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Designing the technical specifications of the propulsion system suitable for electric bus of Tehran and selecting the pilot route

Iman Sadeghi*, mohamadreza nikzad, armaghan aliaskari
Niroo Research Institute, NRI, Tehran, Iran

****Corresponding author, Email: Isadeghi@nri.ac.ir, Mrnikzad@nri.ac.ir***

Abstract

This paper contains an investigation about using electric buses alternatively in a BRT line in Tehran. In order to reach this purpose driving cycle of electric bus for different bus routes are simulated and studied. Also with the aim to choose the pilot route, several criteria such as, air and noise pollutions, terafic characteristics, numbers of passengers on each route have been considered. Hence, Azadi terminal to Tehran-Pars intersection route has been selected. In addition, characteristics and specifications of proposed propulsion and energy storage system based on driving cycle simulation results of different routes in Tehran are determined.

***Keyword**:* Electric buses, Driving cycle, Propulsion system

1. Introduction

Over the course of recent years, most developed countries have used electric propulsion as an alternative in their bus fleets. Among these buses, the old trolley buses can be mentioned, that have been actived in the public transportation lines of some countries, including Iran. Selecting the proper propulsion for city buses has taken a different progression, as the efforts to prevent global warming and concerns about air pollution and its harms have been increased and the technology of and transportation agencies to meet emissions standards to lead them to produce and use new propulsion as much as possible.

battery, electric motors and their driving forces have been developed, simultaneously.

Gradually, by decrease in battery prices and the achived advancement of Technology, the use of all-electric buses has expanded day by day. Many countries such as china, erupean contries, united states of America, south Africa, latin American countries, endeavored to test all-electric buses on their transportation lines. Over time, countries have enacted laws for manufactures

Now its time to examine and investigate of using battery electric buses in Iran. Hence, this goal has been reached by simulating battery electric bus in one line of bus fleet in Tehran, in this research. In general, active buses in the Tehran public transport have operation in two sections: Bus Rapid Transit (BRT) and ordinary transport service (including the private and public sectors). According to the latest statistics published by the Bus Organization, the number of ordinary bus lines in Tehran in the daily public sector is 66 lines, in the overnight public sector is equal to 7 lines, in the daily private sector is 166 lines and in the overnight private sector is equal to103 lines. Moreover, according to these statistics, there are 10 BRT lines in Tehran[1]. Regarding to the technical specifications and advantages of electric buses, many criteria can be considered in pilot route selection. The most important of these criteria are air pollution and noise pollution of the route, traffic characteristics of the route (such as number of stations, length of the route, number of stops, route traffic), number of daily passengers, type of route (local, arterial and highway) , the required technical specifications of the used bus (electric motor power, battery capacity) as well as the capacity of infrastructure charging stations on the route.

Air pollution is known as one of the most significant issues affecting people's health. In accordance with the World Health Organization (WHO) reports, more than two million premature deaths occur worldwide each year due to urban air pollution [2]. In Iran, air pollution is one of the most dangerous environmental factors in terms of health that causes diseases such as asthma, lung cancer, ventricular hypertrophy, Alzheimer's, Parkinson's, autism and stroke. In addition to causing illness, according to the WHO, more than 4,000 people die each year in Tehran due to air pollution [3]. Therefore, one of the criteria for selecting a pilot route will be the amount of pollution in the desired route, which if a more polluted route is selected, can play a greater role in reducing air pollution in Tehran by replacing diesel buses with electric buses.

Regarding to WHO reports, after air and water pollution, noise pollution is the third most dangerous pollution in the world. The sound volume is expressed between 0 dB (hearing threshold) to 130 dB (deaf threshold). Noise pollution in various dimensions endangers human health and in the long run has many different [1]. in urban areas, especially in areas with high noise pollution, buses can significantly increase the amount of noise pollution. In [2-4], the rate of noise pollution in different types of urban buses has been compared. These comparisons were made for 12-meter buses traveling at a speed of 20 (km/h) and at a distance of 7.5 meters. The noise level of diesel and CNG buses is about 77 dB and 70 dB, respectively, which is much higher than other types of buses, and the noise level of electric buses is 63 dB and 60 dB, respectively, for the trolley and electric type (overnight and direct charge). It is worth noting that the dB scale is logarithmic and the reduction of 10 dB is equivalent to a 50% reduction in noise. Therefore, the use of electric buses can significantly reduce noise pollution.

