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The effect of important parameters on the natural gas vehicles driving range

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One of the most important issues regarding Natural Gas Vehicles (NGVs) is the Driving Range, which is defined as capability of a NGV to travel a certain distance after each refueling. The Driving Range is a serious obstacle in the development and growth of NGVs. Thus the necessity of studying the effects of various parameters on the Driving Range could be realized. It is found that the on-board storage capacity and the natural gas heating value have the greatest effect on the Driving Range. The charged mass of NGV cylinders is varied due to the natural gas composition and the final in-cylinder values (temperature and pressure). Underfilling of NGV cylinders, during charging operations, is a result of the elevated temperature which occurs in the NGV storage cylinder, due to compression and other processes could be overcome by applying extensive over-pressurization of the cylinder during the fuelling operation. Here, the effects of the most important parameters on the Driving Range have been investigated. The parameters are natural gas composition, engine efficiency and final NGV on-board in-cylinder temperature and pressure. It is found that, the composition has big effects on the Driving Range. The results also show that as final in-cylinder pressure decreases (or temperature increases), the Driving Range will be increased.

Keywords: Natural gas vehicle, Driving Range, Compressed Natural Gas (CNG), Thermodynamic properties, CNG fuelling station.

INTRODUCTION

The use of natural gas vehicles (NGVs) began in Italy in the mid-1930s. In particular, after the energy crisis in 1970, the NGVs were rapidly developed by the governments of developed countries and the developing ones. Today, there are more than 12 million vehicles and nearly 18000 CNG refueling stations in the whole world[1]. Natural gas as a fuel is used in different vehicles that include: passenger cars, heavy-duty trucks, garbage trucks and buses. In Iran in 1975, related NGVs projects with a conversion 1200 taxis and passenger car to this type of vehicle began. The number of NGVs has been estimated to be around 1.9 million vehicles at the end of 2010 in Iran[2] and is growing rapidly. The NGV has some substantial benefits relative to gasoline and diesel vehicles. These include: lower fuel and maintenance costs, 120+ octane, and, most certainly, cleaner exhaust emissions. On the other hand, the NGV disadvantages are: the cost and complexity of launching natural gas fueling stations, lower power, torque and the Driving Range. The lower driving range of the vehicle is a serious obstacle which the gas industry is striving to overcome, without resorting to unnecessarily high fuelling station pressures, or by applying extensive over-pressurization of the cylinder during the refueling.

Kowalewicz and Wojtyniak[3] studied on alternative fuels and their application to combustion engines such as spark ignition (SI) and compression ignition (CI). Their studies showed that natural gas as an alternative fuel in gas and liquid states has many applications. Furthermore, they have investigated the advantages and disadvantages of Compressed Natural Gas (CNG) as a fuel for SI and CI engines. Yossefi et al.[4] studied the effects of fuel composition and ignition energy on the early stages of combustion in a natural gas spark ignition engine using computational fluid dynamics (CFD) simulation. They focus on comparing the relative influence of gas composition such as ethane content of natural gas on the early progress of the combustion. Their result shows the percent of ethane increases the combustion propagation rate and decreases the delay time. McTaggart-Cowan et al.[5] studied the effects of fuel dilution in a natural gas direct-injection engine. Their studies shows that the principal impacts of diluting a gaseous fuel with nitrogen are: emissions of nitrogen oxides, particulate matter, hydrocarbons, and carbon monoxide are all reduced, with no effect on the engine's performance and efficiency. McTaggart-Cowan et al.[6] studied the influence of natural gas composition on combustion parameters and the amount of pollution released from the NGV (heavy-duty). Their studies showed that the composition has a little effect on the vehicle fuel consumption and the Driving Range. Maji et al.[7] calculated fuel consumption and emissions output percent for NGVs and gasoline vehicles. They optimized the ignition point for NGVs. Their studies showed that fuel consumption in the optimal point for NGVs is less than that of gasoline vehicles. Lopez et al.[8] studied energy consumption and for NGVs and other vehicles. Their studies showed that NGVs greenhouse gas emission percent is less than the other vehicles'.

Since the natural gas is a mixture of different gases with various properties, its compositions strongly influence its thermodynamic properties. Therefore, as the composition varies, its thermodynamic properties are altered as well. Here, the properties are calculated based AGA8 Equation of State (EOS). It is considered to be a very accurate EOS for calculating the compressibility factor[9]. Maric et al.[10,11] have calculated the heat capacity at constant volume and constant pressure, isentropic exponent and Joule-Thomson coefficient based on this EOS. The effects of natural gas composition variation on its heating value could be investigated using different methods. The methods accepted by the worldwide standard include: ANSI/ASTM[12] and the ISO 6976[13]. In the current study, the approach presented by the International standard ISO 6976 is utilized to calculate the heating value.

There have been limited researches on the driving performance of a car. Yamane and Furuhama[14] have studied the effect of the total weight of fuel and fuel tank on the driving performances of a car such as the fuel economy, driving range, acceleration ability, climbing ability and maximum speed. It is found that the total weight has a large effect, particularly on the acceleration ability, climbing ability, fuel economy and the driving range.

