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Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling

Krishna Reddi [a,*], *Amgad Elgowainy* [a], *Neha Rustagi* [b], *Erika Gupta* [b]

[a] *Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA*
[b] *Fuel Cell Technologies Office, U.S. Department of Energy, 1000 Independence Avenue SW, Washington, DC 20585, USA*

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ABSTRACT

Transporting compressed gaseous hydrogen in tube trailers to hydrogen refueling stations (HRSs) is an attractive economic option in early fuel cell electric vehicle (FCEV) markets. This study examines conventional (Type I, steel) and advanced (Type IV, composite) high-pressure tube trailer configurations to identify those that offer maximum payload and lowest cost per unit of deliverable payload under United States Department of Transportation (DOT) size and weight constraints. The study also evaluates the impacts of various tube trailer configurations and payloads on the transportation and refueling cost of hydrogen under various transportation distance and HRS capacity scenarios. Composite tube trailers can transport large hydrogen payloads, up to 1100 kg at 7300 psi (500 bar) working pressure, while steel tube trailer configurations are limited by DOT weight regulations and may transport a maximum hydrogen payload of approximately 270 kg. Using steel pressure vessels to transport hydrogen at high pressure is counterproductive because of the rapid increase in vessel weight with wall thickness. The most economic composite tube trailer configuration includes 30-inch-diameter vessels packed in a 3 × 3 array. A linear relationship between the deliverable payload and the capital cost of a composite tube trailer has been developed for configurations with the lowest cost-per-unit payload. The capital cost is approximately $1100 per kg of deliverable hydrogen payload. Considering the entire delivery pathway (including refueling), tube trailer configurations with smaller vessels packed in greater numbers enable higher payload delivery and lower delivery cost in terms of $/kg H_2, when delivering hydrogen over longer distances to large stations. Selection of the appropriate tube trailer configuration and corresponding hydrogen payload can reduce hydrogen delivery cost by up to 16%.

* Corresponding author.
E-mail address: kreddi@anl.gov (K. Reddi).

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Introduction

Hydrogen use in fuel cell electric vehicles (FCEVs) produces zero pollutant emissions. Hydrogen can be produced from diverse feedstock sources that are available in most regions, including renewable sources such as wind- and solar-derived electricity, biogas, and biomass. Public institutions, industry firms, research organizations, and automobile manufacturers are promoting the use of hydrogen as a transportation fuel worldwide under various projects and initiatives [1]. For example, H2USA, a public-private partnership, coordinates efforts between the partners to enable the widespread use of FCEVs across the United States [1,2]. Similar initiatives are being undertaken across the world: the H2mobility project in Europe, the Research Association of Hydrogen Supply/Utilization Technology (HySUT) in Japan, and the Scandinavian H_2 Highway Partnership [1].

Several automobile manufacturers have launched FCEVs (for sale and lease to the public) or announced plans for commercial production. During the early phases of FCEV introduction in the marketplace, the demand for hydrogen is limited, and the installed refueling infrastructure has low-capacity utilization. Under these circumstances, transporting hydrogen using compressed gaseous hydrogen (CGH_2) trucks, also known as tube trailers, is an attractive and economical option [3,4]. Fig. 1 shows the feasibility of various distribution options to hydrogen refueling stations (HRSs) that have different capacities (i.e., very small to very large). In the face of low utilization, the liquid hydrogen (LH_2) truck and pipeline distribution modes are not economical for the small stations that will likely be constructed during early phases of FCEV commercialization. Of the other options shown in Fig. 1, the economic feasibility of on-site hydrogen production via electrolysis or steam methane reforming is limited by (1) the costs associated with electrical upgrade and (2) the availability/cost of land at the refueling station for reforming. The CGH_2 truck or tube trailer distribution option is already one of the most economical options for the early HRS markets [4].

Tube trailer transport of gaseous hydrogen

Fig. 2 shows the schematic representation of tube trailer delivery pathway [5]. The hydrogen produced at a central production plant may be transported via transmission pipeline to a distribution terminal, where hydrogen is compressed and loaded into pressure vessels mounted on a trailer (tube trailer) for trucking to HRSs. Additional storage may be incorporated at the distribution terminals to address the variation in supply and demand. The tube trailer with the hydrogen payload is then transported from the terminal to an HRS, where it is swapped with the onsite (empty) tube trailer [6]. The tube trailer configuration and loading pressure influence the hydrogen payload, and hence the number of deliveries to HRSs.

The type of pressure vessels mounted on the trailer affect the maximum possible payload and hence the economics of hydrogen delivery. The pressure vessel type and its working pressure determine the minimum weight of the vessel that can hold a unit of hydrogen. Currently there are five pressure vessel types (I to V) available to store and transport gases [6–8], described in Table 1. While type V vessel is relatively a new technology, approved for storage of gases, it has not been tested for hydrogen storage. Tube trailer with type 1 pressure vessels can transport up to 250 kg of hydrogen at pressures of 200 bar, while type III and type IV pressure vessels can transport up to 1000 kg of hydrogen at pressures of 500 bar [9,10].

For this study, we conducted a techno-economic analysis of the tube trailer delivery pathway, including the design and packaging of pressure vessels on the tube trailer, as well as the operation of the HRSs supplied by tube trailer, to estimate the resulting levelized delivery cost of hydrogen. We also investigated the influence of the tube trailer configuration on the fueling operations at the HRSs. We developed and employed a simulation model that mimics the refueling station operations. The model included a compressor that draws hydrogen from the tube trailer at HRSs and fills the high-pressure buffer storage, a dispenser that controls the flow rate of hydrogen from the high-pressure buffer storage to the onboard vehicle storage (tank), and a refrigeration unit that precools the hydrogen to −40 °C before dispensing [11].

Tube trailer definition

A tube trailer consists of pressure vessels designed to store hydrogen at a rated pressure, packaged in a container, and mounted on a trailer to transport the compressed hydrogen gas from distribution terminals to HRSs. The tube trailer can be defined by parameters such as the material used to construct the pressure vessels, the size of the vessels, and the

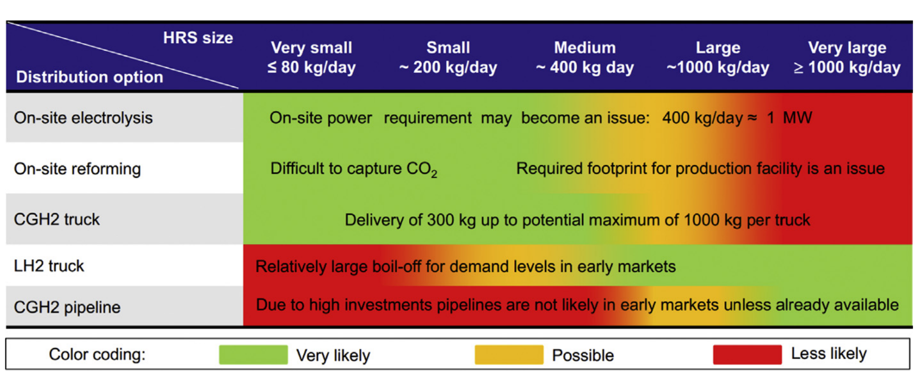

Fig. 1 – Economic feasibility of various H_2 distribution options for various station sizes [3].