System analysis of mobile CNG transport as a way to supply temporary energy end-users

Sorena Sattari, Ramin Roshandel
Energy Management Department, Institute for International Energy Studies (IIES),
subsidiary of Ministry of Oil & Gas
No.14, Sayeh Street, Valiy-e-Asr Street, Tehran, IRAN

Abstract: - To become a mass-market product, compressed natural gas (CNG) cars will need a dense network of filling stations. Most transport of CNG is by pipeline generally. Transport of CNG module by trailers is one of the simple ways to supply temporary demand especially in the rural region and providing an alternative method of moving compressed natural gas to pipelines. For this reason the CNG modules which fill in the main stations (mother stations) are transported to substations (daughter stations) by trucks and trailers. To aim this goal the first step is to determine the number of trailers and trucks applying to supply the demand points. The capacity of daughter station and the distance between mother-daughter stations are two important factors which affect the system economics. In the present study a mathematical model of transport CNG modules is presented and mobile CNG transportation system is analyzed. The cost of the mother and daughter stations is also determined using the CNG Station Cost Model (CNG-SCM). The ultimate goal is to gain insight into the total cost of mobile CNG transport network in different capacities and mother-daughter distance.

Key-words: - energy planning, Compressed natural gas, Transportation, Mother-daughter stations

1. Introduction

It is well known that fossil fuel reserves all over the world are diminishing at an alarming rate and a shortage of crude oil is expected at the early decades of the world. In addition to this, the deteriorating quality of air we breathe is becoming another great public concern and tighter regulation of both 'local' and 'global' emissions from engines is anticipated. In view of the versatility of internal combustion engine (ICE), it will remain to lead the transportation sector as there is a significant restriction for the battery and fuel cell powered vehicles with respect to range and acceleration. The power to weight ratio of the ICE (including the tank and fuel) is much more than that of the battery powered or fuel cell operated vehicles [1]. These factors have lead scientists and researchers to develop environment-friendly technologies and to introduce more clean fuels alternatives to the conventional fuels used to power ICEs for ensuring the safe survival of the existing engine technology.

the world total natural gas (NG) reserve as of January 1, 2005 was 179.83 trillion cubic meters [2] and based on the current consumption rates, the estimated total recoverable gas, including proven reserves is adequate for almost 66.7 years [3]. This has resulted in an increased interest to use CNG as fuel for internal combustion engines. The merits of CNG as an automotive fuel over conventional fuels are many and presented comprehensively by Nylund et al. and Aslam et al. [4–5]. Due to some of its favorable properties, CNG appears to be an excellent fuel for the internal combustion (IC) engine. Moreover, IC engines can be converted to CNG operation quite easily for with the addition of a second fueling system. Natural gas vehicles (NGV) are also seen as having a bridge function for the market introduction of fuel cell vehicles: as hydrogen can be efficiency reformed from methane, the CNG refueling infrastructure and its operation would need only modular extensions to enable hydrogen distribution and refueling. Beside, CNGs give customers the chance to get familiar with the concept of gaseous fuels.

CNG has been used in vehicles since 1930's and the current worldwide NGV population is more than 6.5 million according to the International Association for Natural Gas Vehicle (IANGV) statistics and this figure is fast increasing everyday. However, in order to use CNG as an alternative automotive fuel, a country should have sufficient stations to supply NGVs.

Compressed natural gas cars (CNG) are relatively inexpensive to produce, and they emit around 15–20% less carbon dioxide (CO2) [6]. CNG vehicles have been successfully used for decades, especially in Italy (410,000 CNG cars) and in Argentina (1.6 million CNG cars). Worldwide, 6.9 million CNG cars are in circulation and serviced by 10700 natural gas filling stations (IANGV) [7]. Companies, including Volkswagen, Opel (GM's German subsidiary), Volvo, DaimlerChrysler, Ford and Fiat offer CNG vehicles in Europe. Usually, these are sold as bi-fuel vehicles, which can be driven with either gasoline or natural gas.