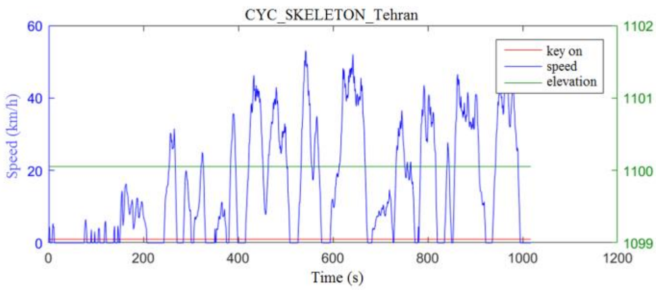
For this purpose, the driving cycle of bus lines in Tehran has been simulated for two types of electric and diesel buses. Also, the final route was selected based on important factors such as importance, number of passengers and traffic characteristics, air pollution and noise pollution, and finally propulsion system and energy storage system for an electric bus has been desinged, based on the results of driving cycle simulations in Tehran bus lines.

2. Bus lines of Tehran simulations

In this section, the driving cycles of electric bus in different routes in Tehran such as Tajrish-Rah Ahan Terminal (BRT) , Imam Hossein Square-Enghelab Square (BRT, round trip), Jomhory Square-Baharestan Square (normal bus-single cabin, round trip), Tajrish-Azgol Square (normal bus - single cabin, round trip),Azadi terminal-Khavaraan terminal, Azadi-Nawab terminal (BRT bus with two cabins), Valiasr crossroads - Azadi terminal (BRT bus with two cabins), Bryank Navab - Azadi terminal, Besat terminal - Imam Hussein Square (ordinary single-cabin bus) and finally the extracted route by Niroo Research Institute (NRI) are simulated. Appendix A provides technical comparisons between battery electric and diesel type buses.

The route extracted by NRI will be discussed, in the following as an example to explain these simulations. Figure 1 shows the driving cycle graph and bar diagram based on percentages for this route.

Table 1 also indicates specifications of this simulation.



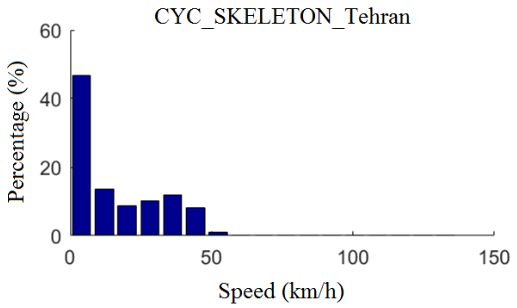


Figure 1. driving cycle skeleton of extracted route in Tehran by NRI

Table 1. Specification of simulated driving cycle of extracted route in Tehran by NRI

specitications	amount	specitications	amount
Time (s)	1017	Avg decal (m/s^2)	-0.7
Distance (km)	4.3	Idle time (s)	344
Max speed (km/h)	53.08	No. of stops	26
Avg speed (km/h)	15.2	Max up grade	0%
Max accel (m/s^2)	2.56	Avg up grade	0%
Max decal (m/s^2)	-2.5	Max dn grade	0%
Avg accel (m/s^2)	0.64	Avg dn grade	0%

Figure 2 and Table 2 show the characteristics of consuming power from the electric motor as well as the charge state during the driving cycle and the amount of energy consumption or production in different parts of the bus, respectively.

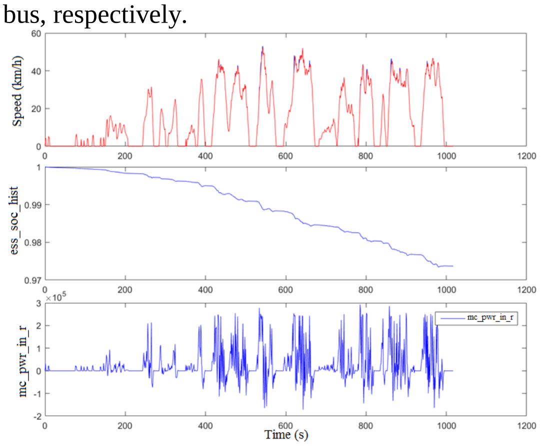


Figure 2. Characteristics of the consuming power from the electric motor and the charge state during the driving cycle extracted by NRI

