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ORIGINAL ARTICLE

Integrated modeling for optimized regional transportation with compressed natural gas fuel

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Abstract Transportation represents major energy consumption where fuel is considered as a primary energy source. Recent development in the vehicle technology revealed possible economical improvements when using natural gas as a fuel source instead of traditional gasoline. There are several fuel alternatives such as electricity, which showed potential for future long-term transportation. However, the move from current situation where gasoline vehicle is dominating shows high cost compared to compressed natural gas vehicle. This paper presents modeling and simulation methodology to optimize performance of transportation based on quantitative study of the risk-based performance of regional transportation. Emission estimation method is demonstrated and used to optimize transportation strategies based on life cycle costing. Different fuel supply scenarios are synthesized and evaluated, which showed strategic use of natural gas as a fuel supply.
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1. Introduction

Although electric vehicles and plug-in hybrid electric vehicles (EVs & PHEV) are expected to be a practical long-term transportation solution, moving from current situation of gasoline-based vehicles might not be the optimum solution. International communities are seeking reliable and alternative fuel sources and technologies to reduce environmental stresses, air pollution, increase fuel availability, decrease the use of and dependence on foreign oil, and optimize the performance of existing fuel supply infrastructures. Compressed Natural Gas vehicles (CNGVs) are argued to be a practical solution for hybrid transportation systems to complement the limitations of EVs & PHEV [1,2]. In order to ensure smooth transportation life cycle and sustainability, it is important to synchronize fuel supply, refueling stations and alternative fuel vehicles. To support the utilization and implementation of alternative fuel vehicles, an efficient fueling infrastructure is essential. However, in order to sustain the fuel supply chain with robust infrastructure it is important to ensure profitability of the proposed alternative fuel. This is only possible if large number of consumers is confirmed to utilize the target alternative fuel, which will balance the overall cost of fueling stations over CNGVs. Recent studies show that the proper implementation with reasonable ratio of refueling stations to alternative fuel vehicle is of great importance [1,3].

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In case of natural gas, the optimum ratio of refueling stations to NGVs is identified using an index of NG vehicle-to-refueling-station, or Vehicle Refueling-station Index, VRI, which was defined as #NG vehicles (in thousands)/#NG refueling stations. This requires proper analysis of vehicle, refueling stations, and utilization modeling with appropriate optimization function to balance the availability of CNG refueling stations while ensuring the profitability of those stations. Measuring the VRI aggregated to the national level suffers from variations within and across countries and adds additional unevenness and uncertainties due to several factors, for example [3]:

- Spatial characteristics and socioeconomic differences.
- Consumer sensitivities to incremental increases in driving distance or waiting time for refueling.
- Capacities of fueling stations.
- The number of public versus private refueling stations.

The optimal VRI was extensively studied by Sonia Yeh and was described as “chicken and egg” dilemma that mainly depends on infrastructure availability. Natural Gas infrastructure exists in most developed countries, except for a few local regions. On the other hand, the case is completely different in less developed countries [3]. Surveys of existing CNGV markets showed an optimal VRI of 1, that is, 1000 NGVs for every one CNG refueling station [4]. In order to be able to compare CNGV to other fuel technologies, it is important to compare both scenarios using a unified index. This requires the study and analysis of infrastructure extension for alternative fuel as integrated with existing gasoline infrastructures, which is essential to minimize implementation costs. This could be implemented as a secondary indicator of the ratio of alternative fuel refueling stations to the existing gasoline refueling stations, which was estimated around 10–20% in [3]. In addition to the fueling stations, the price of NG compared to gasoline should be attractive to consumers, in particular with respect to fueling technologies and pump prices. In order to ensure successful NG implementations, it is imperative to ensure that NG pump prices should be lower than that of gasoline, which will support the Return Of Investment (ROI) of CNGVs [5].

The refueling station distribution and design are another important factor for optimized transportation performance. It is possible to have CNG fueling stations as integrated with gasoline stations or installed separately. This has been studied in different countries in Europe, Americas, Asia, etc. Factors that affect the optimization of CNG fueling stations include the following: accessibility, investment, environmental, and user preferences [1]. The selection of the locations of fueling stations is investigated where there is preference to establish fueling stations close to municipal and major population centers while maintaining adequate distances among stations. This will ensure balanced distribution in both small and large urban areas.

In order to optimize the performance of CNGV, it is important to analyze all operational parameters involved, which include the following: fueling station facility parameters, operation hours, accumulative total trip distance for vehicles, piping expansion costs, environmental impact costs e.g. social cost of CO_2 emissions. In order to establish common basis for comparison, it is important to conduct life cycle analysis of alternative fuel vehicle technologies. Previous studies have commonly assumed a 10–12 year vehicle life cycle or 200,000 km during the lifetime, with linear life cycle fuel cost increase [6,7]. Using quantitative cost analysis, it is possible to synthesize viable scenarios along with the associated conditions to improve cost-benefits to consumers to favor CNGV over other vehicle technologies.

One key factor is the ability to implement practical and promising incentive schemes to motivate suppliers and consumers with balanced benefits based on environmental risks and emission reductions for the use of CNGVs [8]. This should be linked with the cost impacts of health and environmental stresses versus consumer utilization losses, due to decrease in vehicular range, cargo space, and acceleration times with respect to size and weight of CNG tanks [8,9]. This can be achieved via price reduction as prorated based on different types of pollutants such as non-methane organic compounds (NMOG), Carbon Monoxide (CO), nitrogen oxides (NO_x), and sulfur oxides (SO_x). A recent study in Ireland showed possible scenarios for cost reduction of CNGV that reached 22% [10], with general acceptance of CNG and Methanol vehicles as promising green transportation fuel technologies [11,12].

The infrastructure development is another key success factor. Infrastructure expansion should be developed gradually in alignment with the CNG vehicle adoption, which will prevent the loss of solvency [13]. The ratio of CNGVs to fueling stations in Canada should optimally approach 1000:1 with 400:1 being the minimum ratio for profitability as suggested by Gabbar and Bedard [13]. CNG station infrastructure should be built with reference to the existing gasoline infrastructure. This is logically acceptable for developing infrastructures for other alternative fuels as well.

In order to address the transportation process optimization appropriately and completely, this paper proposes a systematic modeling methodology that allows linkage of all life cycle activities with physical systems. Detailed explanations about the proposed modeling methodology are illustrated in the following section where requirement analysis is conducted based on the proposed modeling methodology.

The reviewed life cycle cost and environmental analyses suggest that CNG and EVs & PHEV offer the most attractive alternative fuels currently available [1,3,13–19]. Each article stressed the importance of evaluating environmental and health benefits against financial and utility sacrifices by the consumer. The consensus suggests a vehicle life cycle of 10–12 years over which costs and emissions should be considered [3]. Each analysis to date has failed to consider the variation of fuel costs over the duration of the vehicle life cycle with the corresponding impact on life cycle costs. This paper aims at improving this by assuming non-steady future energy prices in accordance with the trends set forth by the Energy Information Agency’s AEO 2013. Although projected prices are subject to inaccuracies, they offer an improved approximation over the steady state assumptions applied in the literature.

With this introduction, the main objective of this paper is to demonstrate the use of compressed natural gas-based fuel with performance optimization, toward regional implementation of green transportation systems. The following section will explain the NG-based transportation issues, proposed fuel supply chain model, which is followed by life cycle cost modeling, practical transportation process scenario synthesis with evaluation technique in section three, which is applied in case studies on Ontario hybrid transportation. Section four

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