2. Advantages of the CNG as an alternative fuel

Of all the available alternatives, compressed natural gas (CNG) stands out as the most beneficial:

- CNG is the most economical fuel available - from 30 to 60 percent cheaper than gasoline on an equivalent gallon basis.
- CNG is abundant; Iran reserves are estimated 26.74 trillion cubic meters and represent a potential energy for the future supply.
- CNG is environmentally friendly - no cancer causing particulates, less carbon monoxide and hydrocarbon emissions - less acid rain, smog, ground level ozone contamination and greenhouse effects. This is especially important in large metropolitan areas where approximately 60% of urban pollution comes from gasoline - and diesel - powered vehicles.
- CNG is much safer than gasoline, diesel fuels, or propane. If released CNG does not liquefy or accumulate. It dissipates quickly because it is lighter than air and thus less prone to ignite or explode.

3. CNG in Iran

Iran is ranked as the second highest country in the world for natural gas reserves with more than 26 trillion cubic meters of reserves. It has an extensive gas pipeline network to more than 450 cities and 1300 villages. There are also serious concerns about high levels of local air pollution as a result of vehicle use in metropolitan areas.

Fuel prices in Iran are very low, for instance premium gasoline is approximately 0.1 euro per liter. Iran is a major oil exporter but has a shortage of refining capacity and has to import a high proportion of its gasoline. Iran recently introduced petrol rationing. Private car owners are allowed 100 Liters per month. Therefore, It makes sense to export oil and to use its substantial reserves of natural gas in the transport sector.

The total number of vehicles in Iran in 2006 was 9 million and annual vehicle production was 1.1 million vehicles. Under a medium growth scenario, number of vehicles would rises to 15 million vehicles by 2020. The NGV strategy prepared by the Iranian Fuel Conservation Organization (IFCO) has three elements for NGV growth; retrofit vehicles, conversion of new vehicles in the vehicle manufacturers factory and production of OEM NGVs.

At present the total number of NGVs in Iran is 315,000 and Vehicle manufacturers have the capacity to make 1200 NGVs per day. Conversions are 15,000 per month with a capacity of 250,000 per year in 152 conversion centers. There are 211 CNG refueling stations in service with over 300 under construction.

4. Mother – daughter fueling station

The purpose of the refueling station is to introduce compressed natural gas at high pressure into a motor vehicle that has been converted to run on CNG. There are basically two fundamental concepts of refueling station;
Fast Fill Station which refills vehicles in exactly the same manner as normal petrol stations. These are generally suitable for refueling cars, vans & light trucks and are public or fleet operating stations. Trickle Fill Stations which refill vehicles more slowly, for example over night. This concept is suitable for the fleet refueling of heavy vehicles such as buses and trucks. Irrespective of whether the stations are fast fill or trickle fill, there are three main types of CNG Station:

1. On Line or conventional stations
2. Mother stations
3. Daughter stations

Any of these stations can act as Fast Fill or Trickle Fill stations. In some cases, on line and mother functions may be combined in the same station. In other cases a station originally designed as a daughter station may be converted at a later date to an on line station, or even a mother station. The on line station takes gas from an existing supply line, compresses it and dispenses it to the vehicles. The Mother station takes gas from the supply line, compresses it and delivers it to a gas Transport System. The gas Transport System then delivers the gas to a daughter station, which is located at some distance from the mother station. Daughter stations are located in areas that are not connected to gas supply lines. The Daughter station receives Gas from the Transport system and dispenses it to the customers.

5. Mathematical Model

In this section a model for CNG transport is presented. The model consists of three main modules which provide mother economics, daughter economic and the transport system.

4.1. Transport of CNG Modules

The CNG modules are transported by trucks from mother to daughter stations. At the first step the number of trucks and trailers should be determined as a function of capacity and the distance between mother and daughter stations. For this reason in present study the mathematical formulation of the number of trucks and trailers is provided.

