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Well-to-wheel Energy Consumption and CO_2 Emission Comparison of Electric and Fossil Fuel Buses: Tehran Case Study

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ABSTRACT

The development of public transportation is considered a vital issue in reducing traffic as well as urban pollution. City buses play an important role in the city transportation system. In Iran, due to the high average age of city buses, it is necessary to replace the old buses with new ones, To replace the old buses, diesel and CNG, hybrid, and electric buses are proposed as the main alternatives. Global warming and the energy crisis are now considered as two potential serious threats for the world. Therefore, energy consumption and CO_2 emissions are examined as two outstanding criteria for comparing candidate buses in this paper. To make an accurate comparison, the amount of energy consumption and CO_2 emissions have been calculated based on the well-to-wheel approach. The electric bus well-to-wheel analysis has been done for both electricity generation mix and renewable generation. To perform more accurate calculations and simulations, as a case study, a real driving cycle has been constructed for Tehran. For this approach, a modified micro trip method as a novel solution is presented to synthesize the driving cycle. The results show that due to the high share of fossil power plants (about 92%) in Iran, the use of electric buses in the bus fleet may not have much effect on reducing energy and CO_2 eq emissions. By using renewable power plants, the amount of well-to-wheel energy consumption and CO_2 emissions decrease significantly (about 56% and 93%, respectively) compared to that for the generation mix.

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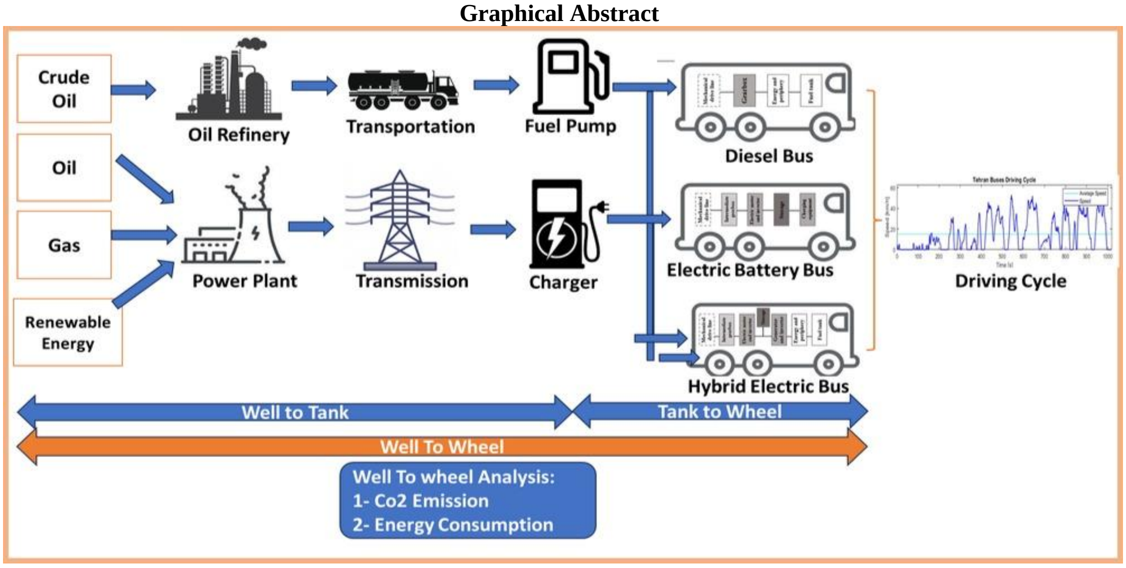
Graphical Abstract



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1. INTRODUCTION

Nowadays, transportation and urban traffic are highly significant challenges for large industrialized cities. The lack of proper development of urban transportation systems may be the cause of many problems in various fields, such as environmental, social, economic, health, and even politics. One of the best solutions to deal with the issue is to develop and strengthen urban public transportation. City buses can play a crucial role in the urban transportation system. Enhancement of city bus fleets can lead to a reduction in the traffic of private cars and decrement in air pollution at a low cost (1, 2).

Furthermore, global warming and the energy crisis are now considered two potential serious threats for the world. Hence, reducing energy consumption and greenhouse gases have become two important requirements while developing the transportation fleet in recent years. The increase in greenhouse gases causes severe crises such as global temperature rise, ocean water level rise, and climate change (3). The importance of this issue has led to the implementation of different international agreements to reduce greenhouse gases and prevent climate change (4, 5).

Regarding energy consumption, a reduction in the transportation sector may be considerable. According to the International Energy Agency, the share of energy consumption in the transportation sector of the total energy consumption is 21% (6).

Tehran is a highly populated city in the world with a population of approximately 12 million, is a good candidate for the evaluation and implementation of fleets for city buses with alternative fuel systems. In the bus fleet of Tehran, which is considered as the case study in this paper, there are about 6000 active city buses. Among these buses, about 3500 are diesel powered, and about 2500 use CNG (7).The average life of Tehran's bus fleet is more than 15 years. Therefore, necessary actions should be taken to purchase new buses and renew the fleet.