In all previous studies, fuel consumption and the Driving Range were not examined independently for a NGV. As the Driving Range is a serious obstacle in the development and growth of NGVs, it is necessary to study the effects of various parameters on the Driving Ranges of the NGVs. Here, the effects of the final thermodynamic properties of the charged gas after the refueling process on the vehicles Driving Range have been investigated. Furthermore, the strategies for the longer NGV Driving Range have been reviewed. In addition, the effects of natural gas composition on Driving Range have been studied.

DRIVING RANGE CALCULATION MODEL

The procedure for calculating the driving range is discussed in this section. The procedure starts by calculating the mechanical energy needed for driving a certain distance. Then, by considering reasonable values for the efficiency of power transmission systems and engine efficiency, the required energy by the engine vehicle is calculated. Finally, by knowing the heating value of fuel, fuel consumption will be calculated. Afterwards, the driving range could be easily calculated.

Calculation of Mechanical Energy

The mechanical energy needed to drive a certain distance is calculated based on Test cycles. Test cycles consisting of standardized speed and elevation profiles have been introduced to compare the pollutant emissions of different vehicles on the identical basis. After that first application, the same cycles have been found to be useful for the comparison of the fuel economy as well. In this study, a test cycle known as MVEG-95 has been employed for calculation. The cycle was introduced by Motor Company Vehicle Expert Group for European vehicle[15]. Figure 1 shows the speed profile for the MVEG-95 test cycle.

The cycle total length is 11.4 km, the average speed in urban and Extra urban are 5.12 m/s (18.43 km/h) and 18.14 m/s (65.3 km/h) respectively. The overall speed is 9.72 m/s (35 km/h). The mechanical energy needed to drive any test cycle should overcome the following three resistance forces: 1. Aerodynamic friction, 2. Rolling friction and 3. Acceleration resistance.

For most test cycles, an expression has been proposed to approximate the mechanical energy. The following expression has been proposed for MVEG-95 test cycle[15]:

$$E \approx 19 * A_f C_d + 0.84 * m_v C_r + 0.011 * m_v [MJ/100km] \quad (1)$$

In equation (1), E is mechanical energy needed to drive 100 km, A_f is the vehicle's frontal area, C_d is the aerodynamic drag coefficient, m_v is the vehicle's mass and finally, C_r is the tire rolling friction coefficient.

Considering equation (1), the mean traction force at the wheel is obtained from the following relationship[15]:

$$F_{trac} = \frac{E}{s} = \frac{E}{100} [kN] \quad (2)$$

Where in equation (2) s is the distance. Considering equations (1) and (2), average traction power at the wheels is obtained from the below equation[15]:

$$P_{trac} \frac{F_{trac} * \bar{V}}{trac} [kW] \quad (3)$$

In equation (3), $\bar{V}$ is an average vehicle's speed. „trac" is the time fraction which, the vehicle is in traction mode. (In the MVEG–95 cycle, the vehicle is in traction mode approximately 60% of the total cycle time).

Calculation of Fuel Consumption

To obtain the vehicle fuel consumption, it is necessary to consider losses during the vehicle motion (see figure 2). These losses include: 1. the losses caused by the gear box and differential, 2. the losses caused by the auxiliary devices (generation of electric energy, etc.) 3. The losses caused by the Internal Combustion Engine (ICE).

Considering the gear box's losses, power at the input of the gear box is obtained from the following relationship:

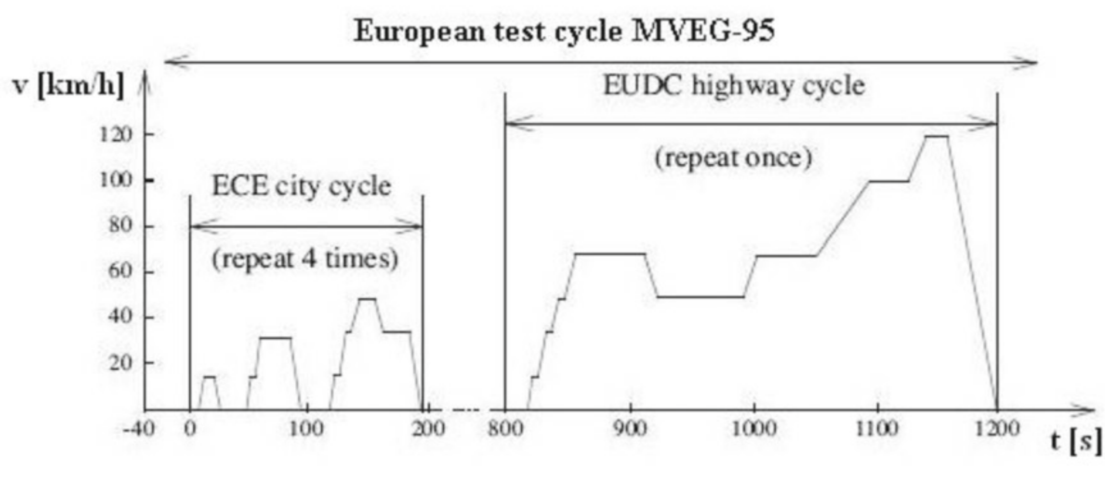

Figure 1. Speed profile for European test cycle MVEG-95 [15]

