Simulation and analysis of HVAC load on electric bus battery pack in various ambient temperatures

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***Abstract*—World is leading toward electric vehicles for its environmentally friendly characteristics. As many innovations and discoveries have been done in this domain. It still has some flaws. Among many, Range of the electric vehicles is still not comparable to IC engine vehicles. The electric vehicle battery has to withstand the driving motor as well as many auxiliary loads. HVAC devours most of the energy for its operation among all the auxiliary loads. With the help of 1-D physics-based model of powertrain and HVAC of electric bus, the energy consumption and range of the bus is estimated for a range of temperature in MATLAB/Simulink. Simulation is done for the range of temperature i.e., 10°C to 42°C for 1 hour. It reflects that during the operation of HVAC, Heating operation is harsher on the battery than AC operation.**

***Index Terms*— Ambient temperature, Electric bus, HVAC, MATLAB/SIMULINK, Simulation.**

I. INTRODUCTION

Energy obtained from the raw materials is perishable in nature. The efforts are being carrying out to switch from fuel powered to a more renewable and less emissive energy source. Switch to electric vehicles from the conventional I.C. engine vehicle is one among the many steps that would possibly reduce the consumption of greenhouse gases while also preserving the valued fossil fuels.

Electric vehicles are aimed to replace the conventional vehicles. This replacement would bring down the ever growing in inflation in the costs of gasoline and diesel. Though it has a high initial investment that has to be dealt with, it has been seen that the sales volume has an exponential growth within the past decade [1] This may owe to that in the near future the earth will be free from harmful emissions that lead to global warming and an alarming decrease in the prices of fossil fuels. There will not only be reduction in air pollution but it will also help with the issue of sound pollution. Hence, use of electric vehicles over conventional ones have been subsidized by the government bodies [2]. The use of electric vehicles over I.C.E vehicles would lead to economic growth of a country. It will also provide job opportunities and support various people and help them to maintain a livelihood.

Electric vehicles or any vehicle in general consists of prominently two systems that derive energy for the energy source i.e., the power-train systems and the auxiliary systems. Powertrain system is a unit of components that provide mobility to the vehicle during their operation whereas any system other than that is regarded as an auxiliary system. A good example of an auxiliary system is the HVAC system of a car. Unlike the conventional I.C. engine vehicles, the battery pack of the electric vehicle is responsible for providing power to both powertrain system as well as the auxiliary loads. The HVAC system consumes most of the power that is reserved for the auxiliary loads and has a significant effect in range that reduces it by 30% in case of Air Conditioning whereas Heating observes further decrease into 35% of the total range reduction [3]. This consumption would happen only if the driver or the passenger prefers to have the HVAC system to be run alongside during their journey.

This paper highlights a project work carried out using the MATLAB-SIMULINK software. The software is utilized to simulate an electric bus that will be running under various ambient temperatures. The results are drawn with regard to important factors such as the state of charge, range in Km, energy consumed per Km etc. Through this article the reader will not only be able to understand the dynamic loads that are to be considered while load calculations but also review the results that are obtained for designing an optimal EV

II ELECTRIC BUS SPECIFICATIONS (VOLVO 7900 ELECTRIC)

Table 1: Specifications of the Volvo 7900 electric [4]

Length (mm)	12134
Width (mm)	2550
Height (mm)	3280
Permitted Gross Vehicle Weight (kg)	19500
Battery	High-capacity Lithium-ion battery
Transmission	Volvo I-Shift AT2412F
Passenger capacity	95
Tyre	275/70 R22.5
Surface Area(m^2)	4*2, 12.0
Voltage(V)	600
Total Energy(kWh)	250
Auxiliary heater capacity(kW)	14
Roof Heating mode Capacity(kW)	28 (Water) 9(Heat pump)
AC Mode (kW)	25
Convector Capacity(W/m)	551

III. MODELLING

There are two major model. They are:

1. Powertrain of Volvo 7900 electric Bus
2. HVAC system.

For the powertrain:

The powertrain model consists of:

1. Vehicle resistive forces
2. Transmission
3. Motor
4. Motor controller
5. Battery

The main input to the system is Drive cycle. In this ECE R68 WLTC CYCLES (class 3). The total distance of the drive cycle is 23.262Km and total time is 1800 seconds.

