Science of the Total Environment 550 (2016) 349–361

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Multi-level multi-criteria analysis of alternative fuels for waste collection vehicles in the United States

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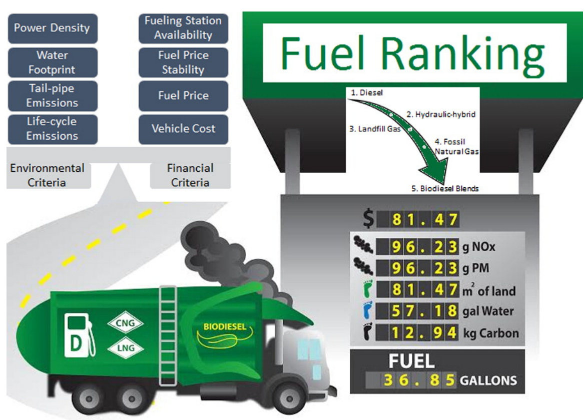
HIGHLIGHTS

- Hydraulic-hybrid vehicles provided environmental benefits over other alternatives.
- Diesel is the best environ-economical option while hybrid is better environmentally.
- Landfill gas sourced natural gas is the best alternative when accessible.
- Considering water footprint and power density as environmental criteria can make a difference.
- Natural gas ranking compared to diesel is very sensitive to fuel prices.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 September 2015
Received in revised form 29 December 2015
Accepted 30 December 2015
Available online xxxx

Editor: Simon Pollard

Keywords:
Alternative fuels
Waste collection
Decisions making
Multi-criteria analysis

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

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http://dx.doi.org/10.1016/j.scitotenv.2015.12.154

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.

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., 2009). 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 1700 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 1000 vehicles running on alternative fuels, plans to add 3100 natural gas and other alternative-fueled WCVs by the end of 2015 (Republic Services, 2012). In 2012, WCV and transfer vehicles accounted for 11% 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 (Josimović 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 alternative 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 position 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 makes recommendations to 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 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, 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, 2015a). BD100 is made of 100% biodiesel, while BD20 is a blend of 20% biodiesel and