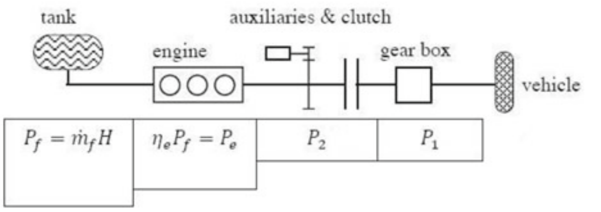

Figure 2. A schematic diagram of energy consumption in a vehicle1[5]

$$P_1 = \frac{1}{\eta_{gb}}(P_{trac} + P_{0,gb}) \quad (4)$$

In equation (4), η_{gb} is gear box efficiency and $P_{0,gb}$ is the power that the gear box needs at idle condition.

The losses caused by the auxiliaries (by power steering, air conditioning …) are taken into account by an additional average mechanical power, P_2 in this study.

There is an energy loss associated during the vehicle motion start, which could be calculated from the below equation:

$$E_c = 0.5 m_v v_0^{\ 2} \quad (5)$$

In equation (5), v_0 is the wheel velocity. Since in the MVEG–95, the average velocity is 9.5m/s, such an event takes place every 105 seconds. Therefore, the average power consumed by vehicle could be expressed in the following form:

$$P_3 = \frac{E_c}{105} \quad (6)$$

In summary, during the traction mode, the engine has to provide an average power which could be expressed by following equation:

$$P_e = P_1 + P_2 + P_3 \quad (7)$$

The average fuel power consumed by the engine in the MVEG–95 cycle could then be calculated using the following equation:

$$P_f = \frac{trac * P_e}{\eta_e} \quad (8)$$

Where, η_e is the vehicle engine overall efficiency. Knowing the average fuel power, the fuel consumption rate could be calculated by employing the following equation:

$$\dot{m}_f = \frac{P_f}{LHV\ (T_1 = 25°C)} \quad (9)$$

In equation (9), LHV is fuel lower heating value at 25°C.

Finally; the fuel consumption to drive 100 km, is obtained from the following equation:

$$m_f = \frac{\dot{m}_f}{\bar{V}} * 10^5 \quad (10)$$

Calculation of Natural Gas Heating Value

For calculating the fuel consumption rate (equation (9)), it is necessary to know the natural gas heating value. To compute the natural gas heating value, the ISO 6976 standard has been employed in this study. This method is discussed in this section.

The lower heating value of a gas mixture on a mass basis at a temperature T is computed from the following equation[13]:

$$LHV = \frac{LHV_m(T_1)}{M_w} = \frac{\sum_{j=1}^{N} x_j LHV_{m,j}(T_1)}{\sum_{j=1}^{N} x_j M_{w,j}} \quad (11)$$

where, $LHV_m(T_1)$ is the molar lower heating value of the mixture at the temperature T_1 and M_w is the molar mass of mixture. x_j is the mole fraction of component j in the mixture, N is the number of the components in the mixture, $LHV_{m,j}(T_1)$ is the molar lower heating value of component j in the mixture and $M_{w,j}$ is the molar mass of component j in the mixture.

Calculation of the Charged Mass of Natural Gas Stored in the on-board NGV Cylinder

To determine the Driving Ranges, it is necessary to know the charged mass of natural gas stored in the on-board NGV cylinder after refueling. The charged mass is related to the gas density (ρ) and the volume of the cylinder (V). It can be calculated using the following relationship:

$$m = \rho V \quad (12)$$

The natural gas density is calculated at the thermodynamic conditions of the cylinder after refueling (base condition). Natural gas density is highly dependent on the thermodynamic conditions (temperature, pressure and the compositions). To calculate the density at the base condition, the AGA8 Equation of State [6] has been employed. The AGA8 equation of state is expressed as follows[9]:

$$P = Z \rho_m R T \quad (13)$$

In equation (13), P is pressure, Z is compressibility factor, ρ_m is molar density, R is universal gas constant and T is temperature. Based on the AGA8 model, the compression factor is calculated as follows:

$$Z = 1 + B \rho_m - \rho_r \sum_{n=13}^{18} C_n^{\ *} + \sum_{n=13}^{18} C_n^{\ *} D_n^{\ *} \quad (14)$$

Where, ρ_r is the reduced density and defined as follows:

$$\rho_r = K^3 \rho_m \quad (15)$$

K is the mixture size parameter and could be calculated as follows:

$$K^5 = \left(\sum_{i=1}^{N} x_i K_i^{\frac{5}{2}} \right)^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} x_i x_j (K_{ij}^{\ 5} - 1)(K_i K_j)^{\frac{5}{2}} \quad (16)$$

In equation (16), x_i is the mole fraction of component i in the mixture, x_j is mole fraction of component j in the mixture, K_i is the size parameter of component i, K_j is the size parameter of component j, K_{ij} is the binary interaction parameter for size and N is the number of component in the gas mixture.