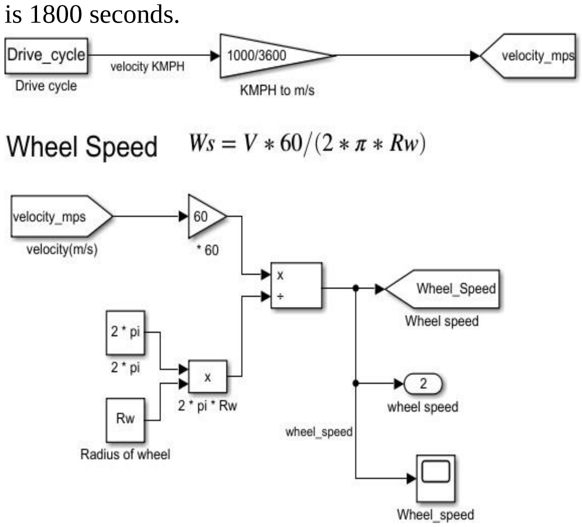

Figure 1: Importing drive cycle and calculating Wheel speed

1.Rolling force

The tire rolling resistance is calculated by:

Fr=GVW*Crf (1)

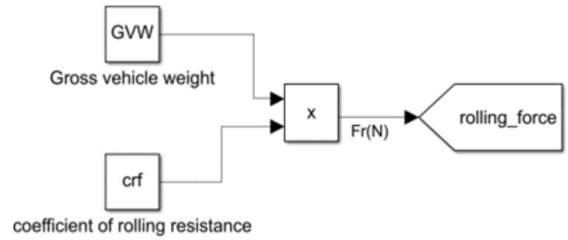

Figure 2: Rolling force model

2. Gradient force

Here the gradient angle is taken as Zero.i. e Bus is driven in a plain road.

$$Fg=GVW*\sin\theta \quad (2)$$

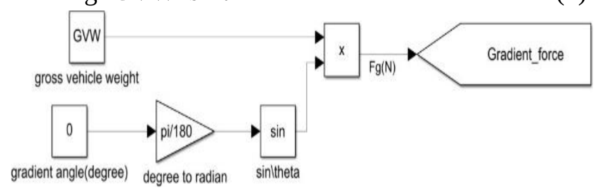

Figure 3: Gradient force model

3. Aerodynamic force

Drag force by the bus is calculated by

$$Fa=0.5*\rho*A*Cd*v \quad (3)$$

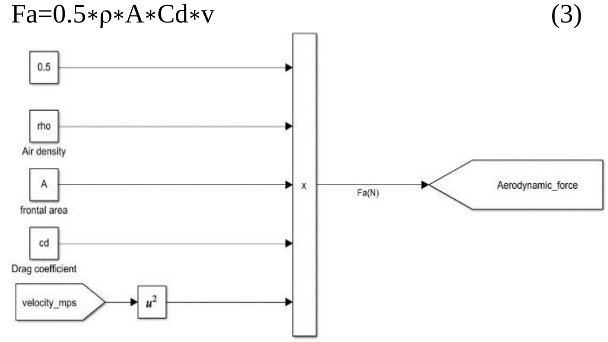

Figure 4: Aerodynamic force model

4. Acceleration force

The force developed during acceleration can be calculated by:

$$Facc=GVM*a \quad (4)$$

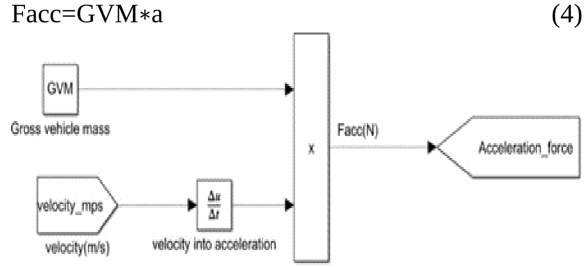

Figure 5: Acceleration force model

From this block the main output is wheel torque and wheel speed, which is passed to the transmission block.

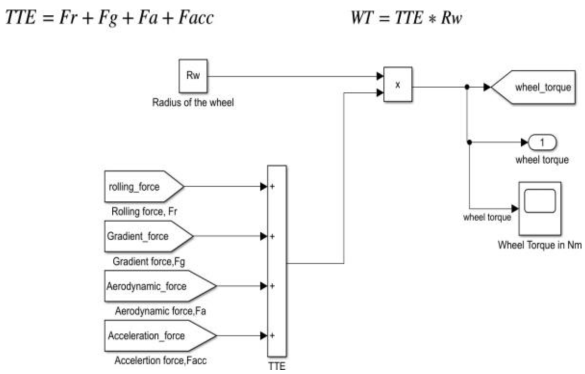

Figure 6: Wheel torque model

2. Transmission

In this block, input from wheel torque model is used. Gear ratio of the electric bus which is 1.6 (from the trial-and-error method). And efficiency is taken as 0.98 for the electric bus. Motor speed and motor torque is calculated by:

