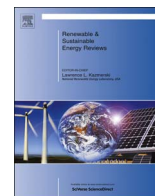




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## Research progress in the development of natural gas as fuel for road vehicles: A bibliographic review (1991–2016)



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### ABSTRACT

Among all alternative fuels, compressed natural gas (CNG) has been considered as one the best solutions for fossil fuel substitution because of its availability throughout the world, inherent clean burning, economical as a fuel and adaptability to the gasoline and diesel engines.

This bibliography reviews the potential of CNG as a transportation fuel. The added bibliography at the end of this article contains 1102 references to papers, conference proceedings and theses/dissertations on the subject that were published between 1991 and 2016. These references have been retrieved from 137 scientific journals. The references are classified in the following categories: Regional Experience with CNG Vehicles; Economic Aspect of CNG Vehicles; CNG Engine's Design, Control and Performance; Combustion and Fuel Injection Characteristics of CNG Engines; CNG/ Diesel Dual Fuel Operations; Hydrogen Enriched CNG Vehicles; Environmental Aspect of CNG Vehicles; Safety Aspect of CNG Vehicles.

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## 1. Introduction

The yield of scientific articles is generally rising fast and professionals are no longer able to be fully abreast with all pertinent information. The rising specialization in various scientific arenas has triggered the dissemination of subject-oriented journals and conference proceedings focused to specialist audiences. The scholars have now more options for sharing the results of their scientific work, but on the other hand exploring the relevant information may be a laborious and time-consuming process. Moreover, sometimes the researchers are not willing to devote time to exploring the relevant information. It has been pointed out that in the field of engineering, informal knowledge channels are most frequently used for getting information [1].

With increasing government restriction of tailpipe emissions from vehicles powered by internal combustion engines and growing concern over the use and exhaustion of fossil fuel, alternative fuels has gained popularity [2,3]. Natural gas has a widely used alternative fuel for a variety of reasons including ready availability and its low cost and low emissions potential relative to conventional fuel and its applicability in convention diesel and gasoline engines [4]. Natural gas is scattered in many regions of the world so that it can stable supply. Therefore natural gas has been subjected widely as a kind of clean alternative fuel for engines [5–7].

The bibliography provided at [Annexure-B](#) contains 1102 references to journal's papers, conference proceedings and theses/dissertations on the subject that were published between 1991 and 2016. These references have been retrieved from 137 scientific journals listed at [Annexure-A](#).

The bibliography is divided into the following parts and concerns:

- Regional Experience with CNG Vehicles
- Economic Aspect of CNG Vehicles
- CNG Engine's Design, Control and Performance
- Combustion and Fuel Injection Characteristics of CNG Engines
- CNG/ Diesel Dual Fuel Operations
- Hydrogen Enriched CNG Vehicles
- Environmental Aspect of CNG Vehicles
- Safety Aspect of CNG Vehicles

It is difficult for the authors to recap the wide topics of this article in a form of the state-of-the-art review article; therefore a bibliography is presented here. Hope, this bibliography will save time for researchers looking for information pertinent with the subjects listed below, not having access to large databases or not willing to spend time on uncertain information retrieval.

## 2. Regional experience with CNG vehicles

The word is turning towards substitute to gasoline and petroleum-based energy that is taking an upward trend in terms of price. Across the globe, various countries have experienced that CNG is good for the consumer and friendly to the environment while pushing the country into more independent state [8]. An increasing number of countries across the globe are jumping on the bandwagon to make use of CNG, due to its various benefits.

This section of the bibliography covered the case studies of various countries and cities regarding their experience for using the CNG as a transportation fuel. The case studies of the countries and cities listed: UK, USA, Pakistan, China, Japan, Germany, Argentina, Switzerland, Brazil, Qatar, Korea, Indonesia, Malaysia, Sweden, Algeria, Nigeria, Ireland, Milan, Tokyo (Japan), Dhaka (Bangladesh), Delhi (India), Santiago (Chile), Madrid (Spain),

Beijing (China), New York (USA), Brussels (Belgium), São Paulo (Brazil), Salvador (Brazil), Rio de Janeiro (Brazil).

## 3. Economic aspect of CNG vehicles

One of the major advantages of CNG is that it offers a cheap source of energy. As the world continues to run with expensive fuels such as and gasoline and diesel, the low-cost CNG offers a glimmer of hope. Although emission reduction using natural gas was the main focus of CNG application as a transportation fuel, especially in metropolitan regions, in recent days, with a sharp rise in oil prices, the increasingly considerable cost benefit of using natural gas has become a real major consideration for many new users. In most countries, natural gas is much cheaper than per equivalent gallon of diesel and gasoline, even after accounting for the costs linked with compression and even considering its lower thermal efficiency against diesel and gasoline, there are significant economic benefits of using CNG as a transportation fuel. Gasoline and diesel must be passed through the complex refining process, while natural gas needs very less processing from field to the vehicle engine. It is also less prone to price fluctuations and as compared to its resources are more evenly distributed around the world.

One of the important factors for comparing the economic aspect of automotive technology is the associated maintenance cost. Although a review of the literature found no previous empirical work that has examined the issue of maintenance cost competitiveness of latest NGV or diesel technologies based on total life-cycle costs. However, there are few studies which examined the operating cost associated with natural gas vehicles. Based on limited studies and research on comparative operating costs, evidence supports both cost increases, cost decreases costs are equivalent [9–14].

However the association of high cost with the development of refueling infrastructure (pipelines and filling stations for CNG vehicles) remains the most significant barrier to the adaptation of CNG as an alternative fuel but with sufficient visibility on demand, supportive economics, and government incentives these barriers appear surmountable. Nearly all of the countries where CNG infrastructure has been developed; incentive programs offered to investors such as loans, subsidies, exemptions from import duties and the lowering or elimination of import tariffs on machinery, equipment, and kits (price-supplier); and exemption from sales taxes for the construction and operation of refueling stations. Once subsidies for fueling stations and NGV customers run out, the expected profitability of new CNG filling facilities is no longer attractive enough. In e.g. Canada, reducing investments in fueling stations caused the collapse of the whole NGV sector [15]. Costs of installing CNG infrastructure can vary significant depending on size, capacity and the way natural gas is dispensed (fast-fill, time-fill). Consequently, costs can vary widely from project to project and country to country. As the land is a significant component in building a CNG station so the cost depends on the decision to build the station on a new site, or incorporate CNG fueling at an existing site such as an existing diesel fuel station. Worldwide the average costs identified in various studies to construct a CNG station ranged between \$600,000 and \$1,000,000 per station excluding land cost. In Pakistan the country having the highest number of CNG station after China, the average cost of constructing a CNG station is comparatively much low and amounting to 150,000 US \$. [Table 1](#) provides estimates of total costs to construct a CNG station in Pakistan.

In addition to short-term economics, there are several socio-economic aspects associated with the development of natural gas as vehicular fuel. One of the significant impacts of the NGVs will be

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