Leenes et al., 2008), therefore, a WFP offset between -2.1 and -2.5 L per Nm$^3$ of LFG converted is associated with energy recovery from LFG.

In a pilot study described by and Rasi et al. (2008) and Läntelä et al. (2012) to convert 7.41 Nm$^3$/h of LFG to vehicular fuel using water scrubbers with complete water recycling, Läntelä et al. (2012) estimated that about 1% of circulating water (700 l in total) was evaporated or lost during the upgrade process (3–6 h) and must be replaced. Therefore, it is estimated that the process WFP is approximately 0.21 L per Nm$^3$ LFG processed. The upgrade process electricity consumption was estimated by Läntelä et al., 2012 to be between 0.43-0.55 kwh/Nm$^3$. The WFP of the US electricity was estimated for the 2013 U.S. electric grid energy mix using the WFP of different energy sources compiled by Hadian and Madani (2013). The overall total WFP of the U.S. electric energy mix was calculated at 9 L per kWh. Therefore, it is estimated that the WFP associated with energy consumption is between 3.9 to 4.95 L per $Nm^3$ of gas.

The total WFP of converting LFG to vehicular fuel is estimated to be between 4.1-5.2 L per $Nm^3$ of LFG processed, while the net WFP (accounting for offset) is estimated between 1.6-3.1 L per $Nm^3$ or between 0.07-0.16 $m^3$ per GJ of vehicular fuel. The net WFP of LFG sourced vehicular fuel is impacted by the high WFP of the U.S. electric grid and relatively low WFP of fossil natural gas. The WFP of LFG-sourced natural gas is comparable to the WPF of fossil natural gas and it depends on the quality of LFG. Also, the process WFP calculations are based on a pilot study and it was assumed that a full-scale facility will operate with similar demands to the pilot scale. This estimate does not include the WFP of potential contamination or water discharge to the surroundings in case of failure of the water recycling system, and initial construction material, e.g. absorption and desorption columns, where no documentation was found. On average, natural gas has the lowest WFP, followed by LFG-sourced natural gas, while diesel has an average to moderate WFP. The production of biodiesel was found to have the highest WFP, associated with growing and processing of energy crops. The WFP of fuels is presented in Table 2.

#### 2.2.1.4 Power Density of Alternative Fuels and Fuel Blends

The power density was represented by Watts generated per area of land ($m^2$). Biodiesel production, either from algaeculture or soybeans, was found to have a very low power density compared to all other alternative fuels. The power density associated with fuel production is listed in Table 2.

Table 2: WFP and power density of alternative fuels and fuel blends.

| | WFP | | | Power Density | | |
|---|---|---|---|---|---|---|
| | $M^3/GJ$ | Source | Assumptions | $W/m^2$ | Source | Assumptions |
| Diesel | 1.06 | Gerbens-Leenes et al. (2008) | WFP of diesel equals crude oil extraction and processing | $10^3$ to $10^4$ | Smil (2010) | The Power Density of Oil Field was used. |
| CNG (Fossil Source) | 0.11 | Gerbens-Leenes et al. (2008) | WFP of CNG equals natural gas extraction and processing | $10^3$ to $10^4$ | | Assumed Similar to Diesel |
| CNG (LFG Source) | 0.07-0.16 | This Study | | 10 | Amini and Reinhart (2011) | |
| LNG (Fossil Source) | 0.11 | Gerbens-Leenes et al. (2008) | Liquefaction of natural gas to LNG consumes water; so it was assumed to be at the high end of CNG WFP | $10^3$ to $10^4$ | | Assumed Similar to Diesel |
| LNG (LFG Source) | 0.07-0.16 | This Study | | 10 | Amini and Reinhart (2011) | |
| Biodiesel (Soybean) | 383 | Singh et al. (2011) | Average WFP of biodiesel | $1.32x10^{-5}$ | Pienkos (2007) | |
| Biodiesel (Algaculture) | <379 | Singh et al. (2011) | Average WFP of biodiesel | $3.3x10^{-4}$ to $2.75x10^{-3}$ | Pienkos (2007) | |

### 2.2.2 Financial Criteria

In this study, four financial criteria were considered; vehicle cost, fuel cost, fuel price stability and fueling station availability. A quantitative measure of each alternative with respect to each criteria is presented in this section.

#### 2.2.2.1 Vehicle Cost of Alternative Fuel Vehicles

Vehicle cost is a significant part of the capital cost that is associated with switching to an alternative fuel, therefore it was considered in the selection criteria. The average vehicle cost was reported for each alternative in U.S. dollars per WCV (Table 3).

#### 2.2.2.2 Fuel Cost

The relatively low priced natural gas compared to diesel shaped the recent history of vehicle purchases by the waste collection industry, reflecting the significance of fuel prices. In order to estimate the fuel cost, the average fuel mileage was adopted from Maimoun et al. (2013). The fuel mileage was used with the national average fuel price during 2012 (U.S. DOE, 2012b) to estimate the fuel cost in U.S. dollars per collection vehicle kilometer of travel (CVKmT).

#### 2.2.2.3 Fuel Price Stability

Fuel price stability was considered a financial criterion. The fuel price stability was measured by the standard deviation of the U.S. national fuel prices during 2012. The cost of conversion of LFG to vehicular fuel was assumed to be stable over the course of one year (2012).

#### 2.2.2.4 Fueling Stations Availability

The limited number of CNG/LNG fueling stations forced waste haulers to invest in building new stations, while gradually switching new vehicles purchases to natural gas as the price of gas plummeted. This demonstrates the significance of fueling station availability to selecting alternative fuels. The number of commercially available fueling stations was reported for each alternative in Table 3. In the case of CNG/LNG from LFG, the number of US landfill gas to vehicular fuel projects was used. In 2008, there were only 20 sites converting LFG to vehicular fuel. However, there were more than 425 landfills in the US of which about 300 are used to generate electricity and 110 commercial/industrial heating fuel (Hesson, 2008). This shows the potential of more landfill sites that can be used to produce vehicular fuel.