Motor Speed= Wheel Speed * Gear ratio (5)

Motor Torque=Wheel Torque÷(Neff∗GR) (6)

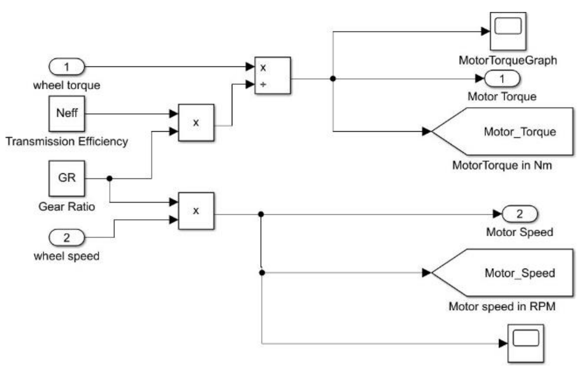

Figure 7: Motor torque and Motor speed model

Motor torque in Nm and Motor Speed in rpm is passed to the next block. i. e. motor block

3. Motor

Motor motoring power is calculated by using input from the previous block.

MMP=2∗π∗Ms∗Mt÷60 (7)

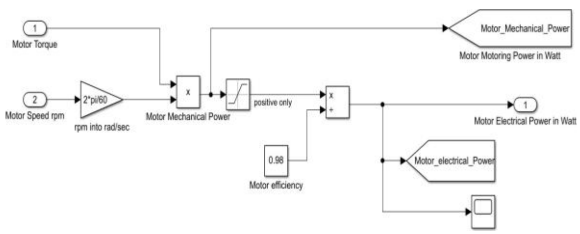

Figure 8: Motor motoring power model

4. Motor controller block

In this block, Electric motoring power from Motor block is used to calculate Motor controller motoring power

MCMP=MEP/MCeff=f(S,T>0) (8)

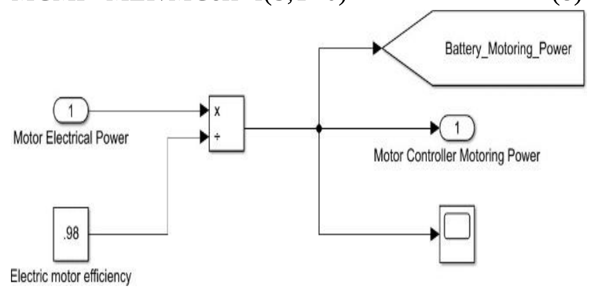

Figure 9: Motor controller motoring power

5. Battery

In this block, motor controller motoring power (BMP) and HVAC power are integrated to get the energy per km and range of the electric bus. Battery capacity of the model is 25KW

E/km =∫(BMP +HVAC) / (Distance *3.6*106) (9)

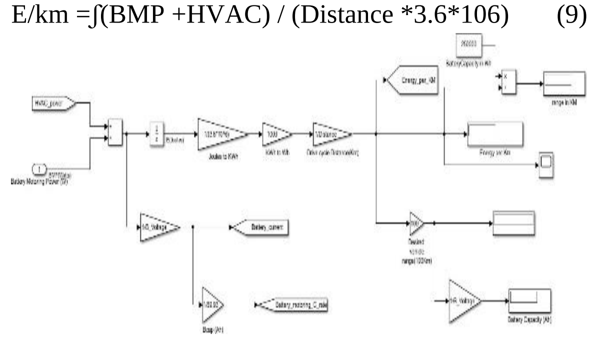

Figure 10: Battery Model

For the HVAC:

Input: Various ambient temperature

HVAC model consist of two main part i.e., AC and Heater

1. AC model

Loads considered while modelling

a. Vehicle body load

i. Qc=h∗Av∗(Tamb−Tc) (10)

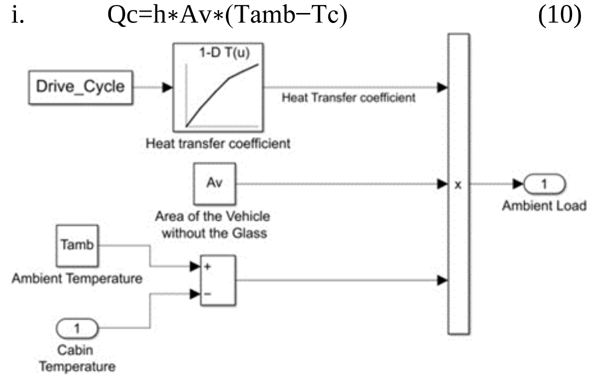

Figure 11: Vehicle body load model

b. Metabolic load

i. Adu=0.02∗W0.425∗H0.725 (11)

ii. Qm=Sigma(AVH∗Adu∗n) (12)