Table 2. The amount of energy consumption or production in different parts of the bus

	Power mode				Regen mode			
	in	out	loss	Eff.	In	Out	Loss	Eff.
Energy storage	4962	64188	968	0.96	-	-	-	-
Energy stored	-60193	-	-	-	-	-	-	-
Motor/Controller	57015	47980	9036	0.84	7622	5890	1732	0.77
Gearbox	47980	46060	1919	0.96	7939	7622	318	0.96
Final Drive	46060	46060	0	1	7939	7939	0	1
Wheel/Axel	46060	45035	1025	0.98	16667	16478	189	0.99
Braking	-	-	-	-	-	-	8539	-
Aux Loads	8100	0	8100	0	-	-	-	-
Aero	-	-	1283	-	-	-	-	-
Rolling	-	-	10850	-	-	-	-	-

According to the simulations, the energy consumption is 1.99 kWh / km and the maximum power and rated power required for the electric motor are 293 and 163 kW. Table 3 show the results of simulations performed for battery electric and diesel buses in the driving cycles of different routes in Tehran.

Table 3. simulation results for battery electric and diesel buses for different routes in Tehran

No.	Line main name	Line name	Battery electric bus					Diesel bus	
			Energy consumption (each route) (kWh/km)	Avg energy consumption (round trip) (kWh/km)	Max power of motor (kW)	Nominal power of motor (kW)	Nominal power of motor (round trip) (kW)	Fuel consumption (each route)	Avg fuel consumption (round trip)
1	Tajrish-Rah ahan Terminal	Tajrish-Rah ahan	3.17	1.885	294	163	163.3	84.4	62.6

	(round trip)	Rah ahan-Tajrish	0.6		258	143.3		40.9	
2	Imam Hossein Square-Enghelab Square (round trip)	Square Enghelab Square - Imam Hossein	1.98	1.79	290	161	161	59.4	54.7
		Imam Hossein Square-Enghelab Square	1.6		278	154		50	
3	Jomhory Square-Baharestan Square (round trip)	Jomhory Square-Baharestan Square	1.65	1.87	274	152	160	60.7	66.1
		Baharestan Square-Jomhory Square	2.09		288	160		71.5	
4	Tajrish-Azgol Square (round trip)	Tajrish-Azgol Square	1.45	1.69	280	152	160	55.2	61.5
		Azgol Square-Tajrish	1.92		291	160		67.9	
5	Azadi terminal-Khavaraan terminal	Azadi terminal-Khavaraan terminal	1.54	-	288	160	–	48.8	-
6	Azadi-Nawab terminal	Azadi-Nawab terminal	1.78	-	287	160	–	53.7	-
7	Valiasr crossroads - Azadi terminal	Valiasr crossroads - Azadi terminal	1.75	-	292	162	–	54.1	-
8	Bryank Nawab - Azadi terminal	Bryank Nawab - Azadi terminal	1.88	-	293	163	–	51.4	-
9	Besat terminal - Imam Hussein Square	Besat terminal - Imam Hussein Square	2.38	-	264	147	–	76	-
10	Route by NRI	Route by NRI	1.99	-	293	163	–	65.8	-

As shown in Table 3, an electric motor with a nominal power of 165 kw will meet the tensile strength required of the electric bus under test on the routes; Therefore, considering a power margin of about 10%, the rated power of the electric motor is 180 kw. Also, according to the simulation functions shown in this table, the instantaneous power of the motor will be considered equal to 300 kw.

3. Pilot route selection

According to the studies based on the mentioned criteria and due to the importance of BRT lines and the high number of passengers on these lines, the line no.1 of Tehran BRT among 10 BRT lines, which includes the route from Azadi terminal to Tehran-Pars intersection, was selected as a pilot route. In the following, the reasons for choosing this route will be discussed.

A. Importance of the route, number of daily passengers and traffic characteristics of the route

Line no.1 connects the west (Azadi terminal) to the east (Tehran-Pars) of Tehran and passes through disrticts 2,6,7,8,9,10,11 and 13. Furthermore, part of this line passes through the crowded central areas and the traffic plan area of Tehran, which shows the importance of the route well. In Appendix B, the performance of Tehran BRT system – 2014 is shown [1].

