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Comparisons of automotive, locomotive, aircraft and marine conversion to hydrogen propulsion using six-sigma methodologies

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ABSTRACT

This paper examines the options and benefits of hydrogen utilization in various segments of the transportation sector through a Six Sigma method. It presents a comparison of four modes of transportation – locomotive, marine, plane, and car – specifically for a case study in Ontario, Canada. Infrastructure requirements, public anxiety, public perception, cost and environmental impacts are used as performance measures through Six Sigma, rigidity index and regression analyses. The results from these analytical methods indicate how each transportation sector benefits in using hydrogen as its main source of fuel. The results show that locomotive transportation has the best advantage of using hydrogen in Ontario, Canada, as it can store more fuel on-board and the methods of refueling hydrogen can be made simpler and handled safely by locomotive operators. By converting the locomotives to operate on hydrogen fuel, this would reduce the pollution generated by diesel fuels significantly, which would assist in Ontario's goal of the Kyoto protocol in an attempt to reduce emissions.

1. Introduction

With today's high energy costs, there exists a challenge to reduce our energy consumption while keeping up with growing energy demands. In June 2007, the Department of Toronto Atmospheric Fund and Toronto Environment Office stated that 35% of greenhouse gases (GHG) annually comes from the transportation sector, while 27% have been generated from cars and light trucks [1]. With about 65% of the oil use by the transportation sector and the growing gap between oil supply and demand, there is an urgent need to reduce GHG emissions, alternative fuels and energy efficiency gains [2].

Thus, researchers have been developing alternative "greener" methods of supplying this growing energy demand while reducing the environmental impact. Though hydrogen energy has received much attention in the last decade with significant progress in performance, reliability and costs, producing hydrogen from fossil fuels is not a clean sustainable approach. However, solar, wind and nuclear energy are some examples of cleaner sustainable sources of electricity production to produce hydrogen. Hydrogen can be used as a source of stored energy to mitigate the intermittency of renewable energy. Then it can be reused at a subsequent time through fuel cells (FC) and internal combustion engine (ICE) applications.

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The use of hydrogen can significantly reduce CO_2 emissions, which are currently about 18.5 tons per capita in the United States, based on a 2009survey [3]. It is important to develop renewable and greener sources of energy in responding to these issues. In the long term of reducing CO_2 emissions, the use of hydrogen produced from CO_2 free or neutral technologies will be advantageous in various transportation sectors. However, a debate exists on which transportation sector would benefit most from the use of hydrogen fuel. Current setbacks with hydrogen include the costs associated with building a hydrogen infrastructure and the cost and volume requirements of hydrogen storage for the transportation sector.

Air Products has announced a 180 mile H_2 pipeline between Louisiana and Texas. The principal reason for this pipeline is to ensure security of hydrogen supply [4]. In Ontario, Canada, such a pipeline could be placed to allow a supply of hydrogen to major city transportation routes, which would be ideal for a hydrogen fueling infrastructure for a majority of modes of transportation. There have been several studies that investigated the energy use emissions and costs associated with hydrogen vehicles [5]. Vehicle hydrogen studies have been performed for various geographical locations such as South Korea [6]. A model was developed to compare emissions and energy demand for different government policy and fuel price scenarios. Other transportation modes such as aircraft have also been considered for hydrogen conversion. In a report by the Swiss Federal Institute of Reactor Research, a pilot project was analyzed for the Zurich Airport [7].

A study of the economics of hydrogen production, storage and delivery was conducted by Balat [8] for transportation use. A summary of environmental benefits were outlined, with key points to show the potential benefits of renewable hydrogen production, and usage for various modes of transportation. Other studies have also considered the various ways of combining fuel cell operations, to create a hybrid system and utilize the onboard air conditioning systems for operations while stationed in the harbor [9]. However, these studies have not compared the CO_2 reductions, demands for energy from other sectors such as electricity and process heat, public anxiety, technology acceptance, and infrastructure for each of the four modes of transportation. This paper examines these additional factors for each transportation sector in a case study for Ontario, Canada. Analytical parameters using Six Sigma methodologies are used to identify the potential drawbacks of using hydrogen in the four modes of the transportation sector [10]. A regression analysis will be used for these comparisons.

2. Hydrogen use in the transportation sector

In this section, four types of transportation modes are examined and the advantages of using and storing hydrogen in each sector are described. In an effort to lower GHG emissions, the four modes of transportation are defined and existing technologies that can be utilized to use hydrogen such as FC (fuel cells) and ICE (internal combustion engines) are discussed.

2.1. *Hydrogen use in marines*

The first marine vessel that utilized hydrogen was demonstrated in Iceland. It was converted to use hydrogen in a commercial whale watching vessel. This marine vessel is based in Reykjavik. The marine Elding is a 125 ton cruiser with a capacity of 150 passengers with two 50 kW generators [11].

In the year 2000, a 22-passenger Hydra, powered by an electric motor using a hydrogen fuel cell was demonstrated to the public on the Rhine River near Bonn, Germany. It is fully certified by the Germanischer Lloyd for passenger transport and the fuel cell system had the ability to start even at temperatures below the freezing point. The boat was withdrawn from service in 2001 [12]. Afterward, a Duffy-Herreshoff water taxi debuted in 2003 in San Francisco's Newport Beach. This 18-passenger hydrogen fueled boat was power-assisted by an electric motor that utilized a hydrogen fuel cell [13].

The Deep Can autonomous underwater vehicle (AUV) was debuted on 2004 and was funded by the German Federal Ministry for Education and Research [14]. In 2004, Yacht XV 1,a 42′ hydrogen fuel cell powered sailboat, was intended to demonstrate Haveblue LLC's patented technology for the production, storage and use of hydrogen onboard a marine vessel. The range was a radius of ~300 nautical miles at 8 knots on a full tank. Unfortunately, management issues at Haveblue LLC prevented the completion of the yacht [15]. In 2006, a 12-person Xperiance hydrogen fuel cell boat was demonstrated in Leeuwarden, Netherlands. An 8-passenger Tuckerboot boat is still in operation in Hamburg, Germany, and refueled with exchangeable hydrogen tanks [16]. In 2008, a 100-passenger hydrogen fuel cell, Zemships (Zero Emission ships) project Alsterwasser went into service in Hamburg, Germany, and ended in April, 2010 [17]. Also, in 2009,in Amsterdam, Netherlands, the Nemo H_2, an 88-passenger fuel cell canal boat, went into service, which utilizes 6 hydrogen tanks with a pressure of 35 MPa for 24 kg of hydrogen fuel [18].

Hjalti Pall Ingolfsson from Icelandic New Energy has commented that ships are rapidly becoming a major source of air pollution in the European Union. It is estimated that by 2020, emissions of sulfur dioxide and nitrogen oxides from ships will exceed land-based emissions in Europe. A key issue to be addressed is the storage of hydrogen on ships, given there is no opportunity to refill them when at sea [19], although one can use wind power and solar PV panels to generate electricity while at sea, then onboard hydrogen [20].

2.2. *Hydrogen use in aircraft*

There have been several investigations and prototypes to demonstrate the use of hydrogen in airplanes. These studies have shown that hydrogen can best be utilized in airplanes for short distances, such as 500 km distances, at lower than normal flight altitudes [21]. This short distance travel is ideal for trips between major cities, such as Toronto and Montreal. This would be a promising candidate for domestic flights for major airlines operating in Ontario, Canada, for example, which desire to reduce their CO_2 emissions, such as the "Green Energy Act" at the Pearson Airport in Toronto [22]. Past research has been conducted on using fuel cells in an airplane to utilize hydrogen that is stored on board [23]. There were