Table 3: Financial performance data.

| | Vehicle Cost | | Fuel Cost | | | | Fuel Price Stability | | Fueling Stations | |
|---|---|---|---|---|---|---|---|---|---|---|
| | U.S. Dollar per Collection Vehicle | Source/ Assumption | Mileage (Km per L diesel equivalent) | Unit Price | | Travel Cost (U.S. Dollar per CVKMT) | Standard Deviation of price (2012) | Source/ Assumption | No of Stations in the US | Source |
| Diesel | 160,000-200,000 | Gordon et al. (2003) | 1.2 | $1.09 per diesel Equivalent L | 2012 National Average Price, U.S. DOE (2012b) | 0.91 | 0.24 | U.S. DOE (2012b) | 128,887 | U.S. DOE (2012c) |
| CNG | 200,000-250,000 | Gordon et al. (2003) | 1.0 | $0.613 per diesel Equivalent L | 2012 National Average Price, U.S. DOE (2012b) | 0.61 | 0.66 | U.S. DOE (2012b) | 1048 | U.S. DOE (2012c) |
| LNG | 200,000-250,000 | Similar to CNG | 0.95 | $0.613 per diesel Equivalent L | LNG price Similar to CNG | 0.65 | 0.66 | U.S. DOE (2012b) | 53 | U.S. DOE (2012c) |
| Hydraulic Hybrid | 260,000-300,000 | Danna, 2011 | 1.5 | $1.08 per diesel Equivalent L | 2012 National Average Price, U.S. DOE (2012b) | 0.81 | 0.24 | U.S. DOE (2012b) | 128,887 | U.S. DOE (2012c) |
| CNG (Source: LFG) | 200,000-250,000 | Inform, 2006 | 1.0 | $5 and 8 per MBtu (Average Price of $6.5 per MBtu was used) | Hesson, 2008 | 0.22 | 0 | The price of LFG is assumed to be constant | 20 | Hesson, 2008 |
| LNG (Source: LFG) | 200,000-250,000 | Similar to CNG | 0.95 | | LNG price Similar to CNG | 0.24 | 0 | The price of LFG is assumed to be constant | 20 | Hesson, 2008 |
| BD100 | 160,000-200,000 | Similar to regular diesel | 1.2 | $1.26 per diesel Equivalent L | 2012 National Average Price, U.S. DOE (2012b) | 1.05 | 0.52 | U.S. DOE (2012b) | 621 | U.S. DOE (2012c) |
| BD20 | 160,000-200,000 | Similar to regular diesel | 1.2 | $1.12 per diesel Equivalent L | 2012 National Average Price, U.S. DOE (2012b) | 0.93 | 0.33 | U.S. DOE (2012b) | 621 | U.S. DOE (2012c) |

### 2.3 MCDA methods

Two MCDA methods were used to rank alternative fuels with respect to the selected criteria, SAW (Churchman and Ackoff, 1954) and TOPSIS (Hwang and Yoon, 1981). The selection of these two methods was based on their ability to handle multi-attribute decision making problems. SAW (Churchman and Ackoff, 1954) is the most widely known MCDA method and compares the weighted average of alternative performance data with respect to a selection criteria (Afshari et al., 2010). TOPSIS is based on choosing a hypothetical ideal solution; the alternative that has the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative solution is the best (optimal) solution. TOPSIS can also accommodate different criteria weights in ranking alternatives (Hwang and Yoon, 1981).

SAW and TOPSIS require a comparable scale for all elements in the decision matrix, therefore performance values were normalized with respect to each criterion (j). The normalized performance values were obtained for beneficial criteria (the higher the rating, the better the performance) using Equation 1 (Nguyen and Gordon-Brown, 2012).

$$r_{ij} = \frac{x_{ij} - min_j}{max_j - min_j} \qquad \text{Equation 1}$$

where:

$r_{ij}$ = Normalized value of alternative (i) with respect to criteria (j) (0-1);

$x_{ij}$ = Performance value of alternative (i) with respect to criteria (j);

$max_j$ = Maximum performance value with respect to criteria (j); and

$min_j$ = Minimum performance value with respect to criteria (j).

For cost criteria (the smaller the rating, the better the performance), the normalized value was calculated using Equation 2 (Nguyen and Gordon-Brown, 2012).

$$r_{ij} = \frac{max_j - x_{ij}}{max_j - min_j} \qquad \text{Equation 2}$$

### 2.3.1 Simple Additive Weighting (SAW)

The SAW method (Churchman and Ackoff, 1954) compares alternatives using the comparison index ($SAW_j$) calculated in Equation 3. The higher the index value, the better the performance.

$$SAW_j = \sum_{j=1}^{n} W_j \times r_{ij} \qquad \text{Equation 3}$$

where:

$W_j$ = Entropic weight of each criterion (j)

The entropic weight ($W_j$) of each criterion (j) is used to determine the weight of each criterion based on the dispersion of the performance values (Chan et al., 1999). $W_j$ of each criterion can be calculated using Equation 4 as described in Madani et al. (2014).

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$ Equation 4

where:

$d_j = 1 - E_j$; and

$E_j$= The entropy of normalized performances under a given criterion and can be calculated using Equation 5 as described in Madani et al. (2014).

$$E_j = -k \sum_{i=1}^{m} P_{ij} . \ln(P_{ij})$$ Equation 5

where:

m = Total number of alternatives;

$k = \frac{1}{\ln(m)}$; and

$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$

### 2.3.2 Technique for Order Performance by Similarity to an Ideal Solution (TOPSIS)

The TOPSIS method (Hwang and Yoon, 1987) selects the alternative that has the minimum relative performance distance from an ideal solution. The relative distance ($CL_i^+$) of each alternative to the ideal solution is calculated using Equation 6 as described in Madani et al. (2014).

$$CL_i^+ = \frac{d_i^+}{d_i^+ + d_i^-}$$ Equation 6

where:

$d_i^+ = \left[\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2\right]^{0.5}$

$d_i^- = \left[\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2\right]^{0.5}$

The normalized utility ($N_{ij}$) is used to calculate the weighted normalized performance ($V_{ij}$) of each alternative under each criterion using Equation 7. The best ($V_j^+$) and the worst ($V_j^-$) performance of the alternatives under each criterion are determined, and used to calculate the distance of each alternative from the best and the worst scenario as shown previously in Equation 6.

$$V_{ij} = N_{ij}.W_{ij} \qquad \text{Equation 7}$$

where:

$$N_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}$$

At every level of the decision matrix, SAW and TOPSIS were used to calculate the comparison indices and relative distances of each alternative. The comparison indices (or relative distances) were normalized using Equations 1 and 2, and used as a performance input value for the upper level.