Because the replacement of new buses involves a huge investment, the development of the bus fleet should be done with proper consideration. According to the powertrain type, hybrid electric bus (HEB), battery electric bus (BEB), diesel bus, and CNG bus are the most common ones in terms of market share (8-10). A schematic of each bus topology is shown in Figure 1. In this paper, these kinds of buses are considered the best candidate alternatives for replacing conventional old ones.

Different criteria, such as total cost of ownership (TCO) (11-14), local pollution (15, 16), CO_2 emission (17-19) and energy consumption (16, 18, 20) may be considered to select the appropriate powertrain type. Regarding the major mentioned challenges, i.e., emissions and energy usage, in this paper, suitable powertrain architecture for the Tehran bus fleet have been investigated from the two perspectives of reducing CO_2 pollution and energy consumption.

Generally, due to the much higher efficiency of the electric motor compared to the internal combustion engine (ICE), BEB has lower tank-to-wheel (TTW) energy consumption than the other types. Furthermore, the amount of BEB CO_2 emission is zero. However, a well-to-wheel (WTW) approach may reveal the energy consumption and emission release of the whole cycle of power generation, transmission, and usage in the vehicle. This analysis evaluates the benefits of increasing the share of renewable and clean power sources in a country. Electricity generation in fossil fuel power plants consumes energy and emits CO_2. Therefore, to have an accurate study, the amount of energy consumption and CO_2 emission should be computed from the source of energy production to the tailpipe of the bus, which is known as the WTW study. In other words, although the TTW CO_2 emission of BEB is zero, its well-to-tank (WTT) emission is not zero and should be investigated for countries, case by case, based on the source of electric energy.

WTW analysis for vehicles in the literature may be conducted using standard driving cycles (9, 21) or real driving data (22-25). A WTW study for heavy-duty vehicles, where different e-fuels are used for the power generation section, is done (17). The WTT emissions of the e-fuel pathways are calculated using an in-house tool. However, a specific driving cycle is not used for data extraction and simulation. A data-driven approach is used to provide a WTW study for vehicle fleet renovation in Roma, where real traffic data is used (20). The study is carried out for private vehicles and city buses. It is concluded that partial electrification may lead to significant CO_2 reduction. However, as it is stated by the authors, the portion of renewable energy sources is about one-third of total electric power generation in Italy, which is a far different case from that in Iran. Another comparative study for Roma has been conducted between five vehicles with different powertrain types, including ICE, hybrid electric, and battery electric, in terms of WTW energy consumption and CO_2 emission (26). Two driving cycles, i.e., NEDC and WLTC, are considered for the tests, and the results were compared with a real driving cycle test in Roma. It is shown in this paper that the results of real tests may deviate significantly from those of the two mentioned driving cycles for some types of powertrains. Using real-life operational data provided by a waste management company in Berlin, an economical investigation is also performed for diesel-powered and electric waste collections vehicles through calculation of WTW emission costs (27).

In most of the previous works, the standard driving cycles of several specific cities, such as New York (NY) City Bus, Millbrook Westminster London bus (London city), and Braunschweig City (Germany), have been used in the simulations (9). However, to perform a proper simulation and accurate prediction, a driving cycle similar to the driving behavior of the area under study should be used. In order to obtain more accurate results, a suitable driving cycle for the city buses of Tehran has been modeled in this paper.

In Iran, about 92% of electrical energy is generated by fossil fuel power plants (28). Therefore, electric power production is associated with the emission of a significant amount of carbon dioxide and energy loss.

In order to calculate the energy consumption and the amount of bus emissions, a simulation tool could be used. For this purpose, different simulator packages, which are mainly MATLAB-based tools, such as ADVISOR (advanced vehicle simulator) (29), PSAT (PNGV System Analysis Toolkit) (30) and QSS toolbox (31), have been developed. The simulator performs computations based on a specific driving cycle, which expresses the vehicle's speed over time. Also, the ADVISOR tool, along with MATLAB software, is used for simulation study.

In this paper, in section 2, the driving cycle modeling method is described. In section 3, the WTW energy consumption of different types of powertrains has been investigated case by case. In section 4, the WTW analysis of CO_2 equivalent emission has been done. In both sections 3 and 4, For BEB, Studies have been done for both mix and renewable energy electricity generation. Finally, the results have been discussed and concluded in section 5.

2. DRIVING CYCLE MODEL

Generally, the driving cycle expresses the driving behavior based on a time-speed profile. A precise driving cycle could be used to determine different vehicle parameters, such as sizing components, predicting fuel consumption, emissions, and optimizing the control strategy (32-34). Depending on urban traffic, city size, geographical characteristics, number of highways, and arterial or local routes, the driving cycle of each city is different from other cities (35-37). Therefore, by using the real driving cycle of a city, it is possible to choose the most suitable type of city bus based on the desired criteria, such as the amount of energy consumption and air pollution.

Different methods have been presented in the literature to synthesize a standard driving cycle. These methods could be classified into four categories: Micro trip based, Segment based, Pattern classification, and Markov chain method (32, 35, 37-40).