As can be seen, among the BRT lines, Line no.1 has the highest number of annual passenger traffic. Also, after line no.7, this line has the highest number of buses. This also highlights the importance of this line. Therefore, line no.1 of BRT of Tehran can be considered as one of the most important routes in terms of communication route, urban traffic and number of passengers.

B. Air pollution criteria

The transportation system generates about 70% of Tehran's particulate pollutants alone, which among the various vehicles of the transportation sector, public transport buses and the private sector produce 24% and 30% of total pollution, respectively. Considering the main contribution of PM pollutants in the annual death rate in Tehran, this issue can be very important.

The pollution rate of the selected route will be investigated based on the annual statistics of Tehran Air Quality Control Company. Based on the location of active air pollution monitoring stations in Tehran, the BRT line no. 1 passes through the location of these stations such as Sharif University, municipality of district 10, municipality of district 11, Tarbiat Modares University, Setad bohran, Pirozi and Golbarg; Hence the level of pollution of line no.1 is measured by these stations [4]. In the following, line no.1 air pollution based on various pollutants is discussed.

i. $PM_{2.5}$ pollutants

Based on investigation in [4], Stations located on line no.1 are among the most polluted stations in terms of average annual concentrations of particulate matter less than 2.5 microns. Also, the level of pollution in all these stations is higher than the annual standard of Iran (12 $\mu g / m^3$). In addition, this investigation shows that In the areas where line no.1 crossing, especially Sharif, Piroozi and Tarbiat Modares stations, there is an unfavorable situation in point of view of the polluted days number (in terms of $PM_{2.5}$ pollutants) during the year.

ii. PM_{10} pollutants

As it can be seen in [4], monitoring stations located in the path of line no.1 are in an unpleasant position in terms of the average annual concentration of particulate matter less than 10 microns. It is noteworthy that, the highest concentration occurred in the stations located in the southwest of Tehran, which are mostly affected by dust-carrying currents.

iii.Ozone pollutants

According to literacture [١], the stations located on the route of line no.1 are among the most polluted stations in terms of average annual concentration of ozone (O_3) pollutants. Moreover, the regions of line no.1, especially Tarbiat-Modares and Setade Bohran stations, have the highest number of polluting days during the year in terms of ozone pollutants.

C. Noise pollution criteria

The permissible limit of noise pollution in the open air and even indoors is defined for certain periods of time of day as an equivalent level. Measuring or calculating the equivalent level of sound pressure has particular importance for those periods, as it will be comparable to the permissible limits. Different countries have adopted different time periods or base the equivalent balance for computations. In Iran, according to the resolution of the Supreme Environment Council (2002), only two time periods of 7 am to 10 pm for daytime and 10 pm to 7 am as night level have been approved. The permissible limits of noise pollution are also determined accordingly [4].

In order to measure the amount of noise pollution in Tehran, different stations have been placed in different regions of the city. In [4], The average sound level in the two time periods of day and night for different areas has been investigated. This study demonsterated that the districts of line No. 1, especially districts 2, 6, 10 and 12 are among the most polluted districts of Tehran in terms of noise pollution during the day and night. Therefore, choosing this line as a pilot route can also be important in terms of reducing noise pollution.

4. powertrain design

It is necessary to determine and select the characteristic of the bus propulsion system, before determining the torque-speed characteristic of the electric motor. Figure 3 shows one of the conventional structures of electric buses that the electric motor is connected to the bus shaft through the transmission system [11].

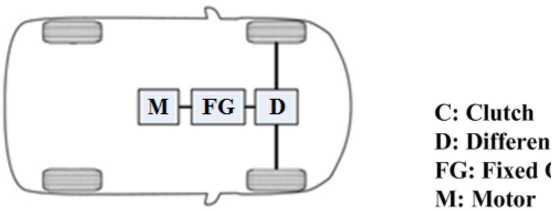


Figure 3. one of the conventional structures of electric buses.

The transmission system can either have a fixed or variable gear ratio as shown in Figure 4. If the transmission is used with a fixed gear ratio, the propulsion system will be simpler, but the design of the motor will be relatively more complex, which can be attributed to the need to provide more torque by the motor at low speeds. On the other hand, due to the increased performance of the motor in the flux weakening zone, the overall efficiency of the motor will be lower. However, in a variable gear ratio, despite the greater complexity of the propulsion system, the motor design will be simpler and its performance will be higher.