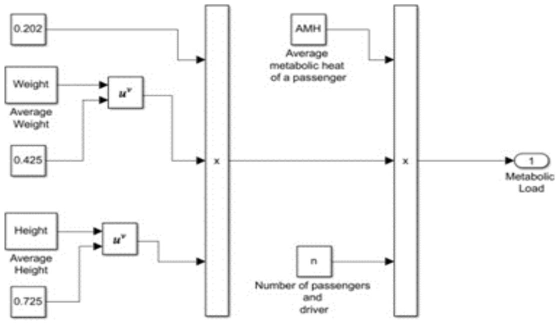

Figure 12: Metabolic load model

c. Radiation load

i. Q=τ∗Ag∗idir (13)

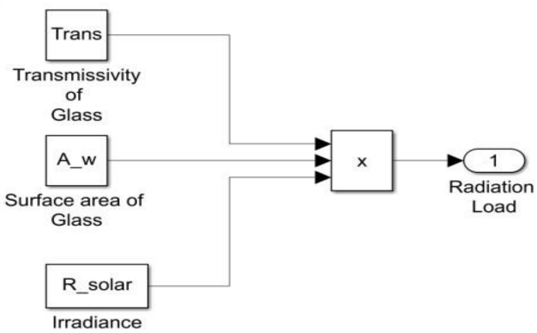

Figure 13: Radiation load model

d. Ventilation load

Qa=m∗Cp∗(Tamb−Tc) (14)

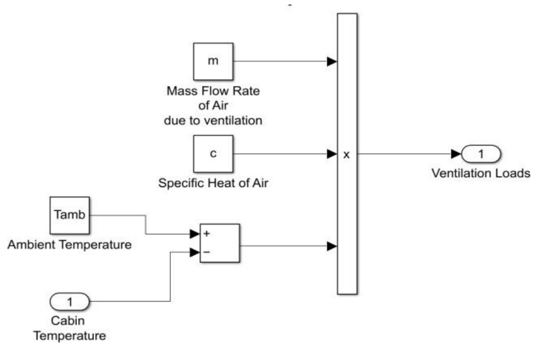

Figure 14: Ventilation load model

The total AC load is calculated as show in below figure.

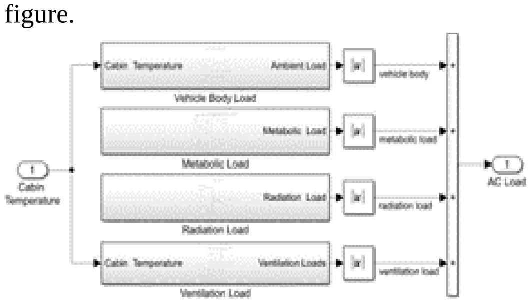

Figure 15: AC load model

2. Heater Model

Heater loads are similar to that of AC loads excluding Radiation load because it helps in Heating the cabin.

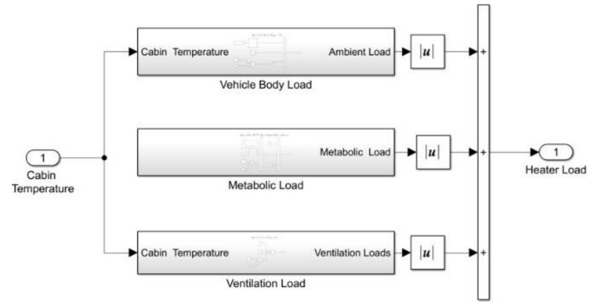

Figure 16: Heater load model

QAC (extra) orQHeater (extra)=m∗Cp∗(Tc−Tc(desired)) (15)

Qc=Qac+Qheater (16)

Qac(battery)=Qac÷COP (17)

dTc=QACorHeater÷(Mcabin∗c) (18)