In equation (14), B is the second virial coefficient and is given by the following equation:

$$B = \sum_{n=1}^{18} a_n T^{-u_n} \sum_{i=1}^{N} \sum_{j=1}^{N} x_i x_j B_{nij}^{\ *} E_{ij}^{\ u_n} (K_i K_j)^{\frac{3}{2}} \quad (17)$$

In equation (17), $B_{nij}^{\ *}$ and E_{ij} are defined by the following equations [6]:

$$B_{nij}^{\ *} = (G_{ij} + 1 - g_n)^{g_n} (Q_i Q_j + 1 - q_n)^{q_n} (F_i^{1/2} F_j^{1/2} + 1 - f_n)^{f_n} (S_i S_j + 1 - s_n)^{s_n} (W_i W_j + 1 - w_n)^{w_n} \quad (18)$$

$$E_{ij} = E_{ij}^{\ *} (E_i E_j)^{1/2} \quad (19)$$

In equation (18), G_{ij} is defined by the following equation[9]:

$$G_{ij} = \frac{G_{ij}^*(G_i + G_j)}{2} \quad (20)$$

In equations (17) to (20), T is the Temperature, N is the number of the component in the gas mixture, $a_n, f_n, g_n, q_n, s_n, u_n, w_n$ are the equations of state parameters, $E_i, F_i, G_i, K_i, Q_i, S_i, W_i$ are the corresponding characterization parameters and E_{ij}^*, G_{ij}^* are corresponding binary interaction parameters.

In equation (14), C_n^*; $n = 1,..., 58$ are the temperature dependent coefficients and defined by the following equation [9]:

$$C_n^* = a_n(G + 1 - g_n)^{g_n}(Q^2 + 1 - q_n)^{q_n}(F + 1 - f_n)^{f_n} U_n^{u_n} T^{-u_n} \quad (21)$$

In equation (21), G,F,Q,U are the mixture parameters and defined by the following equations[6]:

$$U^5 = \left(\sum_{i=1}^{N} x_i E_i^{\frac{5}{2}}\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j (U_{ij}^5 - 1)(E_i E_j)^{\frac{5}{2}} \quad (22)$$

$$G = \sum_{i=1}^{N} x_i G_i + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j (G_{ij}^* - 1)(G_i + G_j) \quad (23)$$

$$Q = \sum_{i=1}^{N} x_I Q_i \quad (24)$$

$$F = \sum_{i=1}^{N} x_i^2 F_i \quad (25)$$

where in equation (22), U_{ij} is the binary interaction parameter for the mixture energy.

In equation (14), D_n^* is defined by the following equation:

$$D_n^* = (b_n - c_n k_n \rho_r^{k_n})\rho_r^{b_n} \exp(-c_n \rho_r^{k_n}) \quad (26)$$

Coefficients of equation (2.14) are introduced in reference[9].

Substituting equation (2.14) in equation (13), the temperature, pressure and the composition of natural gas are known, and the only unknown parameter is the molar density. The molar density is calculated using Newton–Raphson iterative method[16].

The density of the natural gas is then calculated by the following equation:

$$\rho = M_w \rho_m \quad (27)$$

where, M_w is molecular weight of mixture and ρ_m is molar density.

Driving Range Calculation

By knowing the NGV on-board capacity (charged mass after refueling) and fuel consumption per 100 Km driving, it would be possible to calculate the Driving Range of the NGV by employing the following relationship:

$$DrivingRange = \frac{m}{m_f} * 100[km] \quad (28)$$

CALCULATION OF DRIVING RANGE AFTER EACH REFUELING (CASE STUDY)

In this section, the results which could be obtained from the proposed model for a typical NGV are given. It is not intended to study a specific case but rather to show the effects of various parameters on the Driving Range of the NGV. The variation in these parameters is discussed in this section, firstly.

The NGV assumed to have a gross weight of 1200 kg. By assuming an approximate weight of 75 kg for four passengers, the total mass of the vehicle is assumed to be around 1500 kg. The vehicle assumed to be equipped with an on-board CNG cylinder with volume of 70 liters. Table 1 shows the vehicle's characteristics, and the mechanical energy needed to drive 100 km for the vehicle[17].

The average efficiency of an internal combustion engine is about 18% to 20%. Here, the efficiency is assumed to be 0.18, 0.19 and 0.20 for the urban, extra urban and overall cases respectively, unless otherwise mentioned. The value for the other efficiencies/parameters which assumed in this study, are listed in Table 2. They are selected based on the fact that they can be easily obtained in actual components.

In a typical CNG filling station, natural gas provided from the distribution pipeline, usually 'low' pressure at 0.4MPa or possibly 'medium' pressure at 1.6MPa, is compressed using a large multi-stage compressor into a 'cascade' storage system. This system is maintained at a pressure higher than that in the vehicle's on-board storage so that gas flows to the vehicle under differential pressure. Typically, the cascade storage will operate in the range of 20.5MPa to 25MPa, while the vehicle's on-board in-cylinder pressure may vary between 15MPa to 25MPa. In this paper, the effect of the final in-cylinder pressure on the charged gas and Driving Range after each refueling, have been studied.

Final in-cylinder temperature is the other parameter which affects the charged mass and consequently, the Driving Range. Farzaneh-Gord[18] and Farzaneh-Gord et al.[19–20] studied the effect of ambient temperature on the in-cylinder temperature. They show that there would be a rise in the temperature (about 40 K) after charging an empty on-board cylinder. In this paper, the final in-cylinder temperature is assumed to be 40 K above the ambient temperature.