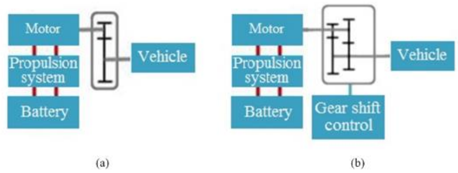


Figure 4. Scheme of transmission system a) with one gear ratio and b) with variable gear ratio (here two gears)

In the following, the electric motor characteristic will be extracted for two modes of transmission system with fixed gear ratio and two-speed variable gear ratio.

4.1.Characteristic of electric motor with two-speed variable gear ratio

The specifications of the BE35 electric bus transmission system, manufactured by Proterra USA shown in Appendix C-figure.a are used in this section. This bus uses a transmission system with two-speed variable gear ratio, model EEV-7202, produced by Eaton (Appendix C- figure. b).

In this transmission system, the gear ratios at low and high speeds are 3.53 and 1, respectively. Also, the conversion ratio of the rest of the propulsion system or Final Drive Ratio (FDR) is considered to be 9.8.

Taking into account the above transmission system and also considering the operational characteristics of the bus including maximum speed, gradient and acceleration after performing the relevant calculations, the characteristic of the electric motor was extracted and listed in Table 4.

Table 4. Characteristic of the electric motor when using a two-speed variable transmission system

characteristic	amount
Maximum instantaneous power	300 kW
Nominal power	180 kW
Maximum instantaneous torque	1000 N.m
Maximum continuous torque	550 N.m

Maximum motor speed	6000 RPM
Motor voltage	600 V

In Figure 5, the torque-speed characteristic of the two-speed transmission system designed is demonsetrated. The amount of propulsive force supplied to the wheels by the electromotor for different speeds in each gear is shown in Fiqure 6. Figure 7 shows the amount of force required to move the vehicle at zero grade (flat surface) at different speeds. As shown in the figure7, depending on the force of the bus, the maximum speed of the bus will be about 108 km/h.

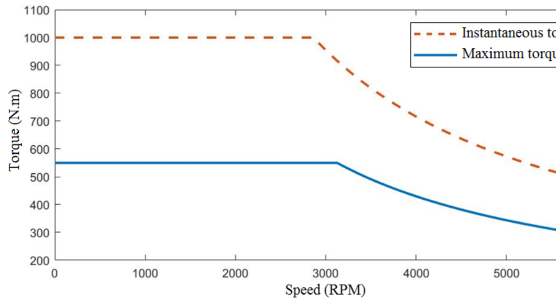


Figure 5. torque-speed characterstic of two-speed transmission system

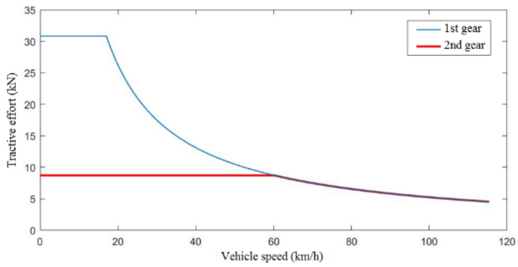


Figure 6. The provided tractive effort diagram by the electric motor of two-speed transmission system.

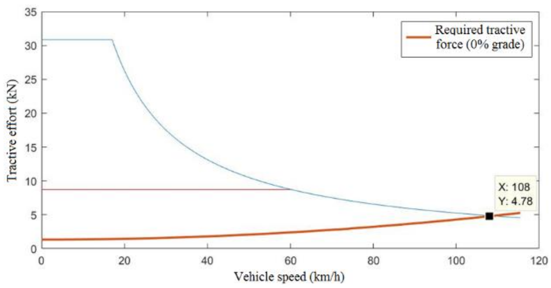


Figure 7. Tractive effort- speed characteristic at zero grade for two-speed transmission system

In order to evaluate the ability of climbing different grades, Figure 8 shows the amount of tractive force required to climb grades. Table 5 also shows the maximum speed of the vehicle on different slopes.