A micro trip is defined as the path traveled by the vehicle between two starting points (41). In the micro trip-based method, the micro trips of the collected data are extracted, and then according to the average speed and the percentage of stopping time of each micro trip, the data are divided into different groups. Then, the

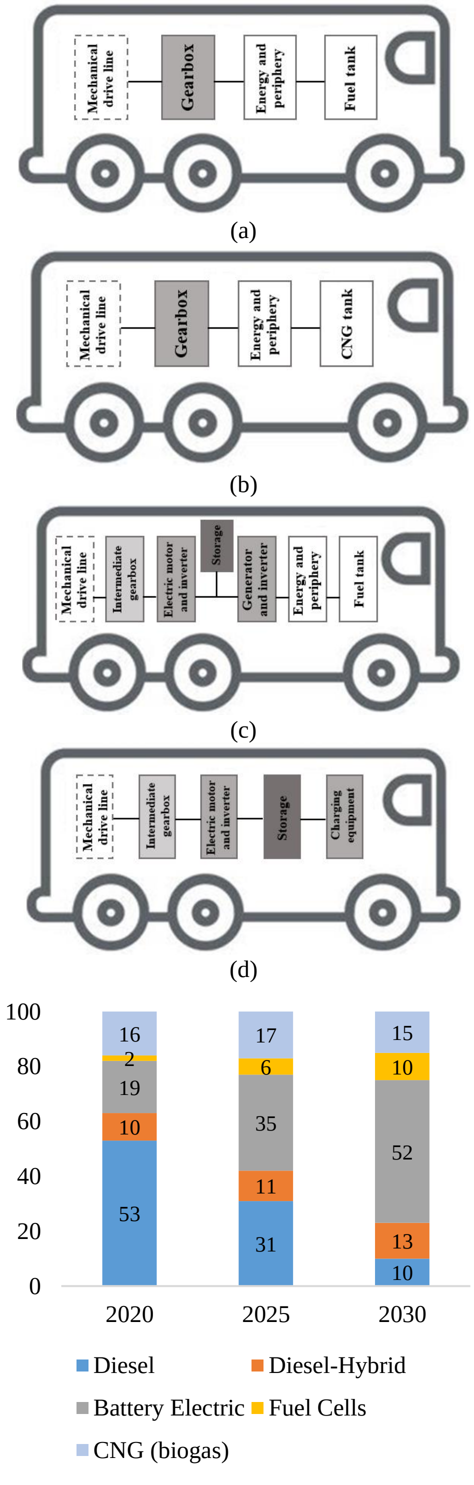

Figure 1. Deposition Different architecture of city busses: a) conventional diesel, b) CNG, c) hybrid electric bus (HEB), d) battery electric bus (BEB) e) market share prediction [10]

driving cycle is made by putting the micro trips together in such a way that the target parameters (population parameters) such as average speed, maximum speed, minimum speed, percentage of stopping time, and any other information according to the purpose of the study are met (41-44). Micro trips are extracted regardless of the conditions of the driving route or Level of Service (LOS) (41, 42). In the modified micro trips-based methods, with the help of micro trip classification algorithms, micro trips are divided into different categories, each of which represents a specific type of driving route or LOS. After categorizing, some micro trips are selected from each category according to the participation percentage. (43, 44). In this way, a driving cycle is obtained by putting the micro trips together.

As mentioned before, in the basic micro trips-based method, the collected data are divided into smaller groups only according to the stops on the route. Therefore, there is no information about the type of route and LOS that the vehicle traveled through. In the segment based method, the accumulative data is divided according to the type of LOS to create a driving cycle. For this purpose, the participation percentage of each LOS in different divisions is used (39, 45).The drawback of the cycle created with this method is that it only looks at the driving cycle from the perspective of the type of route and LOS provided by it. This perspective is not suitable for creating a driving cycle for pollution measurement, because the amount of vehicle pollution depends on parameters such as the percentage of time stopping and average speed (46).

In the pattern classification method, different "kinematic sequences" are used to build a driving cycle. The kinematic sequence is similar to micro-travel, with the difference that many variables are used to define it. For example, in the kinematic sequences used to build a European urban cycle, 20 variables are used, including trip duration, percentage of stop time, trip length, instantaneous speed, effective acceleration of each sequence, standard deviation, maximum speed, etc. (47). Each of these movement sequences is divided into different classes with the help of statistical methods such as principal component analysis (PCA) (48). To construct the driving cycle, these kinematic sequences are put together in a manner that is logical and justifiable in terms of time and statistics. For example, the cycle should start from the inner-city class, and to enter the suburban class, it should enter the arterial class (44). The advantage of this method is that it could obtain the driving pattern with high accuracy and be a real representative of the driving behavior in different areas. However, in this method, a large amount of data is needed to extract the kinematic sequence and categorize the routes, which is time-consuming (35).

In the Markov chain method, every driving pattern in the real world is divided into different modes, such as increasing speed (positive acceleration), decreasing speed (negative acceleration), cruising (uniform speed) and stopping mode (37, 46, 49). In addition to the average speed and the percentage of stopping time, the amount of vehicle emissions and fuel consumption is also dependent on the change of driving mode (50). As a result, for the two scenarios with the same average speed and percentage of stopping time but with different change of modes, the amount of fuel consumption and emissions are different. Therefore, making a cycle by considering the changes in driving mode has been added to the appropriate methods for making a driving cycle. Because the probability of the event of a driving mode in driving depends only on the previous state, the Markov chain method is used to build the driving cycle in this method.