4.1.1. Assumptions

- Gas modules are transported by trailers and trucks
- Each truck, service two times in a day
- Each truck, travel 300 km maximum in a day
- The capacity of one trailer is 5000 m^3

4.1.2. The effect of mother-daughter distance on the number of trucks and trailers

In this paper, 3 situations (Modes) are considered based on the distance between mother and daughter stations as follows:

Mode 1 when the distance between mother-daughter stations is lower than 75km

Mode 2 when the distance between mother-daughter stations is garter than 75km and lowers than 150km

Mode 3 when the distance between mother-daughter stations is garter than 150 km and lowers than 300km

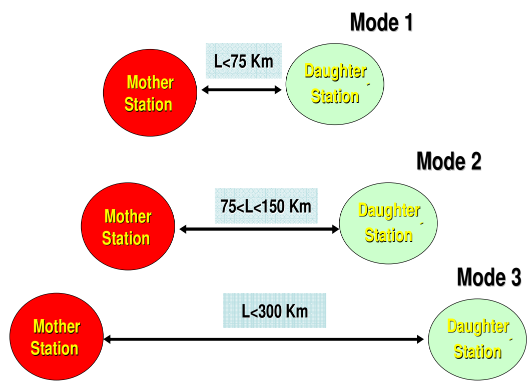

Fig.1. Different modes of CNG transport

If the distance between mother-daughter stations were grater than 300 km, using trucks for transport CNG is not economical and therefore this case is not studied here.

The maximum distance between mother-daughter stations in mode 'n', is obtained form equation (1):

$$L_n = \frac{S_{Max}}{4} \times 2^{n-1} \qquad (1)$$

In the above equation S_{Max} is the maximum distance which could be traveled by a truck in a day (300 km assumed) and n is the mode number.

4.1.3. The effect of daughter capacity on the number of trucks and trailers

It is supposed that each trailer could transport 5000 m^3 CNG in a service from mother to daughter station. Total number of trucks and trailers, in mode 1, when the daughter capacity is limited to 10,000 m^3/day is presented in fig 2. In this case each truck will provide two services in a day.

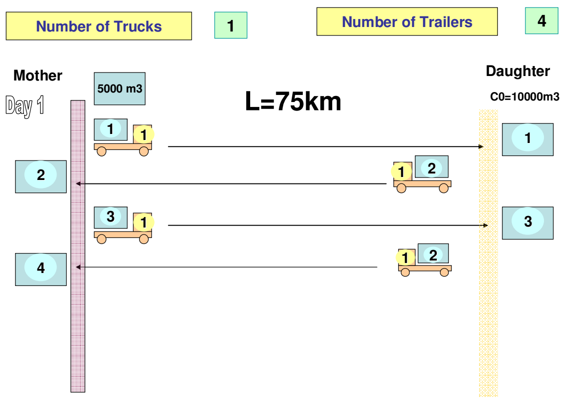

Fig.2. CNG Transport Pattern, Mode 1 and 10000 m^3/Day

Increasing the capacity of daughter station will increase the number of trucks as well. But if the capacity of daughter increases to 15,000 m^3/day, one of the CNG trucks travel one service only. This pattern is shown in fig 3. It means that in this case we have an unused truck.