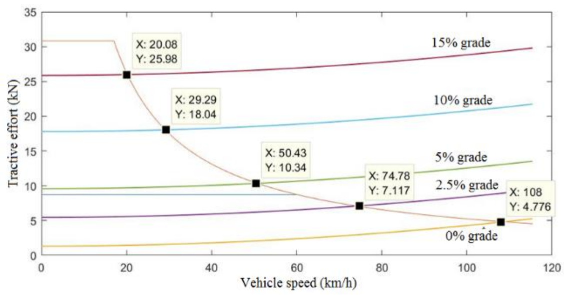


Figure 8. force-speed characteristic of vehicle on different grades

Table 5.maximum speed of vehicle on different grades

Speed (km/h)	grade(%)
108	0
74	2.5
50	5
30	10
20	15

Finally, the graph in Figure 9 is shown to indicate the acceleration of the bus. This graph shows the acceleration time from zero to higher speeds in seconds. Also, the information on the bus acceleration time from zero speed are given in Table 6.

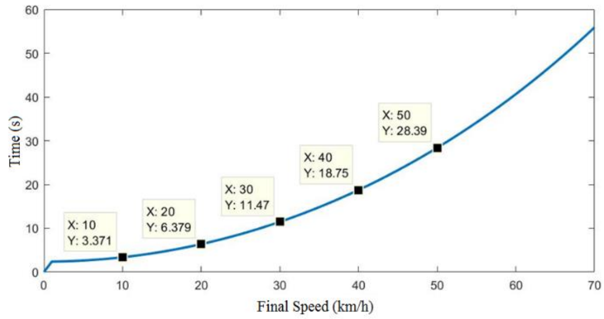


Figure 9. Bus acceleration characteristic

Table 6. Acceleration time of the bus from zero speed

Time (s)	Final speed (km/h)
3.4	10
6.3	20
11.4	30
18.7	40
28.39	50

4.2.Characteristic of electric motor with fixed gear ratio

In this section, the specifications of the propulsion system are calculated based on the transmission system with a fixed ratio. Considering the bus with specifications (Appendix A) and also FDR = 9.8 (similar to two-speed transmission system), the gear ratio of the transmission system is calculated to be 1.83 and also the specifications of the electric motor for

Satisfying the requested functions are given in the Table 7.

Table 7. Characteristic of the electric motor with fixed ratio transmission system

characteristic	amount
Maximum instantaneous power	300 kW
Nominal power	180 kW
Maximum instantaneous torque	1600 N.m
Maximum continuous torque	1000 N.m
Maximum motor speed	11000 RPM
Motor voltage	600 V or higher basede on standard

The torque-speed characteristic of the required electromotor with specifications listed in Table 7, is shown in Figure 10. Figure 11 shows the amount of propulsive force that can be supplied by the electromotor to the wheels, as well as the amount of force required to move the vehicle at zero grade and at different speeds. As shown in Figure 11, depending on the force of the bus, the maximum speed of the bus is about 108 km/h. Force-speed characteristic of vehicle on different grades is shown in Figure 12 and also Table 8 contains the maximum speed of the vehicle on different slopes.

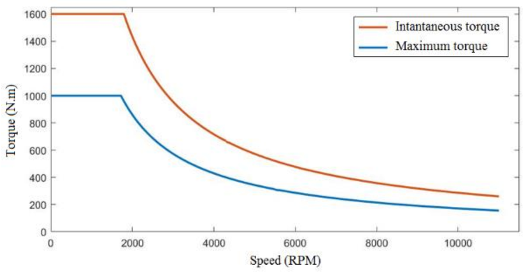


Figure 10. torque-speed characteristic of the required electric motor with fixed gear ratio

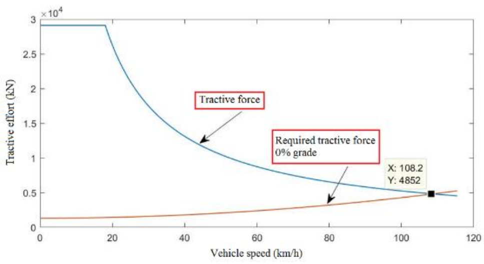


Figure 11. Graph of the amount of tractive effort supplied by the electric motor to move the wheels and the amount of tractive effort required to move the vehicle at zero slope at different speeds with a fixed ratio transmission system