In this paper, a modified micro trip method is used to stablish the driving cycle. The percentage of stopping time and average speed are considered the two significant parameters to construct the driving cycle. The reason for choosing these two criteria is that most of the pollution produced by the buses depends on these two parameters (36). In the proposed method, first, data related to the micro trips have been collected for nine main routes in Tehran. Then, as shown in Figure 2, the data of each route is sorted based on the two parameters of stopping time and average speed. In the following, the data of all routes are cumulated together, as shown in Figure 3. About 500 micro trips have been sampled in this study. To apply the impact of the type of driving route and LOS, the aggregated data of the micro trips are divided into three categories, each of which represents congested, arterial, and highway routes, respectively. The highway routes have the highest average speed and the lowest stopping time. The congested routes are the routes that have the lowest average speed and the highest stopping time, and the arterial routes have a feature between these two

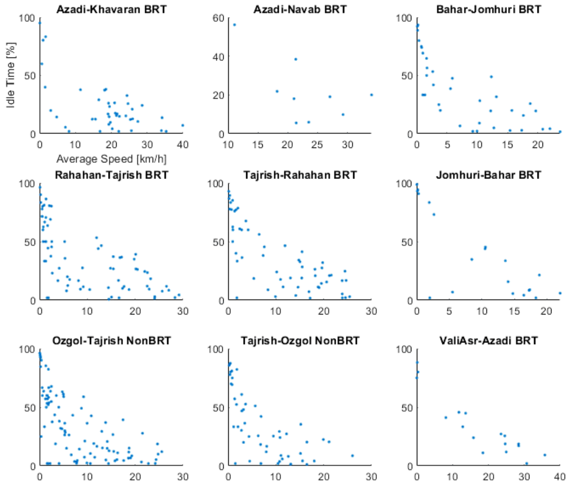

Figure 2. The micro trips characteristics of each route based on stop time and average speed

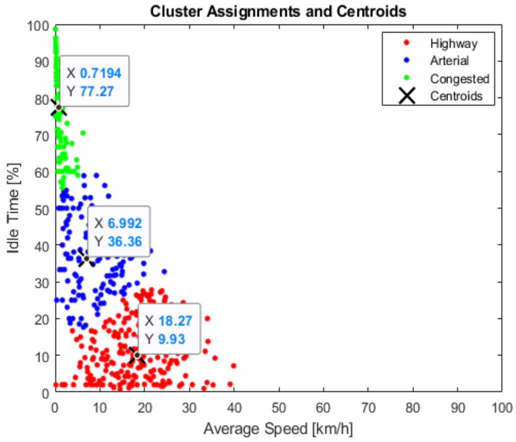

Figure 3. Clustering of the accumulative data using the K-means method

routes. To cluster the data, the k-means method is used in this study. To establish a driving cycle, according to the number of micro trips and their time percentage, some micro trips from each category are randomly selected and placed together. If the average speed and percentage of stopping time and effective acceleration of the constructed cycle have a significant error with those of the cumulative data, the constructed cycle cannot represent the cumulative data. But if this error is small, the constructed cycle is a suitable candidate for expressing the traffic behavior of cumulative data. Figure 4 shows the constructed driving cycle for Tehran. In the following sections, the synthesized driving cycle has been used in simulations to predict the amount of energy consumption and CO_2 emissions of the buses under study.

3. WTW ENERGY CONSUMPTION

In order to have an accurate study and a fair comparison, the energy consumption of each type of bus should be analyzed from WTW. Thus, the amount of energy consumption should be calculated over the entire energy flow process, from the energy source to the tailpipe of the bus . WTW analysis is divided into two parts: WTT and TTW. In fossil fuel buses, WTT analysis is used to calculate the energy consumption in the processes of extracting, refining, and transferring fuel to the bus. While in an electric bus, the purpose of WTT analysis is to estimate the amount of energy consumed in the processes of electricity generation, transmission, and bus charging at charging stations. Also, in the TTW analysis, the fuel consumption of the bus (fossil or electric) is estimated while driving in the considered route.

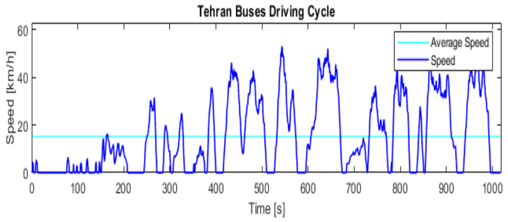

Figure 4. Constructed driving cycle for Tehran city bus

3. 1. TTW Analysis

While a bus is moving, the tractive force must overcome the resistance forces that prevent the vehicle movement. Rolling, aerodynamic, and grading are the resistance forces that act on a bus moving up a grade. Therefore, as shown in Figure 5, in according to Newton's second law, the force balance of the moving bus can be written as:

$$F_t = F_r + F_W + F_g + F_a \quad (1)$$

where F_t represent the tractive force, F_r is the rolling resistance of the tires, F_W is the aerodynamic drag, F_g is the grading resistance and Fa is the accelerating force of the bus. Rolling resistance is the force that resists the forward motion of tires. The main reason for the rolling resistance is the hysteresis of the tire material. But other parameters such as the adhesion between road and tires, the gravity and weight of the vehicle affect it. Rolling resistance is calculated as:

$$F_r = Mgf_r \cos\alpha \quad (2)$$

where M is the mass of the bus, g is the gravity, and α is the angle of the ground incline. In addition, fr is the coefficient of rolling resistance, which is a function of the type of road and tire, tire inflation pressure, tire temperature, and some other parameters.