## 3. Results and discussion

TOPSIS and SAW were used to rank fuel alternatives for the waste collection industry with respect to the multi-level environmental and financial decision matrix (Figures 2 and 3). The overall ranking placed conventional diesel-fueled WCVs as the best option under the decision matrix, followed by hydraulic-hybrid, LFG-sourced natural gas, North American and non-North American natural gas, and biodiesel fuels. The results of the two methods were consistent. Environmentally, WCVs fueled with fossil fuels (diesel and natural) were closer to the ideal than biogenic fuels (BD and LFG); the inclusion of the WFP and power density as environmental measures placed biogenic fuels, biodiesel and LFG, far from being the ideal fuel option. Environmentally, CNG and LNG WCVs fueled by American fossil natural gas had slight advantage over WCVs fueled with non-American natural gas or diesel. Hydraulic-hybrid WCVs were the closest to the optimal solution with respect to the environmental criteria, because fuel savings compared to diesel placed it closer to the optimal environmental option ahead of diesel. Financially, diesel and hydraulic-hybrid ranked closest to the ideal solution under the decision matrix. The vehicle cost of hydraulic-hybrid vehicles averaged $100,000 more than conventional diesel-fueled WCVs; however, the fuel savings associated with hydraulic hybrid WCVs placed it at a similar distance from the ideal solution as conventional diesel-fueled WCVs. Natural gas (CNG and LNG) and biodiesel were affected by the current lack of fueling stations. The fuel price of biodiesel placed this option far from the ideal solution as it is currently the most expensive alternative. LFG has the cheapest price,  however the availability of LFG fueling station impacted the financial and overall performance of this alternative.

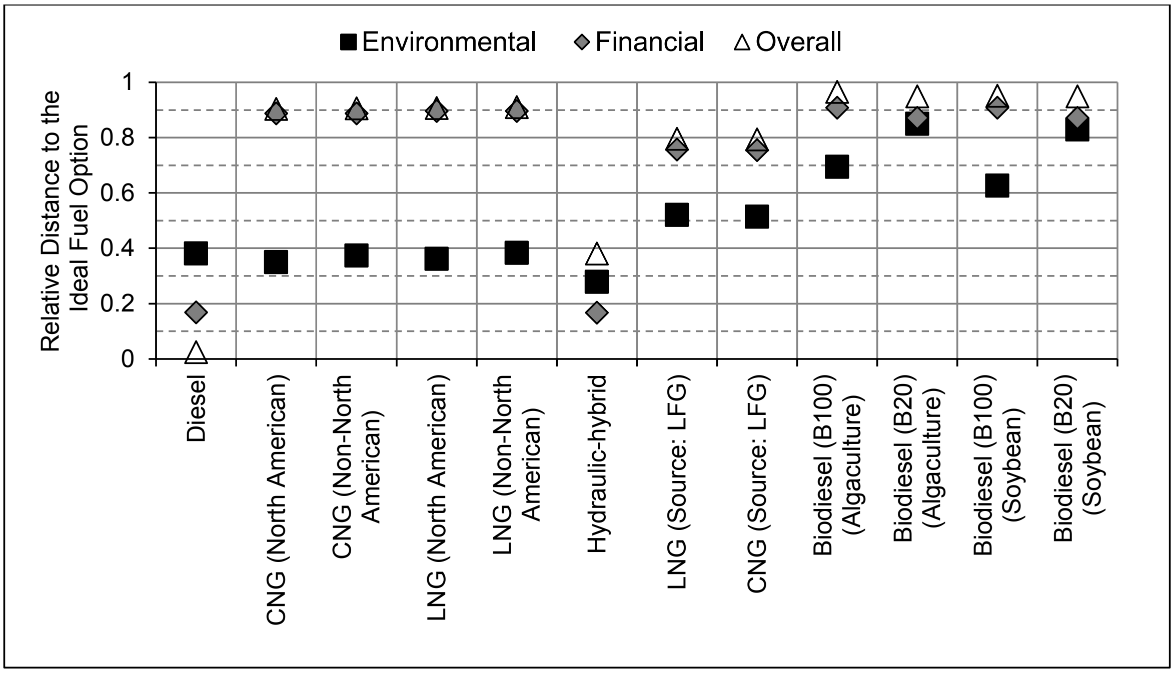

Figure 2: Relative distances (TOPSIS analysis) of fuel options from the ideal option using the selected decision matrix.

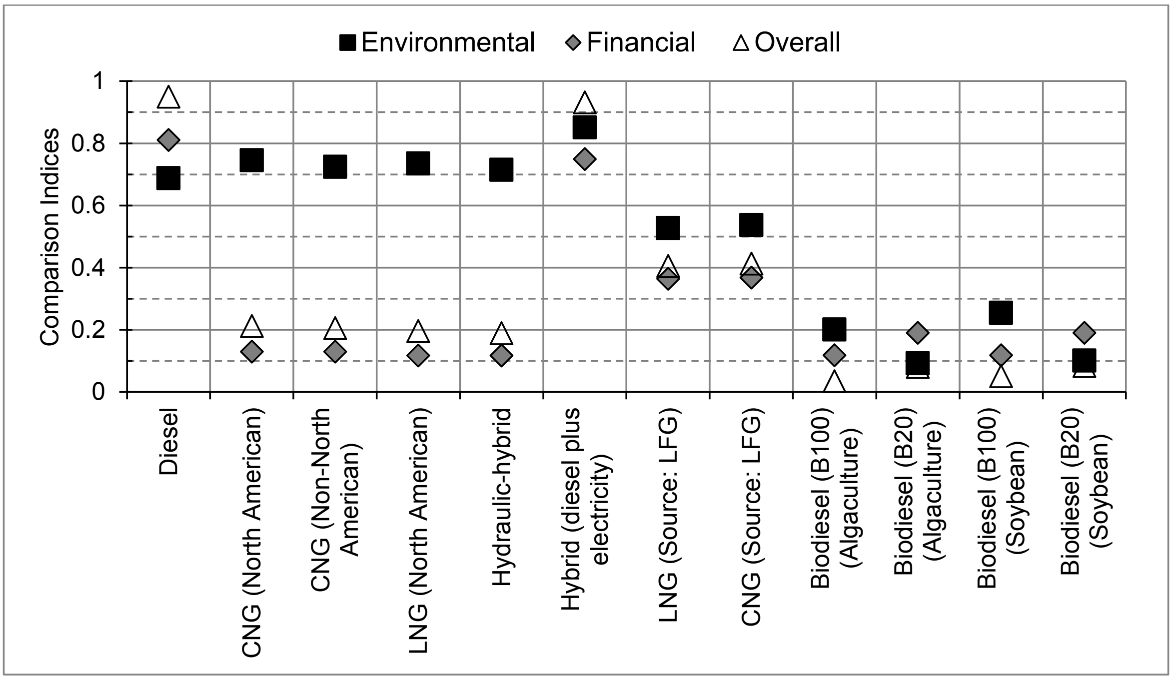

Figure 3: Comparison indices (SAW analysis) of fuel options using the selected decision-matrix.