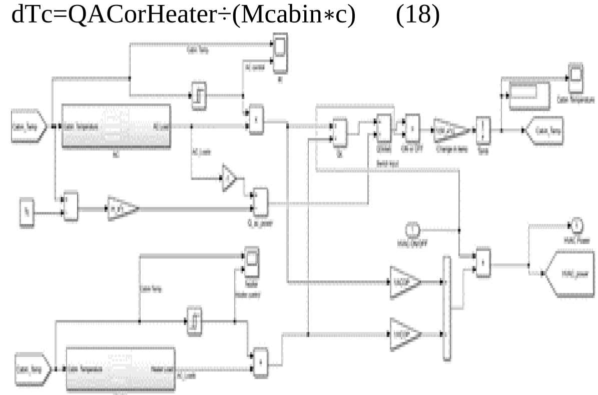

Figure 17: HVAC power model

IV. RESULTS

The Volvo 7900 electric bus 1-D powertrain and HVAC model is under simulation for 1hour over the distance of 23km for temperature range 10℃ to 44℃. The following result are obtained from the simulation:

Table No:2 Energy Consumption by HVAC and Powertrain with respect to ambient

S. No	Ambient Temperature in °C	Energy Consumed in Wh		
		HVAC OFF	HVAC ON	HVAC Energy
1	10	65044	76038	10994
2	12	65044	75808	10764
3	14	65044	75486	10442
4	16	65044	75210	10166
5	18	65044	74934	9890
6	20	65044	74612	9568
7	22	65044	74336	9292
8	24	65044	73968	8924
9	26	65044	68908	3864
10	28	65044	69092	4048
11	30	65044	69230	4186
12	32	65044	69414	4370
13	34	65044	69552	4508
14	36	65044	69736	4692
15	38	65044	69874	4830
16	40	65044	70058	5014
17	42	65044	70196	5152
18	44	65044	70380	5336

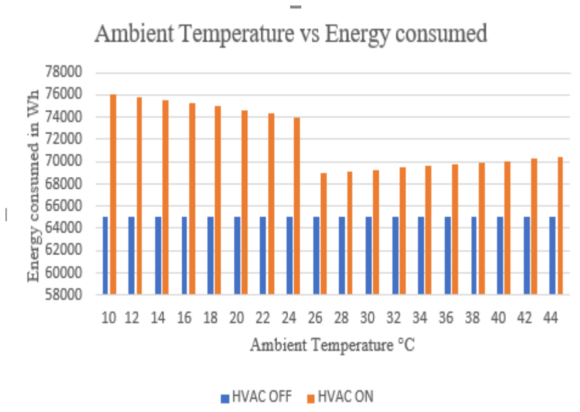

fig. 18: Ambient Temperature vs Energy consumed

The Energy Consumed from the battery can be obtained as simulation results from the model.The results are plotted graphically as show in "Fig. 1". Thus, graphically it can be perceived that the energy consumed when the HVAC system is ON is higher when the cabin temperature is below the desired cabin temperature (i.e. Tc = 24℃) whereas it is less in case where the temperatures is above the desired cabin temperature (Tc>24). The reason for the consumption of more power at lower temperatures is because the heating unit of the HVAC system engaged in rising the car-cabin ambience to the required cabin temperature. Hence proving that heating consumes more load from the battery as compared to cooling.A bar plot for HVAC energy consumed when the HVAC is in off condition is also shown. This plot represents the total energy consumed just by the powertrain system of the E-bus thus showing a constant value of 65044 Wh. It is plotted merely to compare between OFF and ON conditions.

Table 3: State of Charge in various ambient temperature during simulation.

S. No	Ambient Temperature in °C	State of Charge in percent			
		Initial SOC (%)	SOC during HVAC OFF (%)	SOC during HVAC ON (%)	SOC Difference (%)
1	10	100	56.14	48.72	7.42
2	12	100	56.14	48.9	7.24
3	14	100	56.14	49.08	7.06
4	16	100	56.14	49.28	6.86
5	18	100	56.14	49.48	6.66
6	20	100	56.14	49.68	6.46
7	22	100	56.14	49.9	6.24
8	24	100	56.14	50.14	6
9	26	100	56.14	53.52	2.62
10	28	100	56.14	53.42	2.72
11	30	100	56.14	53.3	2.84
12	32	100	56.14	53.2	2.94
13	34	100	56.14	53.1	3.04
14	36	100	56.14	52.98	3.16
15	38	100	56.14	52.88	3.26
16	40	100	56.14	52.76	3.38
17	42	100	56.14	52.66	3.48
18	44	100	56.14	52.56	3.58