Aerodynamic drag force refers to the air resistance that a bus faces while moving. This force is expressed as:

$$F_W = \frac{1}{2}\rho A_f C_D V^2 \quad (3)$$

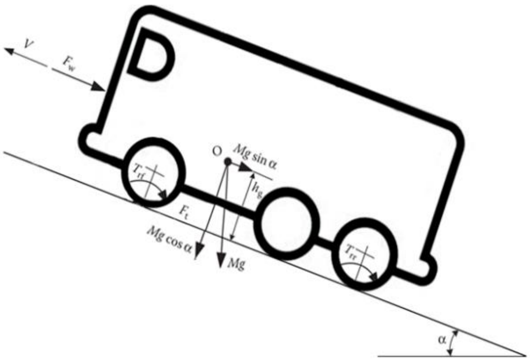

Figure 5. Forces acting on a bus moving up a grade

where V is the bus speed, A_f is frontal area of the bus, ρ is air density, and C_D is the aerodynamic drag coefficient, which is a function of shape and skin friction of the bus.

Grading resistance force opposes the forward motion of the bus during grade climbing, which is calculated as:

$$F_r = Mg\sin\alpha \tag{4}$$

Finally, F_a represents the force required to accelerate or decelerate the bus, which can be expressed as:

$$F_a = \delta M \frac{dv}{dt} \tag{5}$$

where δ is the mass factor that equivalently converts the rotational inertias of rotating components into translational mass.

By using Equation 1, the amount of required power and thus energy consumption of the vehicle could be calculated. It should be noted that the efficiency of powertrain components must be included in the calculations for each operating point.

In this paper ADVISOR software is used to compute the energy consumption. In this software, Equations 1 to 5 are used to model the bus required power. The extracted Tehran city bus driving cycle is considered as the reference in this paper. The specifications of the simulated buses are given in Table 1.

Table 2 shows the computed fuel consumption along with the equivalent energy consumption of each type of bus through simulation. It can be seen that the fuel consumption of the diesel and the CNG buses are higher than the two other types due to the use of low-efficiency ICE. Also, in the case of HEB, because of using the auxiliary electric motor, less energy is consumed than in the ones of diesel and CNG buses. Finally, as expected, in the BEB, energy consumption is much lower than in other types due to the use of the high-efficiency electric motor in the powertrain.

TABLE 1. The characteristics of the simulated buses (29)

Charactristics	BEB	Diesel	CNG	HEB
Frontal Area	7.9 m^2	7.9 m^2	7.9 m^2	7.9 m^2
Weight without passenger	11,945 kg	15,597 kg	11,945 kg	15,597 kg
Length	12.2 m	12.2 m	12.2 m	12.2 m
Wheel radius	500 mm	500 mm	500 mm	500 mm
Aerodynamic coefficient	0.79	0.79	0.79	0.79
Air density	1.23	1.23	1.23	1.23
Rolling resistance	0.008	0.008	0.008	0.008
Gravity	9.81 m/s^2	9.81 m/s^2	9.81 m/s^2	9.81 m/s^2
Transmission system efficiency	93%	92%	92%	92%
Maximum power	200 kW	205 kW	209 kW	209 kW
Auxiliary loads	3.5 kW	7.5 kW	3.5 kW	7.5 kW
Battery Capacity	300 kWh	-	-	30 kWh
Battery weight	3,000 kg	-	-	30 kg

TABLE 2. The fuel consumption and the equivalent energy consumption of the simulated buses

Bus Type	Fuel Consumption	Equivalent energy consumption per Km
Diesel[1]	0.59 (L/km)	21.1 MJ
CNG[2]	0.6 (kg/km)	30 MJ
HEB	0.48 (L/km)	17.2 MJ
BEB[3]	1.99 (kWh/km)	7.1 MJ

[1] The energy per liter of diesel is equal to 35.9 MJ (51).

[2] The energy per kilogram of CNG is equivalent to 50 MJ (52).

[3] 1 kWh=3.6 MJ

3. 2. WTT Analysis

In order to WTT analyze of the diesel and the HEB, the energy loss of diesel production and refining processes and the loss of fuel transportation to fueling stations are considered 10% and 2%, respectively (53). For the CNG bus, the energy loss for the extraction, transmission and compression of natural gas, for a gas transmission system with a length of 1000 km is considered 13% (53).