### 3.1 Significance of the Selection Criteria

In the previous analysis, fuel rankings were based on the selected decision matrix; however it is imperative to assess how sensitive the fuel rankings are to the selection criteria considered by decision makers. Therefore, an analysis was conducted by eliminating one or two criteria from the decision matrix, then determining the relative distance of alternatives to the ideal solution (TOPSIS analysis). The following five sensitivity analysis scenarios were considered:

**Scenario 1:** Eliminate the water footprint criterion,

**Scenario 2:** Eliminate the WFP and the power density criteria,

**Scenario 3:** Eliminate the fueling station criterion,

**Scenario 4:** Eliminate the fuel price stability criterion,

**Scenario 5:** Eliminate the fueling station and fuel price stability criteria.

The five sensitivity analysis scenario results are illustrated in Figure 4. For comparison, the results from the original analysis using the complete decision matrix were labeled **Scenario 0**. In **Scenario 1**, the elimination of the WFP criterion from the decision matrix did not impact the environmental or overall fuel ranking because the ranking of agricultural-based fuel alternatives was also affected by low power density as compared to fossil fuels. Alternative fuels with high WFP are associated with low power density. As a result, the elimination of the WFP alone did not affect the environmental or overall ranking of agriculture-based fuel alternatives. In **Scenario 2**, the elimination of the WFP and the power density from the decision matrix changed the environmental ranking of fuel alternatives so that biofuels (LFG-sourced natural gas and biodiesel) ranked ahead of fossil fuels. Biogenic fuels were considered the best based on life-cycle emissions and some tail-pipe emissions. However, they are associated with high WFP and low power density. LFG-sourced natural gas ranked as the best alternative followed by BD100 (soybean then algaculture). The overall ranking of alternatives was slightly affected by removing the WFP and power density criteria from the decision matrix, as LFG-source natural gas ranked third after conventional diesel and hydraulic-hybrid. Biodiesel has favorable life-cycle emissions; however, its production is associated with high WFP and low power density. These results signify the importance of considering the WFP and power density criteria as environmental measures in addition to traditional life-cycle and tail-pipe emissions. It also suggests that the use of different feedstock (e.g. waste) for the production of biodiesel should be considered, which might reduce the WFP and the power density of biodiesel production, making it more favorable.

In **Scenario 3**, the fueling station criterion was eliminated from the decision matrix and LFG-sourced natural gas ranked as the best alternative from the financial prospective. Diesel and hydraulic-hybrid were ranked next, followed by BD20, North American, non-North American natural gas, BD100. Therefore, LFG-sourced natural gas is considered as the best option for WCVs when available. In **Scenario 4**, the fuel price stability was eliminated from the decision matrix moving diesel and hydraulic-hybrid to be the optimal financial solution followed by LFG-sourced natural gas, however the overall ranking did not change significantly from Scenario 0. In **Scenario 5**, the elimination of fueling station and fuel price stability criteria ranked LFG-sourced natural gas as the best financial alternative followed by North American fossil natural gas. This scenario was found to represent the status quo of the waste collection industry as the industry is leaning toward fossil natural gas, driven by low natural gas prices. A sensitivity of the fuel ranking to instability of fuel prices was evaluated for the status quo scenario. In the next section, the results of dynamic sensitivity analysis to determine the impact of changing the actual fuel price on the fuel ranking are reported.