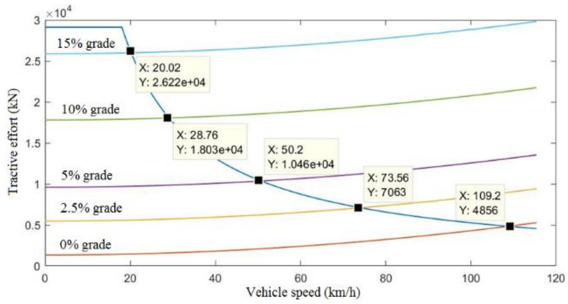
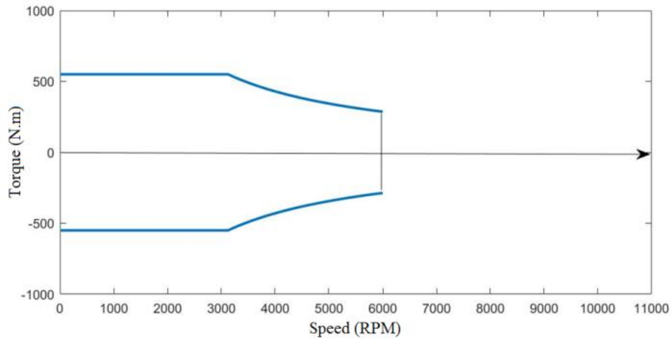


Figure 12. Tractive effort-speed characteristic of vehicle on different grades

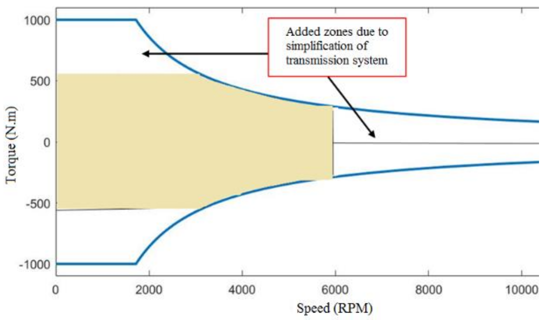
Table 8. the maximum speed of vehicle in different slopes

speed (km/h)	grade(%)
108	0
74	2.5
50	5
30	10
20	15

Figure 13 shows the torque-speed characteristics of two motors designed using a two-speed and one-speed transmission system in generator and motor operating modes. As can be well seen in Figure 13-b, by simplifying the transmission system and using a single-speed system, the torque-speed zone of the electromotor is wider than that of a two-speed transmission system; Therefore, the design and construction of electromotors will be more complex. On the other hand, as shown in Figure 13-b, the flux weakening zone in the motor with a fixed gear ratio is higher, which due to the low efficiency of PMSMs in this zone, the losses of the electromotor in this motor will be higher.



(a)



(b)

Figure 13. Motor torque speed characteristic in generator and motor operating modes: a) in two-speed transmission system, b) in single-speed transmission system

5. Energy storage system design (battery)

In this section, the battery system is designed and its capacity and output power are determined. As it can be seen in Appendix B the distance of line no.1 between Tehran-Pars terminal and Azadi terminal is about 19 km. The following equations are used to design the bus battery system:

Daily activity= annual mileage ÷(12×number of monthly active days) (1)

Number of daily round trips= annual mileage ÷ (2×distance of route) (2)

daily energy consumption of each bus = Daily mileage × average energy consumption (3)

In order to compute the daily bus activity, equ. 1 is used. Assuming the annual mileage of the bus is 60,000 km and also assuming that the bus operates 26 days a month, daily activity of the bus is 192 kiloometer . Then, considering the distance traveled and the daily travel of the bus, the number of daily round trips of it based on Equation 2 will be equal to 5. In the simulation section, the average energy consumption for this route was equal to 1.79 (kwh / km), so according to Equation 3, the daily energy consumption of each bus for this line is equal to 340.1 kwh. Taking into account the 80% charge and discharge range, the total capacity of the battery is equal to 420 kwh. In addition, the battery must be able to provide maximum power to the electromotor. Therefore, by assuming 85% efficiency of the inverter and motor at maximum power, the battery power is considered equal to 360 kw. Table 9 shows the calculated specifications of the battery pack.

Table 9. the calculated specifications of the battery pack

parameters	values
Energy	430Kwh
Power	360Kw
Voltage	600 V or higher based on standards

6. conclusion

By examining and simulating the driving cycles of different BRT lines in Tehran, the route of Tehran-Pars-Azadi terminal was selected. This route can be considered as one of the most polluted routes based on various factors Studied including, importance, number of daily passengers, traffic characteristics, air pollution, noise pollution for the pilot route in Tehran; Therefore, the development of electric bus fleet in this route can significantly reduce the amount of air pollution and noise pollution (up to 50%) in areas of this route.