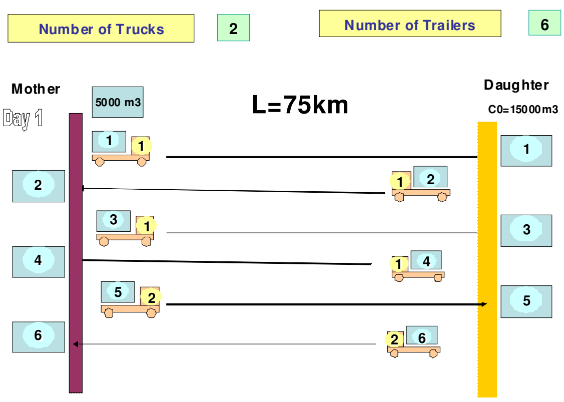

Fig. 3. CNG Transport Pattern, Mode 1 and 15000 m^3/Day

In mode 2, the maximum distance between mother and daughter station is 150km and there is no way for a truck to travel more than one service in a day. In this case, when the daughter capacity is limited to 10,000 m3/day, the number of truck and trailers is shown in fig. 4

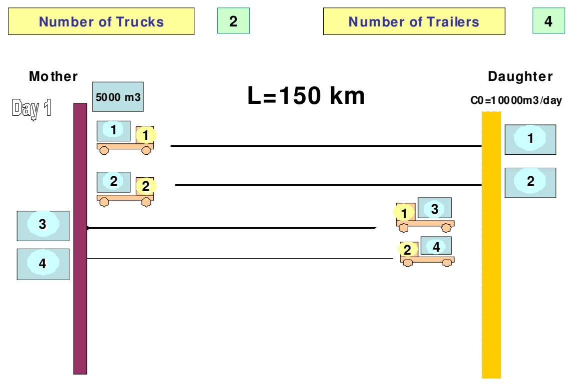

Fig .4. CNG Transport Pattern, Mode 2 and 10000 m^3/Day

In higher daughter station capacities the above patterns are applied as well and the number of trucks and trailers will increase linearly as it shows in fig. 5

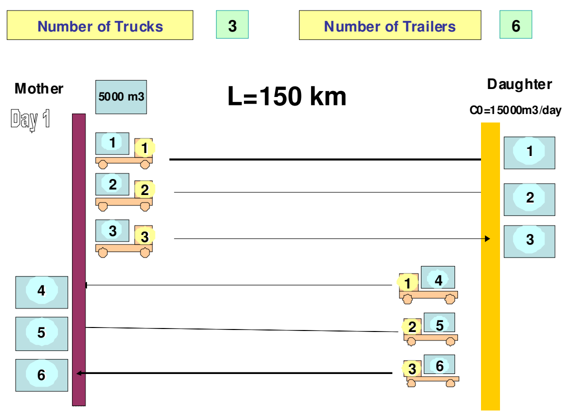

Fig .5. CNG Transport Pattern, Mode 2 and 15000 m^3/Day

In mode 3, the maximum distance between mother and daughter station is 300km and each trucks requires 2 days to travel between the mother and daughter stations. For this reason, the trucks should supply the daughter station for 2 days. The transportation patterns for three different capacities are presented in figs. 6 and 7.