For the case of the BEB, the TTW efficiency is dependent on the power generation method. Based on the data published by the Ministry of Energy of Iran, about 92% of electricity is generated by fossil fuels in Iran (28). The share of different sources in the overall electricity generation in Iran is shown in Figure 6. As shown in the figure, the contribution of electricity generation by combined cycle, steam, gas, Hydroelectric, nuclear, and renewable power plants are 45.9%, 24.8%, 20.9%, 6.4%, and 0.4%, respectively. In addition to the share of each type of power plant, their average efficiency is listed in Table 3 (28). The generation mix efficiency could be calculated according to the portion and the efficiency of the power plants. As shown in Table 3, the efficiency of mixed electricity generation in Iran is about 43.9%. It is clear that the reason for the low mix generation efficiency is the low contribution of renewable sources to the overall electricity mix in Iran.

According to ministry of energy report, the electricity transmission and distribution losses in Iran are 2.8% and 9.5%, respectively (28). Therefore, considering the loss of 6% of the charger, the losses of transmission and charging is 13.2%.

3. 3. WTW Analysis

By including WTT and TTW components the WTW energy consumption of the buses can be computed as:

$$WTW_e\left[\frac{MJ}{km}\right]=WTT_e\left[\frac{MJ}{km}\right]+TTW_e\left[\frac{MJ}{km}\right] \tag{6}$$

where WTT energy consumption, WTTe, can be obtained as:

$$WTT_e\left[\frac{MJ}{km}\right]=TTW_e\left[\frac{MJ}{km}\right].WTT_{loss}\left[\%\right] \tag{7}$$

and WTT_{loss} is the total WTT loss.

The WTT, TTW, and WTW energy consumption of each type of city bus is shown in Table 3. The results are also depicted in Figure 6. It can be seen that the WTW energy consumption of the CNG and diesel buses are higher than the other two types due to the higher TTW energy consumption. However, despite the much lower TTW energy consumption in BEB, the amount of the WTW energy consumption is not substantially different from that in the other buses, especially the diesel and HEB. The reason is that the efficiency of generation mix in Iran is low due to the large share of fossil fuel power plants.

Alternatively, it is supposed that instead of fossil fuel, renewable energies are used to supply electricity. Therefore, as seen in Table 4 and Figure 7, the WTT energy consumption and as a result, the WTW energy consumption are significantly reduced. In this case, the WTW energy consumption of the electric bus reduces by 56% and provides a significant advantage over the other types of buses.

TABLE 3. The average efficiency of difference power plant (28)

Type of Power Plant	Share of Generation	Average Efficiency
Combined Cycle	45.9%	46.1%
Steam	24.8%	37.1%
Gas	20.9%	29.7%
Hydroelectric	6.4%	100%
Nuclear	1.6%	33%
Renewable	0.4%	100%
Generation mix efficiency	43.9%	

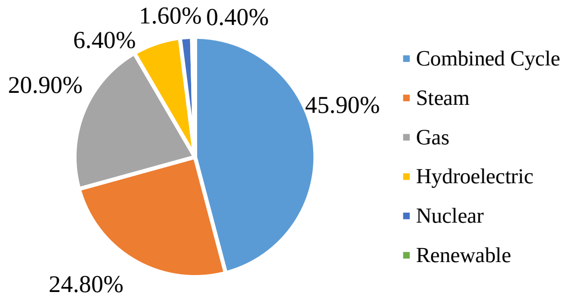

Figure 6. Share of electricity generation of various power plants

TABLE 4. The WTT, TTW, and WWT energy consumption of different buses.

Bus Type	TTW (MJ/km)	WTT (MJ/km)	WTW (MJ/km)
Diesel	21.1	2.8	23.9
CNG	30	4.5	34.5
HEB	17.2	2.3	19.5
BEB With Generation Mix	7.1	11.5	18.6
BEB with Renewable Sources	7.1	1.1	18.6

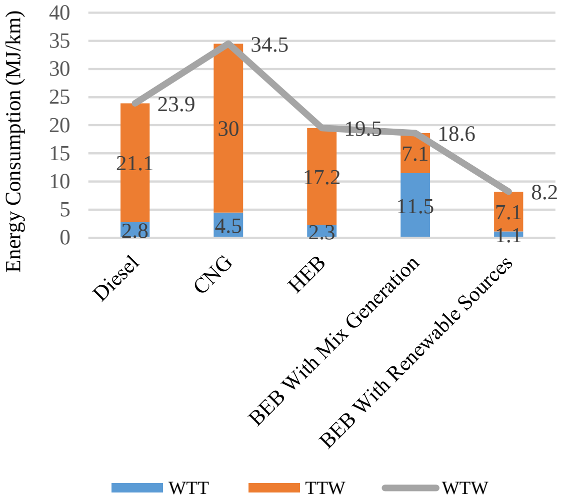

Figure 7. WTT, TTW, and WWT energy consumption of buses

4. WTW CO_2 EMISSION

To analyze the emission of CO_2 for each type of powertrain, in addition to the emission of each bus during operation, the amount of CO_2 emission in the production process of the energy source (diesel, natural gas, or electricity) should be considered. Therefore, similar to the energy consumption calculations, for an accurate comparison, the CO_2 emission should be studied from the production process of the energy source to the bus tailpipe.