Table 2. Parameters used for calculating the average fuel power

Parameter	η_{gb}	$P_2[kW]$	$P_{0,gb}[kW]$	$v_0[\frac{m}{s}]$
Value	0.95	0.25	0.3	3

Table 1. The vehicle's Characteristics

Parameter	$m_v[kg]$	$A_f C_d [m]^2$	C_r	$E[\frac{MJ}{100km}]$
Value	1500	0.8	0.013	48

Table 3. Mole fraction of natural gas extracted from various region of Iran

Component	Mole Fraction [%]			
	Khangiran	Kangan	Pars	Bidboland
CH_4	98.6	90.04	87	85.01
C_2H_6	0.59	3.69	5.4	9.38
C_3H_8	0.09	0.93	1.7	3.49
$i\text{-}C_4H_{10}$	0.02	0.2	0.3	0.34
$n\text{-}C_4H_{10}$	0.04	0.29	0.45	0.65
$i\text{-}C_5H_{12}$	0.02	0.14	0.13	0.1
$n\text{-}C_5H_{12}$	0.02	0.08	0.11	0.09
$n\text{-}C_6H_{14}$	0.07	0.14	0.07	0.09
C_7^+	0	0.01	0.03	0
N_2	0.56	4.48	3.1	0.44
CO_2	0	0	1.85	0.41

Natural gas is a mixture of several gases with various properties, Therefore its thermodynamics properties are dependent on its components. To obtain the thermodynamics properties accurately, the effect of the gas compositions must be also considered. For this purpose, the AGA8 Equation of State has been employed. Table 3 shows the molar percent of four different compositions employed in this study. These gases are extracted from various regions within Iran[21].

RESULTS AND DISCUSSION

Figure 3 shows the effects of natural gas compositions on lowering the heating value of the mentioned gases at reference temperature and pressure (T_1=25°C, P_1=0.101325*MPa*). It could be noticed that there is 1.5% difference between the highest and lowest heating values. This is due to the fact that carbon dioxide and nitrogen in the gas mixture do not take part in the combustion and only take up space and thus reduce the energy release (such as Kangan and Pars gas fields).

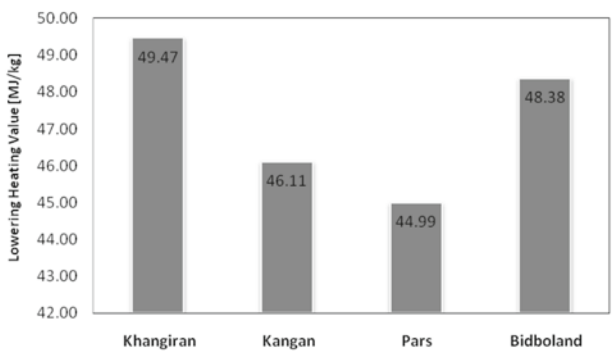

Figure 3. Lower heating value of natural gas from different regions of Iran (T_1=25°C, P_1=0.101325*MPA*)

Based on the discussed model, the vehicle's characteristics and the lowering heating value, fuel consumption to drive 100 km has been calculated. Figure 4 shows the fuel consumption in the overall case with average speed 35 km/h (9.72 m/s) for various natural gases. Figure 5 shows the fuel consumption in urban case with average speed 18.43 km/h (5.12 m/ s) and extra urban with average speed 65.3 km/ h (18.14 m/s). In all cases, Pars and Khangiran regions have the highest and lowest fuel consumption respectively. Of course, it could be

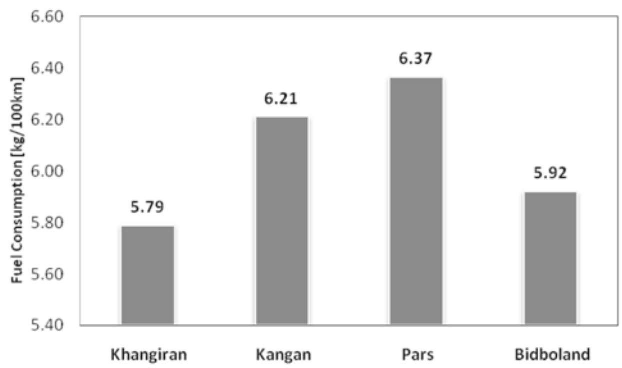

Figure 4. 4 Fuel consumption to drive 100 km (Overall case: average speed 35 km/h or 9.72 m/s)

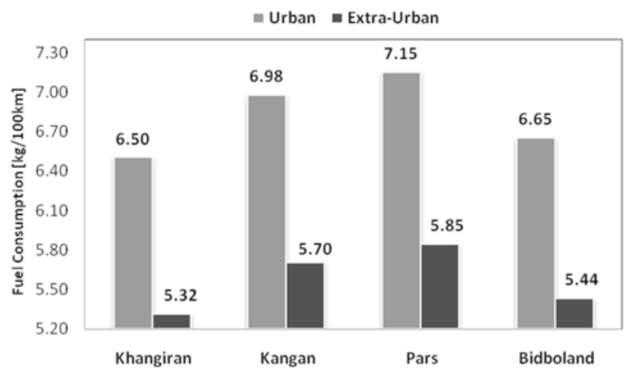

Figure 5. Fuel consumption to drive 100 km (Urban case: average speed 18.43km/h or 5.12m/s; Extra Urban case: average speed 65.3km/h or 18.14m/s)

concluded that the fuel consumption is least while the gases with highest heating value are consumed.