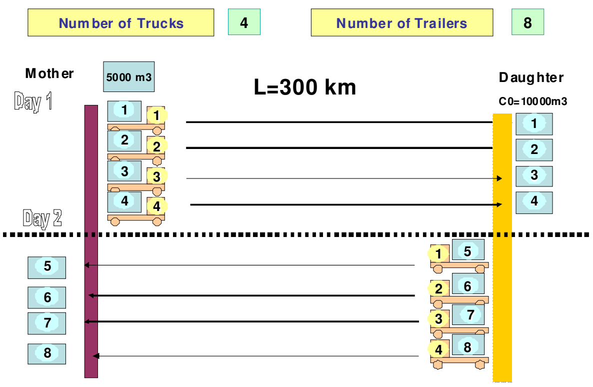

Fig .6. CNG Transport Pattern, Mode 3 and 10000 m^3/Day

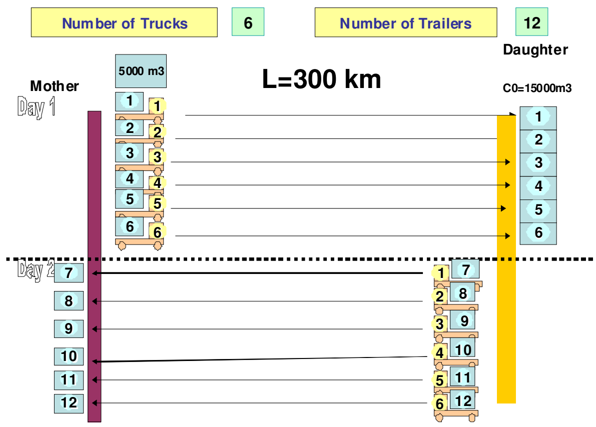

Fig .7. CNG Transport Pattern, Mode 3 and 15000 m^3/Day

As mentioned earlier, based on the distance between mother-daughter stations, we face to three modes. The summery of tracks and trailers numbers in each mode is presented in tables 1.

	Mode 1			Mode 2		Mode 3	
Capacity M^3/Day	# Truck	# Trailer	Service	# Truck	# Trailer	# Truck	# Trailer
10,000	1	4	2	2	4	4	8
15,000	2	6	2,1	3	6	6	12
20,000	3	8	2,2	4	8	8	16
25,000	3	10	2,2,1	5	10	10	20
30,000	3	12	2,2,2	6	12	12	24

Table 1, the summery of tracks and trailers numbers in different modes

4.1.4. Estimating CNG transportation Costs

Estimating the total cost of CNG transportation involves capital costs of trailers packages and trucks, maintenance cost, fuel cost and drivers salary. Total cost per year is calculated using the following equations:

$$I_0 = (n_{Truck} I_{Truck} + n_{Trailer} I_{Trailer} + n_{Pakage} I_{Pakage})/20 \qquad \textit{Total Capital Cost} \quad (2)$$

$$M = 3\% I_0 \times D_{Factor} - S \times 3\% \left(I_{Truck} + 2I_{Trailer} + 4I_{Pakage}\right) \times 0.5 \times D_{Factor} \qquad \textit{Maintenance Cost} \quad (3)$$

$$F = L_{Total} \times \left(\tfrac{40lit}{100Km}\right) \times 165 \times 365 \qquad \textit{Fuel Cost} \quad (4)$$

$$P = n_{Truck} \times 6000000 \times 12 \times D_{Factor} - S \times 3000000 \times 12 \times D_{Factor} \qquad \textit{Drivers Salary} \quad (5)$$

$$D_{Factor} = \begin{cases} \frac{L}{75} & \text{Mode 1} \\ \frac{L}{150} & \text{Mode 2} \\ \frac{L}{300} & \text{Mode 3} \end{cases} \qquad \textit{Distance Factor} \quad (6)$$

$$L_{Total} = \begin{cases} Mode\ 1 \begin{cases} S = 0 \longrightarrow n_{Truck} \times 4L \\ S = 1 \longrightarrow (n_{Truck} - 1) \times 4L + 2L \end{cases} \\ Mode\ 2 \longrightarrow n_{Truck} \times 2L \\ Mode\ 3 \longrightarrow n_{Truck} \times L \end{cases} \qquad \textit{Total traveled distance} \quad (7)$$

$$I_{Total} = I_0 + F + M + P \qquad \textit{Total Cost} \quad (8)$$

4.2. Mother – Daughter Stations

The following mother station types are considered in this model:

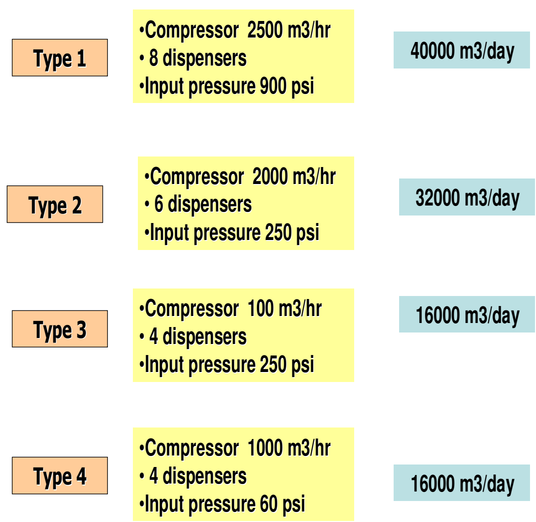

Fig. 8. Mother station types considered in this model

Annual Cost accounts for the cost of mother and daughter station and involves capital cost ($), operation and maintenance cost ($/year) and staff salary. The capital cost for different mother and daughter stations is presented in tables 3 and 4.

