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# Comparison study on life-cycle costs of different trams powered by fuel cell systems and others

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ABSTRACT

Proton exchange membrane fuel cells have shown great promise for powering trams. Hydrogen refueling stations and a fuel-cell system incur initial vehicle costs that are higher than a pantograph/catenary tram or contact-rail tram. In this paper, a life-cycle cost analysis is conducted for five trams: a pantograph/catenary tram, a contact-rail tram, and three fuel-cell hybrid trams. Characteristics of fuel-cell hybrid trams are compared with contemporary transit systems. A simplified life-cycle cost model, including costs for the initial infrastructure and powertrains, daily operation and power plant replacement, is proposed and calculated with parameters. A sensitivity analysis is also performed. Results show that the life-cycle costs of trams are almost proportional to the rail-line length. The initial costs of a fuel-cell hybrid tram are less than a pantograph/catenary tram or contact-rail tram. The life-cycle costs of fuel-cell hybrid trams are highly dependent on combination factors of hydrogen price, fuel-cell price and battery price. Charging facilities for fuel-cell hybrid trams are favorable when hydrogen price is in a high level. Greenhouse gas emissions of trams are almost equivalent.



## Introduction

Proton exchange membrane fuel cells produce electric power by reacting oxygen and hydrogen to yield water as the sole by-product. The past decades have seen a rapid development of fuel cells for vehicular applications, motivated by concerns for energy security, global climate change and air quality [1]. A hydrogen economy is developing [2]. Hydrogen supply chains have been quantified more than forty [3,4]. Three criteria of evaluating hydrogen pathways are: primary energy demand, cost expectation and emission index [5,6]. Hydrogen storage, transport and delivery offer significant challenges. Hydrogen is commonly stored in lightweight, high-pressure vessels at ambient temperature. Commercially available high-strength steel and aluminum glass-fiber-reinforced pressure vessels are inexpensive, but they are heavy and the storage pressure is low (25 MPa) [7]. Carbon-fiber nanocomposites are compact

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and can resist storage pressures up to 70 MPa [8,9], but they are expensive. There is a compromise between cost, weight and size in choosing between glass-fiber and carbon-fiber storage vessels.

Trams are one type of transit systems listed in Table 1 [10]. Compared with subways and light rails, trams have low carbon emissions, low noise, low investment and operating costs and short construction periods; and compared with bus rapid transit systems and buses, trams are more comfortable and environmentally friendly and have a greater passenger capacity, lower energy consumption and longer service life. Therefore, trams are more and more popular in large and medium-sized cities in China. From 2012 to 2020, 74 tram lines, which total planning length is 1066 km, are proposed herein.

Fuel cells will be promising power suppliers for rail vehicles such as locomotives, railcars or trams due to their high efficiencies and zero emissions. Rail vehicles require ~250 kW more power than passenger automobiles or buses; they operate in a more demanding operating regime with frequent starts and stops [11]. The fuel-cell rail vehicles that have been operating or proposed [12–23] to date are listed in Table 2.

Fuel-cell hybrid trams are concerned in this paper and compared to steam locomotives, diesel locomotives and electric locomotives on the basis of energy source, traction chain and total energy efficiency in Table 3. Fuel-cell hybrid trams have short traction chain and their efficiencies are higher than other types of locomotives and they perform better than other type of locomotives.

A fuel-cell hybrid system is powered by a fuel cell module and an auxiliary energy storage system, such as batteries, ultra-capacitors or their combination. For a self-sustaining hybrid vehicle, the fuel cell must continuously provide at least the mean power of a duty cycle. To continuously operate, the auxiliary energy-storage device must store sufficient energy to provide power in excess of the continuously rated power of the fuel cell [24]. It should also have a fast transient response at start-ups, provide peak power during the duty cycle and have the ability to recover energy by regenerative braking [25]. In this paper, the hybrid system comprises a fuel cell and a battery pack. By optimizing the power allocation of the hybrid configuration, the fuel cell can operate in the high-efficiency regime, minimizing the system costs [26,27].

Life-cycle cost analysis is a powerful tool for evaluating fuel-cell powered projects in the design phase. Jeong KS et al. [28] found that the life-cycle costs of a fuel cell-hybrid vehicle were largely affected by the size and cost of the fuel cell along with the cost of hydrogen. Baptista P et al. [29] presented a life-cycle costs analysis of fuel cell hybrid taxis in terms of energy consumption and $CO_2$ emissions; the fuel cell-powered configurations had lower energy consumption (4.34 MJ/km) and $CO_2$ emissions (235 g/km) than those with a diesel engine (9.54 MJ/km and 738 g/km) or a battery electric vehicle (5.81 MJ/km and 269 g/km). Simons A et al. [30] assessed the life-cycle impact on the production of fuel cell systems and their end-of-life. They used a sensitivity analysis to predict that a substantial reduction in greenhouse gas emissions

**Table 1 – Indices of five public traffic systems [10].**

| Indices | Subways | Light rails | Trams | Bus rapid transit systems | Buses |
|---|---|---|---|---|---|
| Right-of-way | sole | sole | shared or sole | shared or sole | shared or sole |
| Line forms | closed, underground | closed, underground or elevated | closed, partial interSection open or completely open | closed, partial interSection open or completely open | completely open |
| Application scope | population over 300 million | population over 100 million | population less than 300 million | population over 50 million | – |
| Passenger capacities (people) | 1200–3000 | 400–800 | 150–400 | 70–150 | 50–80 |
| One-way passenger capacities (thousands of people per hour) | 30–60 | 10–30 | 8–15 | 8–12 | <5 |
| Maximum speed (km/h) | 100 | 80–100 | 80 | 80 | 80 |
| Average station spacing (km) | 1.2–2 | 0.8–2 | 0.8–1.8 | 0.8–1.5 | 0.8–1.5 |
| Operating speed (km/h) | 35–45 | 30–40 | 20–35 | 20–30 | 10–15 |
| Power supplies | pantograph/catenary | contact-rail or pantograph/catenary | contact-rail or pantograph/catenary | oil or electric | oil or electric |
| Project investment (million US$/km) | 60.7–106.3 | 45.5–75.9 | 10.6–15.2 | 6.1–8.3 | – |
| Construction cycles (years) | 4–5 | 4 | 2–3 | 1–2 | 1 |
| Operating cost level | high | somewhat high | low | low | low |

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