Assuming 340 K and 20MPa as the gas temperature and pressure of the gas within NGV on-board cylinder after the refueling process, the charged mass has been calculated for the cylinder with 70 liters volume using the AGA8 Equation of State. Figure 6 shows the charged mass for various natural gases. It could be realized that the Bidboland gas could be charged most. The difference between the lowest and highest charged mass is 20%, which is a significant value. This is mainly due to the higher compressibility factor (density) for the Bidboland gas comparing to the other gases. The compressibility factor increases as the percentage of heavier hydrocarbon in the mixture increases. For the studied gases,

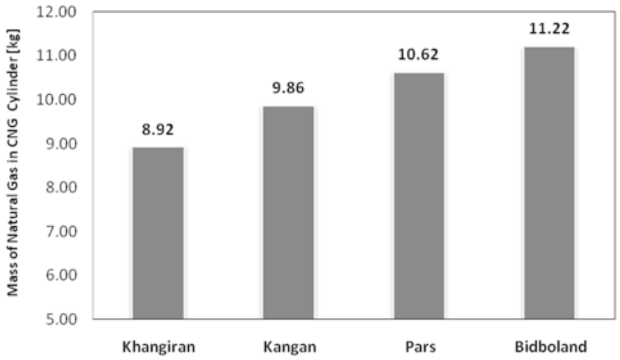

Figure 6. Mass of natural gas stored in CNG cylinder after refueling for different natural gas compositions (Final temperature: 340 K, final pressure: 20MPa, Volume: 70 L)

the Bidboland gas has the lowest Methane percentage (lightest hydrocarbon).

Considering the charged mass of natural gas (Fig. 6) and fuel consumption to drive 100 km (Fig. 4 and 5), one could easily calculate the Driving Range for the studied gases. Figure 7 shows the Driving Range in the overall case. Figure 8 shows the Driving Range in urban and Extra urban cases. According to Figure 7 and Figure 8, a NGV charged by the Bidoland and Khangiran gases could be derived the most and the least respectively. The difference between the highest and lowest value of the Driving Range for the urban case is about 31 km (23%), for the Extra urban case is about 39 km (23%) and for the overall case is about 36 km (23%), which is significant. So one could conclude that the natural gas compositions have strong effects on the Driving Range.

As previously discussed, Farzaneh-Gord et al.[19,20] showed that the ambient temperature has a significant influence on the final in-cylinder temperature. They

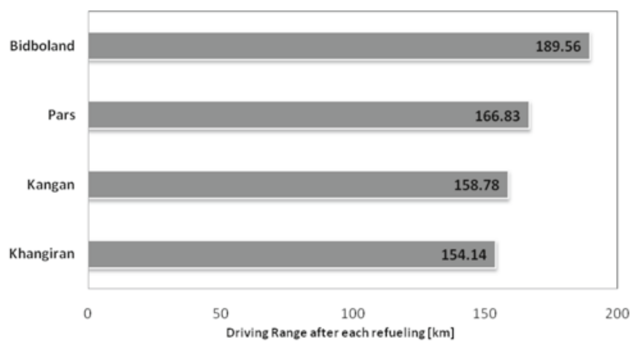

Figure 7. Driving Range after each refueling (Overall case: average speed 35km/h or 9.72m/s)

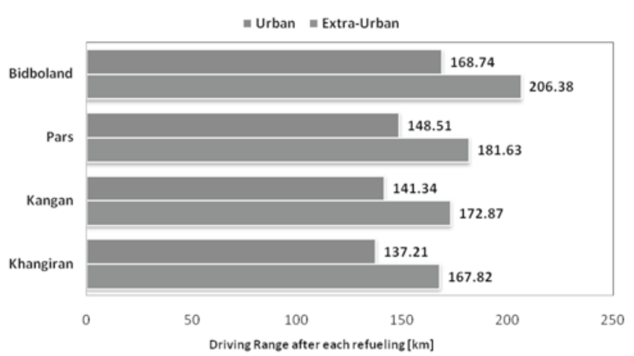

Figure 8. Driving Range after each refueling (Urban case: average speed 18.43km/h or 5.12m/s; Extra Urban case: average speed 65.3km/h or 18.14m/s)