Type of mother station	Capacity m3/day	Equipment $	Total investment $	Total investment without land cost $
1	40000	418000	1520000	821739
2	32000	410000	1511957	818043
3	16000	306000	1174348	653804
4	16000	340000	1208261	687826

Table 1, the capital cost for different mother stations

Type of daughter station	**Capacity m3/day**	**Moving CNG module $**	**Fixed CNG module $**
1	100000	316087	130435
2	55000	243370	119565
3	40000	201522	108696
4	20000	133370	86957
5	15000	111304	76087

Table 1, the capital cost for different daughter stations

6. Results and discussion

As mentioned earlier, because of high capital costs, the number of trucks and trailers have effective role on the overall system economic. In Fig. 8 the number of trucks in terms of capacity and mother-daughter distance is presented.

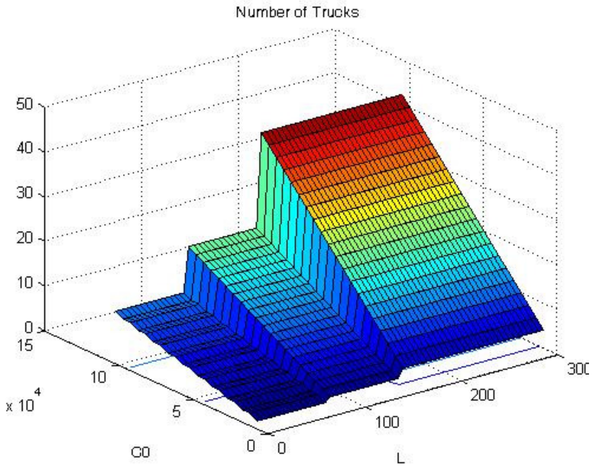

Fig. 9, Number of trucks in terms of capacity and mother-daughter distance

There are two jumps in the number of trucks which indicate the change in mode in term of mother-daughter distance. Therefore the total investment and capital cost will be increased dramatically in the mode-change points. Fig. 10 shows the number of trailers in different capacities and mother-daughter distances. There is no difference between mode 1 and 2.

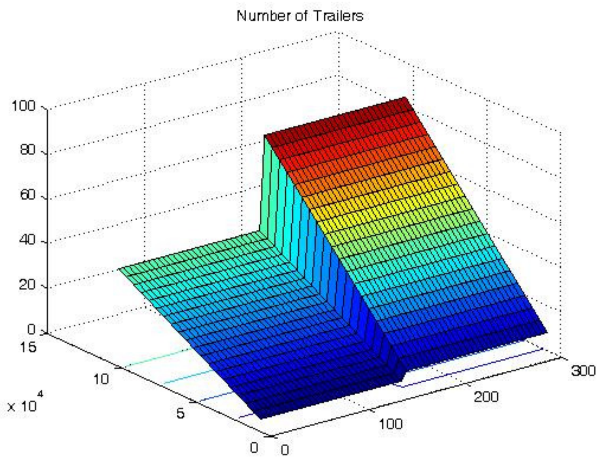

Fig.10. number of trailers in different capacities and mother-daughter distances

Fig.11 presented total distance traveled by trucks in a day, the sharp gradient in high capacities and mother-daughter distance indicates that the operating cost will increase effectively in these regions similarly.