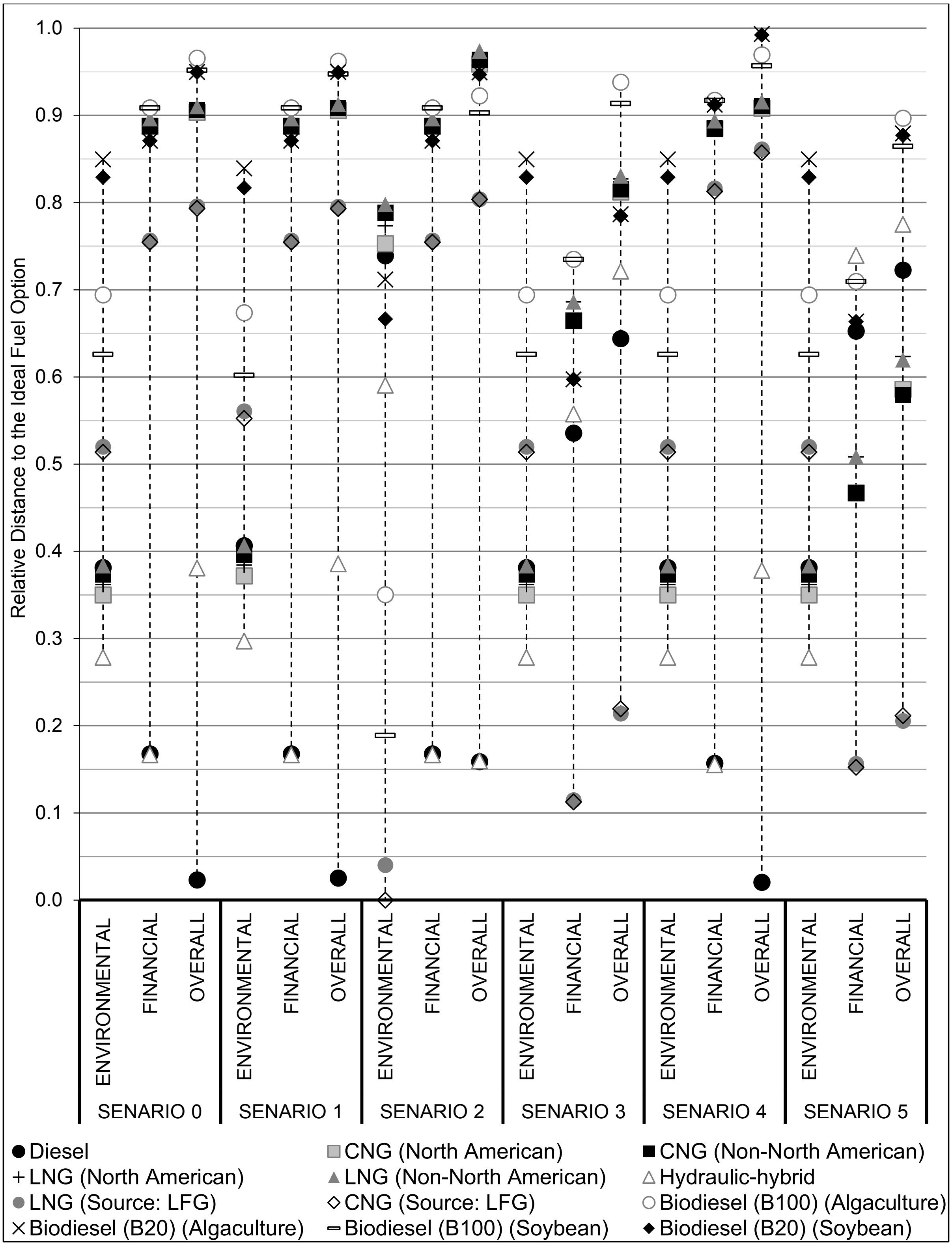

Figure 4: Significance of the selection criteria.

### 3.2 Systematic Sensitivity Analysis of Alternative Fuel Price

A systematic sensitivity analysis of alternative fuel price was conducted by evaluating the relative distances (TOPSIS) of each alternative from the ideal financial fuel option (Figure 5) and ideal overall fuel option (Figure 6), using five different price scenarios for diesel, natural gas, LFG, and biodiesel. In the analysis, the relative distances were calculated for each alternative while varying the fuel price of each alternative by -50%, -25%, +25%, and +50% of the current fuel price. The fueling station and fuel price stability criteria were eliminated from the decision matrix during the analysis to illustrate the status quo scenario determined by the sensitivity analysis. The financial criteria consisted of the vehicle cost and fuel price, while environmental criteria included life-cycle emissions, tail-pipe emissions, WFP, and power density. The number of fueling stations gave advantage to some alternatives over the others, while the fuel price stability criterion was excluded as the analysis gauges the sensitivity of ranking to changing fuel prices. The purpose of this analysis was to determine how sensitive the fuel ranking is to changing fuel price, as the industry builds more natural gas fueling stations based on the current natural gas prices.

Financially, CNG and LNG collection vehicles fueled with LFG-sourced natural gas ranked as the best alternatives. However, it was noticed that 50% decrease in diesel fuel price placed diesel in the same rank as LFG-sourced natural gas. Also, a 50% decrease in fossil natural gas prices moved fossil CNG and LNG closer to LFG-sourced natural gas; however, the LFG-sourced natural gas continued to rank as the best alternative. The ranking of diesel and hydraulic-hybrid was found to be more sensitive to fuel price. A drop of diesel price by 25% ranked diesel better than natural gas, while a 50% drop ranked hydraulic-hybrid as favorable as fossil natural gas. On the other hand, a 25% increase in diesel price ranked diesel and hydraulic-hybrid behind all other alternatives. Fossil CNG and LNG ranked behind LFG-sourced natural gas. However, any increase in natural gas prices moved the alternative away from the ideal solution and in the case of a 50% increase, fossil natural gas ranked behind diesel and hydraulic-hybrid. LFG-sourced natural gas continued to rank as the best alternative even at a 50% increase in fuel price. Finally, BD20 and BD100 rankings are sensitive to changing fuel price. A 50% decrease in biodiesel price ranked BD20 and BD100 second after LFG-sourced natural gas, while a 25% ranked BD20 in between fossil CNG and LNG. An increase in biodiesel prices moved diesel toward fossil natural gas, a result of dispersion of fuel prices as biodiesel prices currently are highest.

Overall, LFG-sourced natural gas continued to rank as the best alternative with respect to the overall environmental and financial criteria, except at a 50% decrease in diesel prices (Figure 6). CNG and LNG collection vehicles fueled with North-American natural gas ranked second after LFG-sourced natural gas. But, any increase in prices could move diesel and hydraulic-hybrid ahead of fossil natural gas (North American or non-North American). Fossil natural gas continued to rank as the second alternative after LFG-sourced natural gas except when natural gas prices increased by 50% or diesel prices dropped by 25 to 50%. The overall ranking of LFG-sourced natural gas, BD 20, or BD100 was not as significantly affected by changing fuel prices.