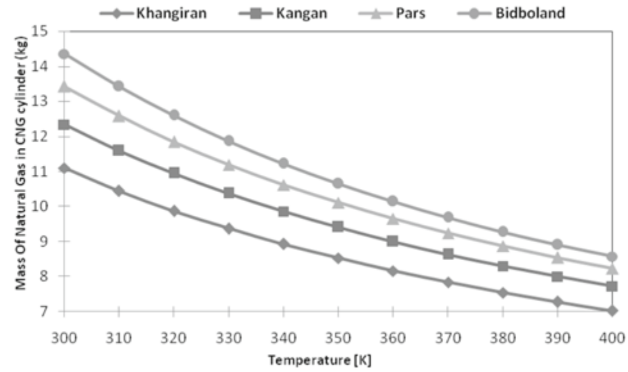

Figure 9. The effect of final in-cylinder temperature on mass of natural gas in CNG cylinder

showed that the final temperature about 40 K higher than the ambient temperature, so the effects of ambient temperature on the driving range could be represented by the final temperature. As the final temperature varies, the compression factor and the density of natural gas will be changed. Therefore, the charged mass and consequently, the Driving Range will be affected. Figure 9 shows the effect of the final temperature on the charged mass for the studied natural gases. In these cases, the final in-cylinder pressure set at 20MPa and volume of the cylinder is considered to be 70 liters. Figure 10 shows the effect of the final temperature on the Driving Range in overall case (average speed: 35Km/h or 9.72m/s). According to Figure 9, as the final temperature increases, the charged mass and consequently, the driving range decreases noticeably. By 1K change in the final temperature (or the ambient temperature) during refueling, the driving range changes 1.2 km. So it could be suggested that refueling should be carried out at the lower ambient temperature (e.g. nights rather than days).

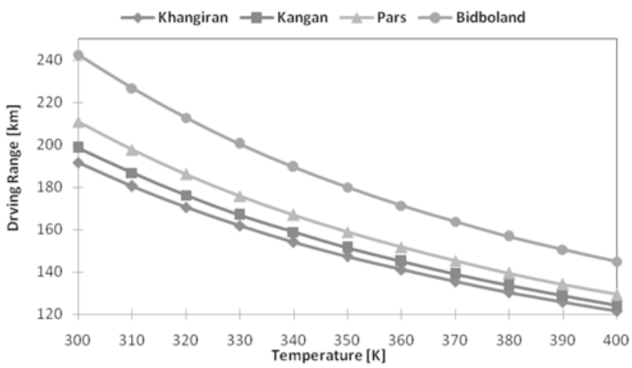

Figure 10. The effect of final in-cylinder temperature on Driving Range after refueling (Overall case: average speed 35km/h or 9.72m/s)

Natural gas final in-cylinder pressure could be assumed a little lower than the station reservoir pressure. In the general case, the station pressure is in the range of 15MPa to 25MPa. As the natural gas final pressure varies, the gas compression factor and density are subject to change. So as the reservoir pressure varies, the charged mass will also change. Figure 11 shows the effect of the final in-cylinder pressure on the charged mass for the studied natural gases. In these cases, the gas temperature set at 340 K and volume of the cylinder is assumed to be 70 liters. According to Figure 11, as the pressure increases from 15 to 25MPa, the charged mass increases between 4 to 6 kg. Figure 12 shows the effect of the final pressure on the Driving Range in the overall case and for the studied natural gases. According to Figure 12, as pressure increases about 10MPa, the Driving Range increases between 71 km to 86 km.

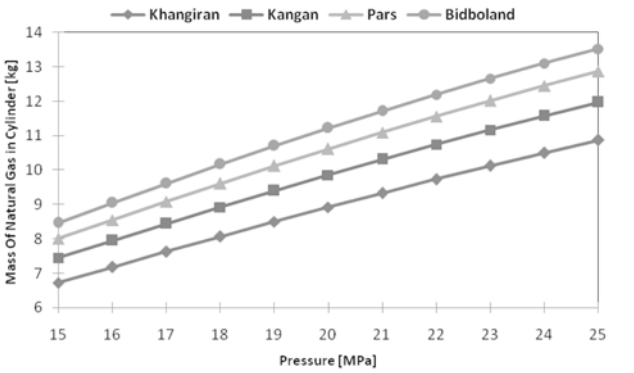

Figure 11. The effect of the final in-cylinder pressure on the charged mass (The overall case: average speed 35km/h or 9.72m/s)

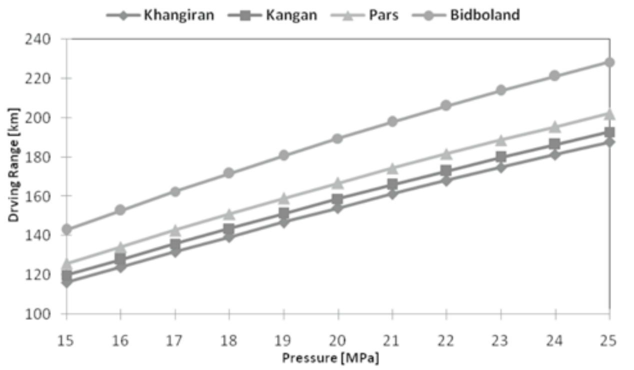

Figure 12. The effect of the final in-cylinder pressure on Driving Range (The overall case: average speed 35km/h or 9.72m/s)

The efficiency of the vehicle engine is the other important parameter which affects the fuel consumption and Driving Range of a NGV. So the effect of this parameter on the two quantities has been investigated. The Engine efficiency has been considered in the range of 0.14 to 0.25. Figure 13 shows the effects of Engine efficiency on fuel consumption for the overall case and for the studied gases. According to figure 13, by increasing the engine efficiency about 11%, the fuel consumption decreases between 3.4–3.7 kg/100 km. Figure 14 shows the effects of the engine efficiency on the Driving Range for the overall case. As shown in figure 14, by increasing the engine efficiency about 11%, the Driving Range will increase 89 km to 100 km.