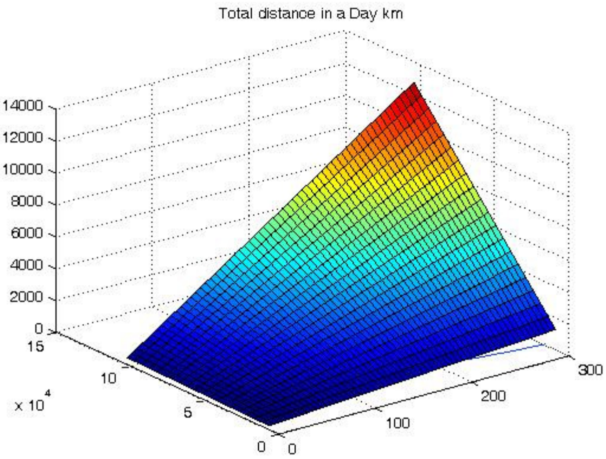

Fig.**11 Total distance traveled by trucks in a day**

The comparison of capital cost, operational cost and driver salary in the total cost of one cubic meter CNG in daughter station is one of the important factors for decision makers and presented in Fig. 12. As it shows, the operational cost for daughter station has important role on the total cost. It indicates that in the long period time the mother-daughter system could not be a suitable method to supply CNG.

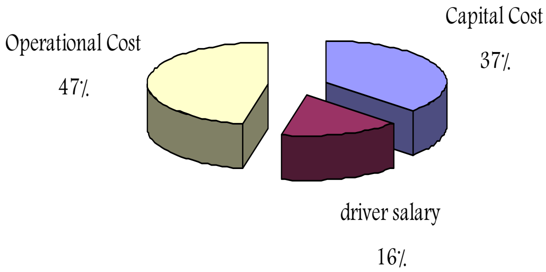

Fig.12 The comparison of Capital cost, Operational cost and driver salary in one cubic meter of CNG for daughter station

Fig. 13 shows the contribution of different cost in total investment of a mother CNG station. It is concluded that the land cost is the major part of the total cost. In many cases the on line and mother CNG stations is combined in the same station. Therefore these stations should be placed on valuable region in the cities and as a consequence the land cost in this area is quit high.

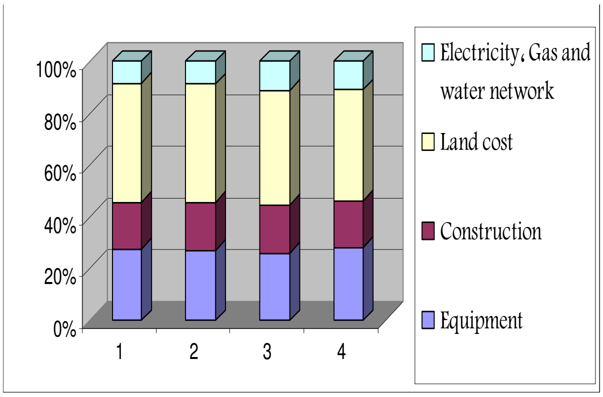

Fig. 13 The contribution of different cost in total investment of a mother CNG station

It seems that by eliminating the land cost by involving the land owners in station construction, the total cost of mother station is reduced dramatically. Based on our calculations, the total cost of one cubic meter CNG could be highly reduced by providing the land by owners. It could be possible by providing proper encouragements for land owners. Table 4 shows the difference between the total costs of one cubic meter of CNG for mother station.