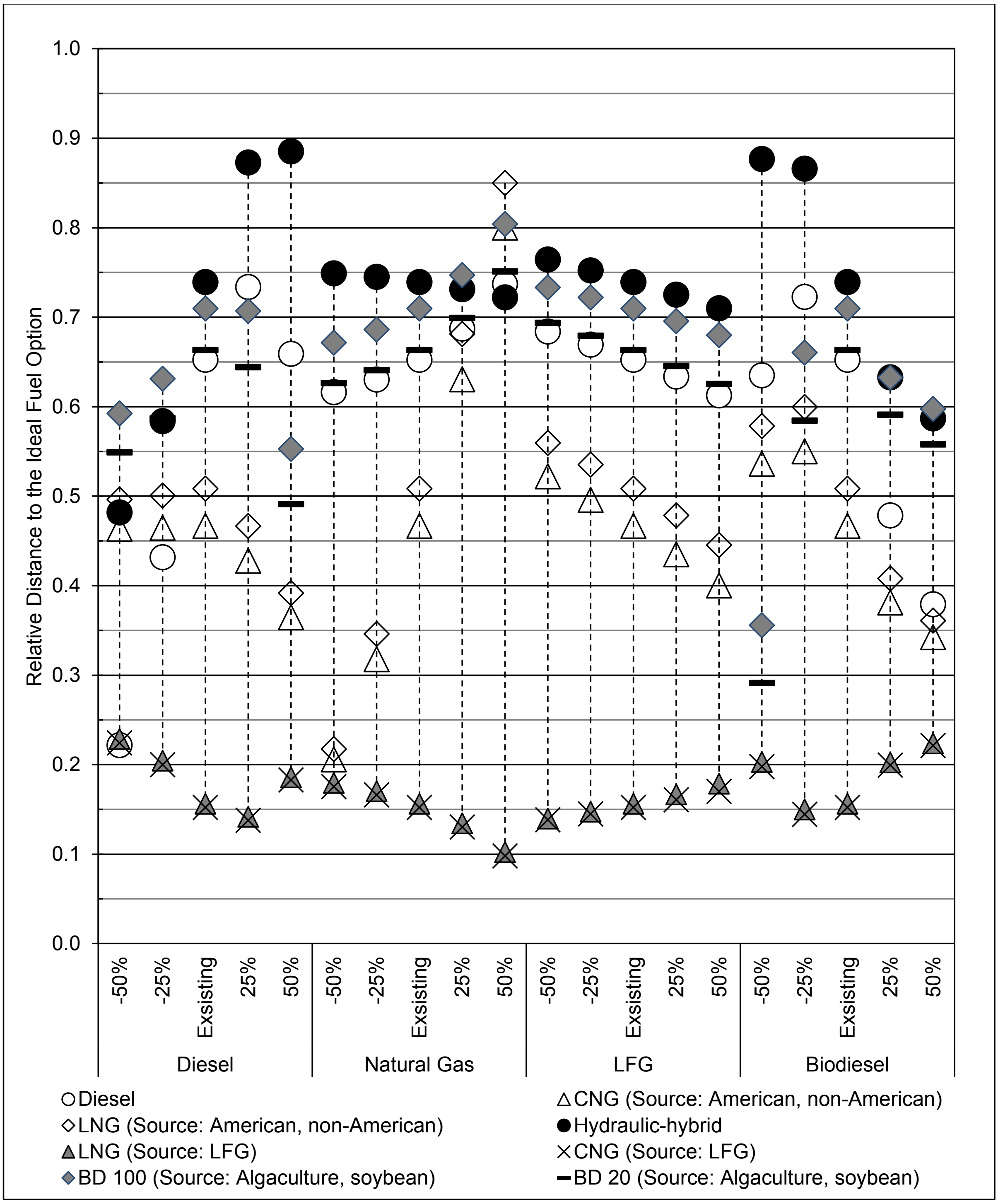

Figure 5: Systematic sensitivity analysis of the financial performance. (Relative distances (TOPSIS analysis) were calculated for each fuel using five different fuel pricing for each alternative; -50% of the current fuel price, -25% of the current fuel price, existing, +25% of the current fuel price, and +50% of the current fuel price).

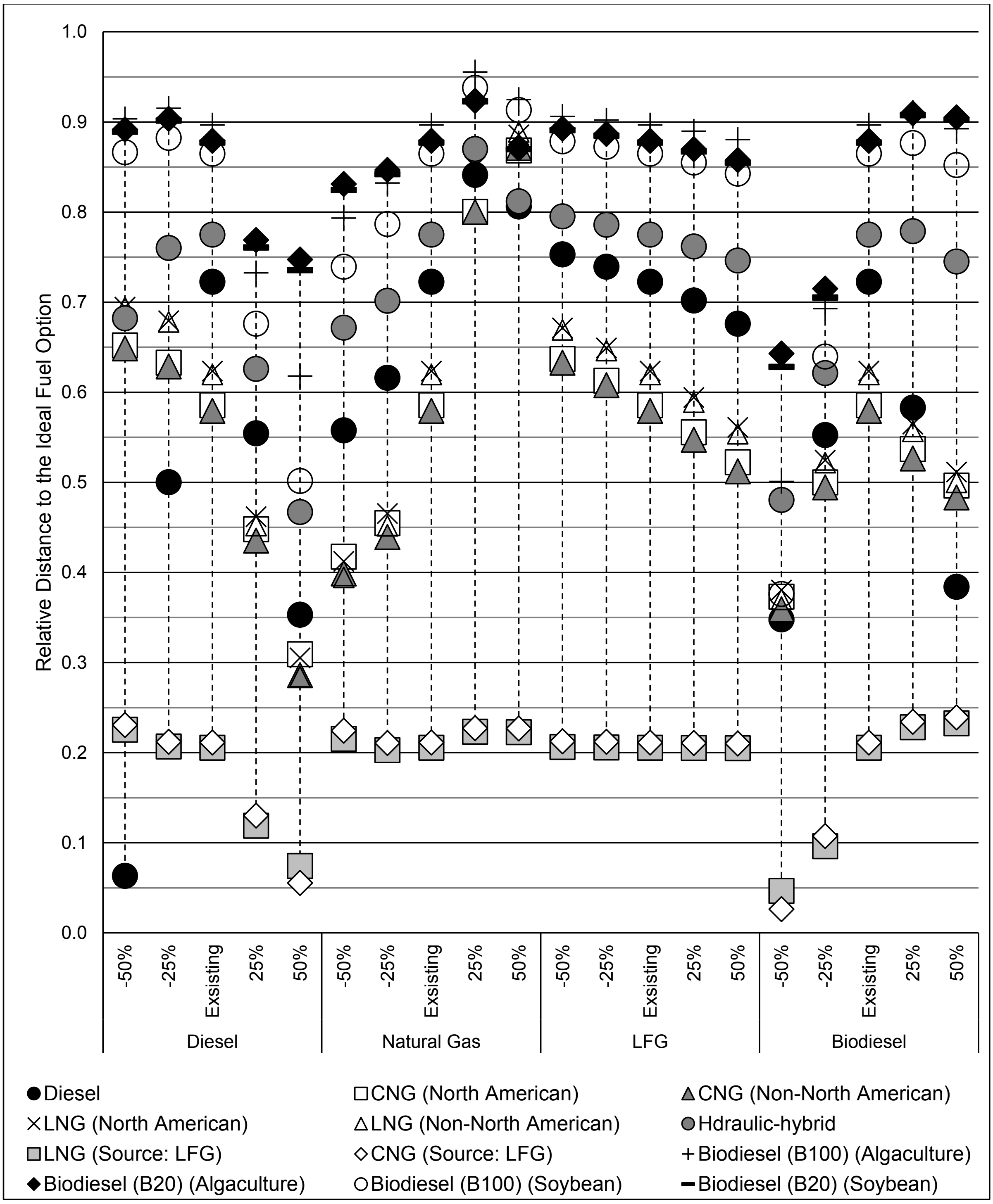

Figure 6: Systematic sensitivity analysis of the overall performance. (Relative distances (TOPSIS analysis) were calculated for each fuel using five different fuel pricing for each alternative; -50% of the current fuel price, -25% of the current fuel price, existing, +25% of the current fuel price, and +50% of the current fuel price).