As in the previous section, carbon dioxide gas emission calculations should be performed in two stages: 1) WTT, i.e., production and extraction of energy source, and 2) TTW, i.e., during bus operation.

4. 1. WTT Analysis The energy source of the electric bus is the electricity produced in the power plants. Therefore, to study CO_2 emissions during the electricity production process, it is necessary to investigate the electricity production methods in each country. Countries that use more renewable energy in electricity production will have lower CO_2 emissions. The share of power plants in Iran's electricity production, along with the amount of greenhouse gas emissions in each of them, are listed in Table 5 (28).

To consider the effects of various types of greenhouse gases on climate change and their different atmospheric lifetimes, the Intergovernmental Panel on Climate Change (IPCC) has presented the "Global Warming Potential" (GWP) index. According to this index, as stated in Table 6, every greenhouse gas is converted into CO_2 equivalent (54). For example, as listed in the table, the effect of one kilogram of N_2O is equivalent to 298 kilograms of CO_2. In this case, the total of greenhouse gases is considered as a CO_2 equivalent (CO_2 eq).

By using Table 6, the amount of CO_2 eq emission of each type of power plant has been calculated and reported in Table 6. Considering the share of each power plant in electricity production and its CO_2 eq, the amount of CO_2 eq emission of the generation mix is calculated. As shown in Table 6, the CO_2 eq generation mix equals 600 grams. This means that about 600 grams of CO_2 eq is produced per kWh of electricity generation in Iran.

To calculate the WTT emission of the diesel and CNG buses, the CO_2 eq emission from the processes of fuel extraction, refining, and transportation should be considered. Here, taking into account the GREET model (55), the amount of WTT CO_2 emission for diesel and CNG fuel are 19 (g CO_2 eq /MJ) and 25 (g CO_2 eq /MJ), respectively.

4. 2. TTW Analysis The amount of CO_2 eq emission of each bus after traveling the reference driving cycle is shown in Table 7. As expected, the CO_2 eq emission for the CNG and diesel buses is higher than that for the other two types. Also, due to the use of clean electric energy in the BEB, the CO_2 eq emission of this type of bus is zero.

4. 3. WTW Analysis Using the WTT and TTW of CO_2 eq emissions, the amount of WTW CO_2 eq emissions is calculated as:

$$WTW_{CO_2}[\frac{g\,CO_2\,eq}{MJ}] = WTT_{CO_2}[\frac{g\,CO_2\,eq}{MJ}] + TTW_{CO_2}[\frac{g\,CO_2\,eq}{MJ}] \qquad (8)$$

Besides, the WTT CO_2 eq emission, WTT CO_2, is obtained as:

$$WTT_{CO_2}[\frac{g\,CO_2\,eq}{MJ}] = TTW_{CO_2}[\frac{g\,CO_2\,eq}{MJ}].WTT_{Loss}[\%] \qquad (9)$$

where WTT_{loss} is the WTT loss.

The calculated values of WTT, TTW, and WTW of the CO_2 eq emission are shown in Table 8 and depicted in Figure 8. As can be seen, despite the zero emissions of the BEB, the WTW of the CO_2 eq emissions is close to that of fossil fuel buses due to the significant contribution of electricity generation from fossil power plants in Iran. However, as stated in Table 8 and Figure 8, if renewable power plants are used instead, the amount of TTW and

TABLE 5. The WTT, TTW, and WWT energy consumption of different buses (28)

Type of Power Plant	CH_4	N_2O	CO_2	CO_2 eq (g/kWh)	Share of Generation (%)	Share of CO_2 eq Emission (g/kwh)
Combined Cycle	0.012	0.002	540.076	540.972	45.9%	243.43
Steam	0.018	0.003	723.798	725.142	24.8%	179.83
Gas	0.017	0.002	837.844	838.865	20.9%	175.32
Hydroelectric	-	-	-	8.22	6.4%	0.52
Nuclear	-	-	-	12.23	1.6%	0.19
CO_2 eq						600

TABLE 6. CO_2 eq for each type of greenhouse gas (54)

Greenhouse Gas	CO_2 eq
1 kg CO_2	1 kg eq CO_2
1 kg CH_4	25 kg eq CO_2
1 kg N_2O	298 kg eq CO_2
1 kg CF_4	7,390 kg eq CO_2
1 kg C_2F_6	12,200 kg eq CO_2

TABLE 7. The Amount of CO_2 eq Emission of the Simulated Buses.