Table 4 the difference between the total costs of one cubic mere of CNG for mother station

Type of mother station	Rial/m^3	Rial/m^3 (eliminating land cost)
1	47.9	26
2	59.5	32.2
3	97.2	56.2
4	99.9	58.9

7. Conclusion

Natural Gas is well suited to deliver cleaner power production and provides the opportunity to displace petroleum products. Natural Gas can be used to supply industrial or residential heating, power generation, or CNG refueling stations for vehicular application. Mobile CNG is providing an alternative method of moving compressed natural gas to pipelines. In this method, Natural Gas is compressed and filled into truck mounted cascades (modules) in the mother compressor station and transported to daughter units for dispensing to CNG vehicle. The advantages of mother-daughter CNG transport system are:

- Provide temporary supply of natural gas to pipelines undergoing scheduled or unscheduled maintenance
- Service customers not connected to existing distribution systems
- Offer emergency distribution service in the event of a line break

In this paper a model for analysis the mother-daughter system is presented. The model consists of mother and daughter station economics and the transport system analysis. Based on model results the numbers of trucks are increased suddenly when the mother-daughter distance exceeds the quarter of the maximum travel length of a truck. Our simulations also confirm that the mother-daughter system is not suitable for long period time because the operational cost of daughter system is quit high compare to the total investment. Furthermore the land cost is the major expense in the total cost of a cubic meter of CNG and eliminating that by proper encouragement for land owners could improve the mother-daughter system economical justification. However, it is concluded that mother-daughter system could be used for short term-temporary or emergency CNG supply for customers not connected to existing distribution system.

7. References

[1] Das LM, Gulati R, Gupta PK. International Journal of Hydrogen Energy 2000; 25:783

[2] Institute for International Energy Studies (IIES), Iran's Hydrocarbons Energy Balance 2005, Ministry of oil and gas, 2005

[3] International Energy Outlook, Energy information administration. Washington, DC: Department of Energy; 2005. EIA-048. pp 38–9

[4] Nylund NO, Laurikko J, Ikonen M. Pathways for natural gas into advanced vehicles. IANGV (International Association for Natural Gas Vehicle) 2002; Version 30.8 2002

[5] Aslam MU, Masjuki HH, Maleque MA, Kalam MA, Mahlia TMI, Zainon Z, et al. Introduction of natural gas fueled automotive in Malaysia. Proc. TECHPOS'03 2003;160, UM, Malaysia

[6] Cleaner Drive (2003) Wie sauber farhrt Dein Auto. http://www.cleaner-drive.ch/tools/news.cfm?lang=de, Cleaner Drive, November 2003

[7] IANGV, 2007, Latest International NGV Statistics. www.iangv.org/jaytech/default.php?PageID=130, NGV

[8] Martin Frick, K.W. Axhausen , Gian Carle, Alexander Wokaun, Optimization of the distribution of compressed natural gas (CNG) refueling stations: Swiss case studies, Transportation Research Part D 12 (2007) 10–22

[9] Sydney Thomas, Richard A. Dawe, Review of ways to transport natural gas energy from countries which do not need the gas for domestic use, Energy 28 (2003) 1461–1477

[10] Gian Carle, Peter Keller, Alexander Wokaun and K.W. Axhausen, Market potential of compressed natural gas cars in the Swiss passenger car sector, Conference paper STRC 2004, 4th Swiss Transport Research Conference

[11] Martin Frick a, K.W. Axhausen a, Gian Carle b, Alexander Wokaun, Optimization of the distribution of compressed natural gas (CNG) refueling stations, Transportation Research Part D 12 (2007) 10–22

[12] Arthur Janssen, Stephan F. Lienin, Fritz Gassmann, Alexander Wokaun, Model aided policy development for the market penetration of natural gas vehicles in Switzerland, Transportation Research Part A 40 (2006) 316–333

[13] Peter C. Flynn, Commercializing an alternate vehicle fuel: lessons learned from natural gas for vehicles, Energy Policy 30 (2002) 613–619

[14] S. Anyogita, Amit Prakash, V.K. Jain, A study of noise in CNG driven modes of transport in Delhi, Applied Acoustics 65 (2004) 195–201

[15] Marko P. Hekkerta, Franka H.J.F. Hendriksa, Andre P.C. Faaijb, Maarten L. Neelis, Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development, Energy Policy 33 (2005) 579–594