### 3.3 Additional Financial Criteria

There are other financial criteria that can influence the selection process; however they were excluded from the initial analysis due to data availability concerns. The maintenance cost of alternative fueled WCVs is a vital component of the running cost and is often considered by decision makers. According to U.S. waste haulers, the cost of maintaining a diesel-fueled WCV average $8.5 per hour of operation (personal communication with Major Hauler Manager, 2012). The maintenance cost of alternative fueled WCVs is not available for newly acquired fuel technologies, therefore it is not as easily accounted for as conventional diesel-fueled WCVs. Secondly, municipalities and private waste haulers are often interested in retrofitting existing diesel-fueled WCVs to support alternative fuel technologies. In the previous analysis, fuel rankings were based on the assumption that WCVs will be purchased new.

Accordingly, this analysis was conducted to determine the impact of maintenance cost and the possibility of vehicle retrofitting to operate an alternative fuel. The status quo scenario "Scenario 5" determined in Section 3.1 was compared to the result drawn from this analysis. In this analysis, the vehicle cost criterion was replaced by the cost of retrofitting an existing diesel-fueled WCV to run on natural gas or hydraulic hybrid. Gordon et al. (2003) reported that the cost of switching an existing WCV to natural gas ranges from $30,000 to $100,000. Moreover, Baseley et al. (2007) stated that existing WCVs can be retrofitted with a second hydraulic system easily. The cost of adding a hydraulic system to an existing diesel-fueled WCV was reported to be less than 50,000 (Drozdz, 2005; Baseley et al., 2007). For the purpose of this analysis, it was assumed that additional vehicle costs for a municipality or the private hauler to run diesel-fueled WCVs using biodiesel (BD-20 and 100), natural gas (CNG and LNG), and hydraulic hybrid vehicles were $0, $65,000, and $25,000 per vehicle. Moreover, the analysis assumed that the waste haulers can continue to operate their diesel-fueled vehicle at no additional cost (vehicle cost $0).

The results of this analysis (Scenario 5 retrofitted) are shown in Figure 7. The analysis indicated that diesel-fueled WCVs are still the best alternative financially; however if decision makers are interested in switching to an alternative fuel, biodiesel blends can be considered as the second best alternative, followed by hydraulic-hybrid. This is mainly due to the fact that no vehicle cost is associated with switching to diesel or biodiesel blends. The possibility of retrofitting existing diesel-fueled WCVs to support hydraulic hybrid technology ranked hydraulic hybrid as a better financial alternative.

For the purpose of recognizing the impact of maintenance cost on the financial ranking of alternative-fueled WCVs, three different hypothetical scenarios were evaluated. The financial analysis of alternative-fueled WCVs was conducted using the financial criteria of the status quo scenario (Scenario no. 5 - vehicle cost and fuel cost) and by adding maintenance cost as a criterion. The assumption made in estimating the maintenance cost of alternative-fueled WCVs are as follows:

**Scenario X:** The maintenance cost of running natural gas WCVs is the same as diesel ($8.5 per hour), while hydraulic hybrid WCVs' maintenance cost is 50% more than diesel;

**Scenario Y:** The maintenance cost of hydraulic hybrid WCVs is the same as diesel ($8.5 per hour), while natural gas WCV's maintenance cost is 50% more than diesel; and

**Scenario Z:** The maintenance cost of hydraulic hybrid and natural gas WCV's maintenance cost is 50% more than diesel.

It was assumed that the cost of maintaining diesel-fueled WCVs running on biodiesel fuel blends to be the same as vehicles running using fossil diesel. However, it should be noted that waste haulers complain about the use of biodiesel blends especially during cold weather (personal communication with Joseph Grusauskas, 2012). The results of the three scenarios are illustrated in Figure 7. For each scenario, two analyses were performed; one assuming that WCVs will be purchased new, and the second assuming the possibility of retrofitting existing diesel-fueled WCVs to support alternative fuels. It is very clear that adding an additional financial criteria changed the financial ranking of fuel alternatives.

In Scenario X, the financial fuel rankings were similar to Scenario 5. However, the hypothetical increased maintenance cost of hydraulic hybrid WCVs pushed the alternative away from the optimal financial solution. In Scenario Y, the hypothetical maintenance cost of natural gas WCVs being 50% more than diesel-fueled WCVs pushed natural gas WCVs, using either fossil natural gas or LFG-sourced natural gas, behind diesel, hydraulic hybrid and biodiesel. This shows that hydraulic hybrid WCVs would be considered better than natural gas WCVs if their maintenance cost were lower than natural gas and closer to conventional diesel WCVs. This also shows the sensitivity of natural gas fueled WCVs financial ranking. Also, biodiesel WCVs ranking moved closer to the optimal solution. This is assuming that the cost of maintaining biodiesel WCVs to be the same as diesel.

Scenario Z ranked diesel and biodiesel as the best alternatives when other alternative fuels, e.g. natural gas and hydraulic hybrid, cost 50% more than diesel and biodiesel to maintain. Finally, in almost all cases that involve retrofitting existing WCVs, biodiesel blends are the best alternative to diesel if decision makers are interested in switching away from diesel.