Then, the propulsion system and energy storage system for this route were designed based on the simulation results. Finally, among the two proposed systems, preference is given to the simpler system (with variable gear ratio - two speed), because although the use of propulsion system with fixed gear ratio leads to the expansion of the flux weakening zone in the torque-speed diagram of the electromotor, increases the complexity of electromotor design and construction. On the other hand, due to the low efficiency of PMSMs in this zone, the losses of electromotors will also increase. Designing a storage system (battery) and determining its main characteristics including total capacity and battery capacity based on the amount of daily activity, number of daily round trips, average energy consumption of the route and daily electrical power consumption of each bus and considering the battery charging and discharging ranges and total inverter and motor efficiency have been done.

7. Appendix

Appendix A. Specifications and propulsion of electric and diesel buses under study

Bus specifications	diesel	electric
Front surface (m^2)	7.9	7.9
unmanned bus weight (Kg)	15597	11945
Bus length	12.2	12.2
Passenger weight (Kg)	75 ×40	75 ×40
Wheel radius(mm)	500	500
Aerodynamic coefficient	0.79	0.79
Air density	1.23	1.23
Wheel Rolling resistance	0.008	0.008

Earth's gravity	9.81	9.81
Transmission system efficiency	92%	92%
Maximum power (kW)	205	200
Lateral loads (kW)	7.5	3.75
Battery capacity (KWh)	–	300
Battery weight (Kg)	–	3000

Appendix B. the performance of Tehran BRT system – 2014

Line No.	Origin	destination	Path length	Number of stations	Numbers of buses	Maximum passengers capacity
1	Tehranpars intersection	Azadi terminal	19	31	291	600,000
2	Khavaran terminal	Azadi terminal	18.4	54	199	400,000
3	Khavaran terminal	Elm-o-sanat terminal	14.4	20	120	160,000
4	South terminal	Afshar terminal	22.1	36	145	90,000
5	Beyhaghi terminal	Elm-o-sanat terminal	9.9	10	71	70,000
6	Laleh terminal	Afshar terminal	14.4	22	21	60,000
7	Rahahan square	Tajrish terminal	18.3	71	499	450,000
8	South terminal	Khavaran terminal	7.6	8	28	40,000
9	Javanmard qasab metro station	Laleh terminal	36.1	69	82	65,000
10	olom tahghighat station	Azadi terminal	11.6	16	60	90,000
Total			171.8	337	1516	2,025,000

Appendix C . industrial prototypes figures

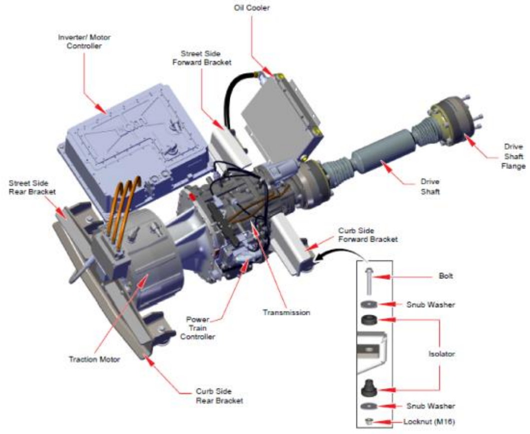


Figure a. Scheme of BE35 electric bus propulsion system by Proterra

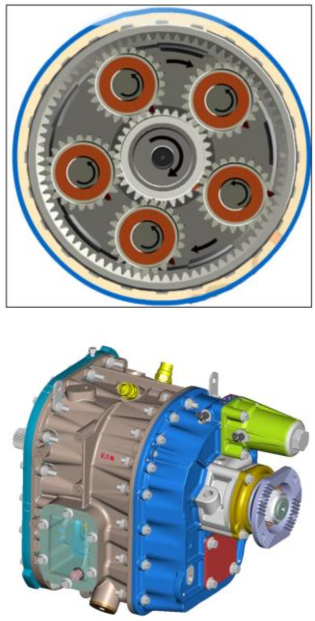


Figure b. Transmission system with gear ratio model EEV-7202 produced by Eaton

8. Refrences

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