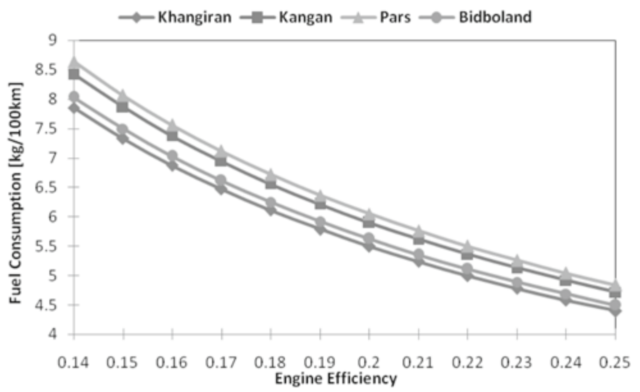

Figure 13. The effect of engine efficiency on fuel consumption (The overall case: average speed 35km/h or 9.72 m/s)

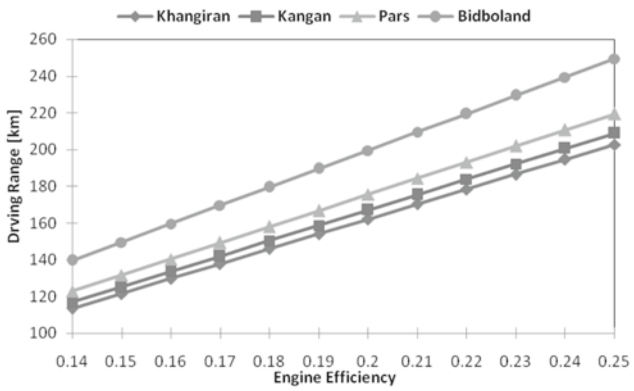

Figure 14. The effect of engine efficiency on Driving Range after each refueling (The overall case: average speed 35km/h or 9.72 m/s)

CONCLUSIONS

In this study, the effects of the most important parameters on the NGVs Driving Range after each refueling have been investigated. These parameters are the final on-board NGV in-cylinder temperature and pressure, the gas composition and the vehicle engine efficiency. The AGA8 state equation has been employed to study the effects of the thermodynamics properties on the charged mass and consequently the Driving range.

To calculate the amount of energy consumed by the vehicle during a desired distance, the MVEG-95 test cycle is considered to be applicable. For studying the effect natural gas compositions on the amount of energy release by the gas, the ISO 6979 standard was employed.

The results show that the gas composition has a small effect on the energy release during the combustion process. The gas compositions in the other hand, has a strong influence on the gas density and consequently, the charged mass. The charged mass then affects the Driving Range significantly. Briefly, a NGV which fuelled by the natural gas with higher density, is able to travel more after refueling.

The other two parameters which affect the charged mass and consequently, the Driving Range, are the final in-cylinder temperature and pressure. The final temperature is directly depended on the ambient temperature. As the temperature increases, the charged mass and the driving range is reduced strongly. For a typical passenger car, each 1 K rise in the ambient temperature during refueling resulted into 1.2 km reduction in the driving range. The final in-cylinder pressure is affected by the fuelling station reservoir pressure directly. As the pressure increases, the Driving Range increases too. For the studied vehicle, each 10MPa growth in the pressure, resulted into 71 km to 86 km rise in the driving range.

As expected, the vehicle engine efficiency has an effect on the fuel consumption and consequently the driving range. For the studied NGV, by increasing the engine efficiency about 11%, the Driving Range will increase 89 km to 100 km.

Acknowledgments

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NOMENCLATURE

A_f – Vehicle's frontal area, m^2
C_d – Aerodynamic drag coefficient
C_r – Tire rolling friction coefficient
E – Mechanical energy, MJ/100 km
F_{trac} – Mean traction force, kN
LHV_m – Lower heating value on molar basis, kJ/kmol
LHV – Lower heating value on mass basis, MJ/kg
m – Mass of Natural gas, kg
$\dot{m}_f$ – Fuel mass flow rate, kg/s
m_f – Fuel consumption to drive 100 km, kg
m_v – Vehicle's mass, kg
M_w – Molar mass, kg/kmol
P_f – Average fuel power, kW
P_{trac} – Average traction power, kW
P_e – Average power, kW
V – Volume of CNG cylinder, m^3
$\bar{V}$ – Average vehicle's speed ,m/s or km/h
Z – Compression Factor

Subscript

d – drag
e – engine
f – fuel
gb – gear box
m – molar basis
trac – tractions
v – vehicle

Greek Letters

ρ – Natural gas density, kg/m^3
η_e – Vehicle engine overall efficiency
η_{gb} – Gear box efficiency

Abbreviations

CNG – Compressed Natural Gas
NGVs – Natural Gas Vehicles

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