Bus Type	CO_2 eq Emission (g CO_2 eq/km)
Diesel	1,005
CNG	1,092
HEB	784
BEB	0

TABLE 8. The WTT, TTW, and WWT CO_2 eq emission of The Buses

Bus Type	**WTT (g CO_2 eq/km)**	**TTW (g CO_2 eq/km)**	**WTW (g CO_2 eq/km)**
Diesel	466	1,005	1,471
CNG	579	1,092	1,671
HEB	375	784	1,159
BEB With Generation Mix	1,367	0	1,367
BEB with Renewable Sources	95	0	95

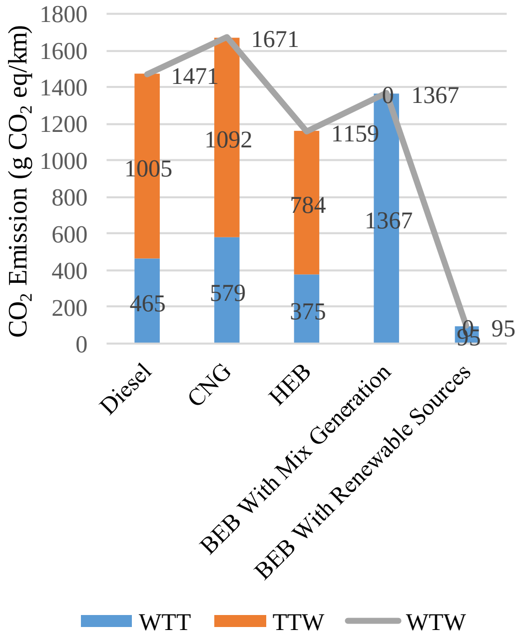

Figure 8. WTT, TTW, WWT CO_2 eq Emission of the Buses

WTW of CO_2 emissions significantly decreased (about 92%) compared to that for the generation mix. In this case, a large difference in CO_2 eq emissions between the BEB and the other types can be observed.

5. CONCLUSION

In this paper, a comparison was made between four types of city buses, including diesel, CNG, hybrid, and electric, to find the best choice for contributing to Tehran, Iran, bus fleet renovation. Energy consumption and CO_2 emissions were considered as two criteria for comparing candidate buses. In order to perform more accurate simulations and calculations, a real driving cycle was derived for Tehran using the micro-trip method. In this method, micro trips were extracted regardless of the driving route conditions and the Level of Service (LOS). Therefore, in the first stage, to apply the impact of the type of driving route and LOS, the accumulated data of the micro trips were divided into three categories, each of which represents congested, arterial, and highway routes, respectively. Then, the k-means method was used to cluster the data.

The energy consumption of the candidate buses was compared. The energy consumption of each type of bus was computed from well-to-wheel (WTW) to have a fair comparison. The WTW analysis was divided into two parts: WTT and TTW. For the fossil fuel buses, WTT analysis was used to calculate the energy consumption in the processes of extracting, refining, and transferring fuel. While for the electric bus, in the WTT analysis, the amount of energy consumed in the processes of electricity generation, transmission, and bus charging at charging stations was estimated. To estimate the WTT energy consumption of the electric bus, the generation mix efficiency was calculated according to the portion and the efficiency of the power plants of Iran. Accordingly, the results show that there is no significant difference between the WTW energy consumption of electric buses and that in the other buses. In addition, according to the results, it can be concluded that if renewable power plants are used, the energy consumption of electric buses reduces by 56% compared to the generation mix.

The WTW CO_2 eq emission comparison was also conducted. The results state that despite the zero pollution of the electric bus, the WTW CO_2 eq emission is not much different from its values for the other bus types due to the major contribution of electricity generation from fossil power plants in Iran. Alternatively, by using renewable power plants, the amount of WTW CO_2 eq emission decreases significantly (about 93%) compared to that for the generation mix.

As a result, considering the high share of fossil power plants (about 92%) in Iran, the use of electric buses in the bus fleet may not have much effect on reducing energy and CO_2 eq emissions. Therefore, to enjoy the advantages of electric buses in Iran, the share of renewable energy production should be increased.

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Persian Abstract

چکیده

توسعه حمل و نقل عمومی به عنوان یک راه‌حل حیاتی برای کاهش چالش ترافیک و همچنین آلودگی شهری محسوب می‌شود. اتوبوس‌های شهری نقش مهمی در سیستم حمل ونقل شهری دارند. در ایران با توجه به بالا بودن میانگین سن اتوبوس‌های شهری، جایگزینی آن‌ها با اتوبوس‌های جدید ضروری است. بدین منظور اتوبوسهای دیزلی مدرن، CNG هیبریدی و برقی به عنوان راهکاری جایگزین پیشنهاد شده‌اند. گرمایش جهانی و بحران انرژی به عنوان دو تهدید بالقوه جدی برای جهان در نظر گرفته می‌شود. بنابراین مصرف انرژی و انتشار گازهای گلخانه‌ای (CO_2) به عنوان دو معیار برجسته برای مقایسه اتوبوس های پیشنهادی در این مقاله بررسی می‌شوند. به منظور مقایسه دقیق، میزان مصرف انرژی و انتشار CO_2 براساس رویکرد چاه تا چرخ محاسبه شده است. تجزیه و تحلیل چاه تا چرخ اتوبوس الکتریکی هم برای تولید برق بصورت ترکیبی از انواع نیروگاه‌ها و هم برای نیروگاه های تجدیدپذیر انجام گرفته است. در این مقاله برای انجام محاسبات و شبیه‌سازی ها دقیق تر، به عنوان مطالعه موردی، چرخه رانندگی واقعی برای شهر مدل شده است. برای این هدف، یک روش مبتنی بر روش ریز–سفر اصلاح شده به عنوان یک راه حل جدید برای ساخت چرخه رانندگی ارائه شده است.