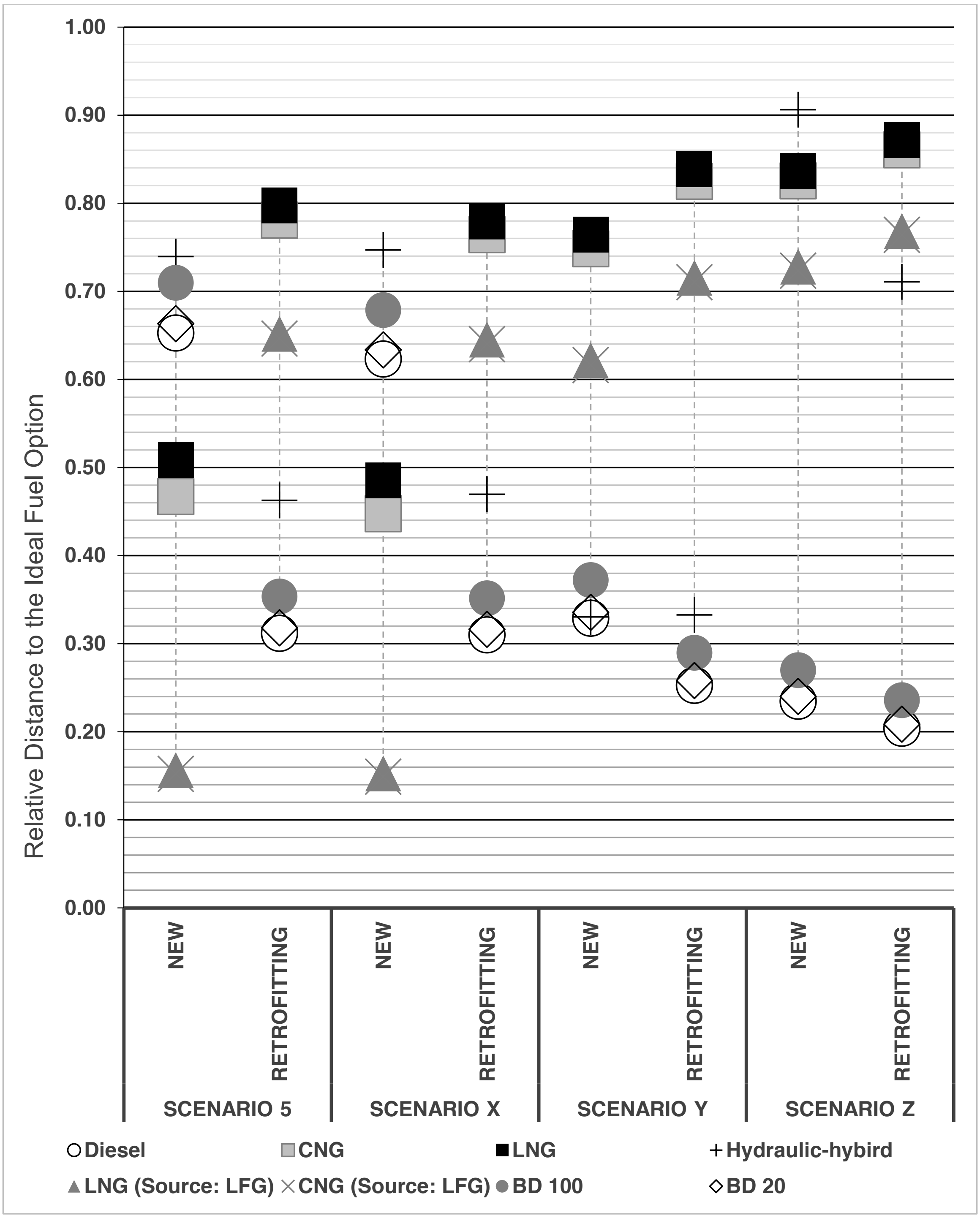

Figure 7: Sensitivity analysis of the financial performance of alternative fuel technologies, using additional financial criteria. (Relative distances (TOPSIS analysis) were calculated for different Scenarios).

### 3.4 Operational Issues and Community Acceptance

Decision makers often have to consider other social and operational criteria that may not necessary fit into the economic or environmental criteria described in this study. It is often difficult to quantity the impact of such criteria due to data availability or variability (e.g. changes in social aspects across communities). Operational criteria such as refueling time, vehicle noise level, maintenance complexity, and reliability might be considered. The aforementioned criteria are crucial for waste haulers due to the limited number of replacement vehicles available, long driving distances, and customer service concerns over delayed or missed waste pickups. Public acceptance of an alternative fuel is also vital for waste haulers. In recent years, waste haulers utilized switching to alternative fuels as an advertisement tool to gain public acceptance over environmental friendly "green" infrastructure. This study did not address social aspects of the selection process, however it is recommended that future studies evaluate the influence of public acceptance and other operational criteria on the decision making process.

### 3.5 Conclusions

MCDA tools were used to rank fuel alternatives for the waste collection industry with respect to a multi-level environmental and financial decision matrix. The environmental criteria consisted of life-cycle emissions, tail-pipe emissions, water footprint, and power density, while the financial criteria included vehicle cost, fuel price, fuel price stability, and fueling station availability. Environmentally, hydraulic-hybrid and fossil natural gas, performed better than conventional-diesel. The vehicle cost of hydraulic-hybrid and lack of fueling stations for natural gas affected the financial ranking, although fuel price savings were observed for both options. The overall analysis using the environmental and financial criteria showed that conventional-diesel and hydraulic-hybrid WCVs are the best alternatives, followed by LFG-sourced natural gas, fossil natural gas, and biodiesel. This fuel ranking changed as different decision matrices were used, signifying the importance of the selection criterion considered by decision makers. The elimination of the WFP and power density criteria from the environmental criteria ranked biodiesel 100 (BD100) as an environmental-friendly alternative compared to other fossil fuels (diesel and natural gas). This result signifies the importance of considering WFP and power density criteria as environmental measures in addition to traditional life-cycle analysis and tail-pipe emissions. The elimination of the fueling station criterion from the financial decision level ranked landfill gas (LFG) sourced natural gas as the best option; suggesting that LFG-sourced natural gas is the best alternative to fuel WCV when accessible. The elimination of the fueling station criterion and fuel price stability criterion from the decision matrix ranked fossil natural gas second after LFG-sourced natural gas. This scenario characterizes the status quo of the industry. The waste collection industry is driven by low natural gas prices compared to other alternatives, and has set investment plans to build natural gas fueling stations. A systematic sensitivity analysis was used to determine the impact of changing fuel prices on decisions. The financial ranking of all alternatives, except LFG-sourced natural gas, was found to be sensitive to changing fuel prices. The overall ranking of diesel and natural gas was found to be more sensitive to changing fuel price as compared to LFG-sourced natural gas, BD20 or BD100.

## Conflict of Interest

The authors declare that there are no conflicts of interest.

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