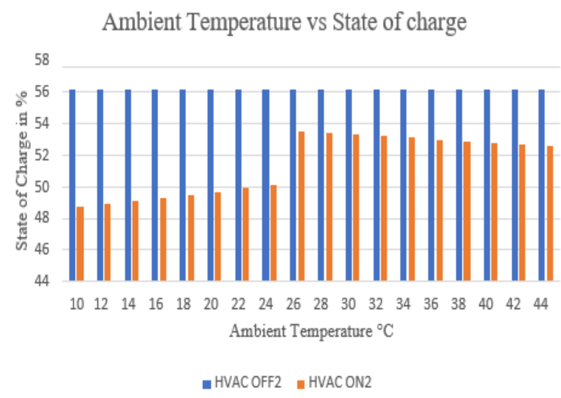

Fig. 19: Ambient Temperature vs State of charge

The given plot is of Ambient Temperature and the State of Charge of the battery. The state of charge of the battery is accounted for both "ON" and "OFF" conditions of the HVAC system of the E-Bus. Graphically, it can be concluded that at lower temperatures i.e., when Heating is employed the %SOC of the battery drops drastically as compared to Cooling where the drop in the %SOC is not as severe as Heating.

Table 4: Effect of ambient temperature on Ventilation load and Vehicle body load.

S. No	Ambient Temperature in °C	Ventilation Load		Vehicle Body Load	
		HVAC OFF	HVAC ON	HVAC OFF	HVAC ON
1	10	0	131	0	1452
2	12	0	135.2	0	1249
3	14	0	131.9	0	1045
4	16	0	121	0	838.7
5	18	0	102.5	0	631.2
6	20	0	76.16	0	422.3
7	22	0	42.03	0	211.9
8	24	0	0.0002944	0	0.00136
9	26	0	94.5	0	221.8
10	28	0	189	0	443.6
11	30	0	180	0	665.4
12	32	0	378	0	887.2
13	34	0	472.5	0	1109
14	36	0	567	0	1331
15	38	0	661.5	0	1553
16	40	0	756	0	1774
17	42	0	850.5	0	1996
18	44	0	945	0	2218

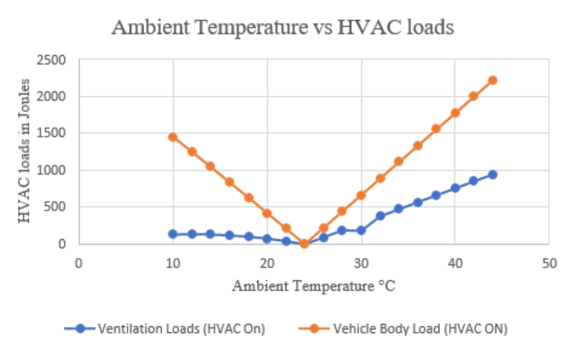

Fig. 20: Ambient Temperature vs HVAC loads

The two loads considered which vary with the required cabin and ambient temperature are "Ventilation Loads" and "Vehicle body loads". The results obtained when represented graphically exhibit that at lowest temperature i.e., at Tamb = 10℃ the both the loads are high. Although these loads gradually decrease and eventually become negligible at the ambient temperature, Tamb = 24℃. This is because the target temperature for the car-cabin in the model is set to Tc = 24℃. Thereafter, from Tamb = 24℃, there is a gradual increase in both loads as seen in the nature of the graph.

To summarise, the plot shows us the variance of Ventilation loads as well as Vehicle body loads. It also makes us aware that vehicle body loads are higher in comparison to the ventilation loads in Volvo 7900 electric bus.

Table 5: Range of the electric Bus in different ambient temperature.

S. No	Ambient Temperature in ℃	Range in Km			HVAC STATE
		HVAC OFF	HVAC ON	Difference	
1	10	176.8	151.2	25.6	HEATER
2	12	176.8	151.7	25.1	HEATER
3	14	176.8	152.3	24.5	HEATER
4	16	176.8	152.9	23.9	HEATER
5	18	176.8	153.5	23.3	HEATER
6	20	176.8	154.1	22.7	HEATER
7	22	176.8	154.8	22	HEATER
8	24	176.8	155.5	21.3	HEATER
9	26	176.8	166.8	10	AC
10	28	176.8	166.4	10.4	AC
11	30	176.8	166.1	10.7	AC
12	32	176.8	165.7	11.1	AC
13	34	176.8	165.3	11.5	AC
14	36	176.8	164.9	11.9	AC
15	38	176.8	164.5	12.3	AC
16	40	176.8	164.2	12.6	AC
17	42	176.8	163.38	13.42	AC
18	44	176.8	163.4	13.4	AC

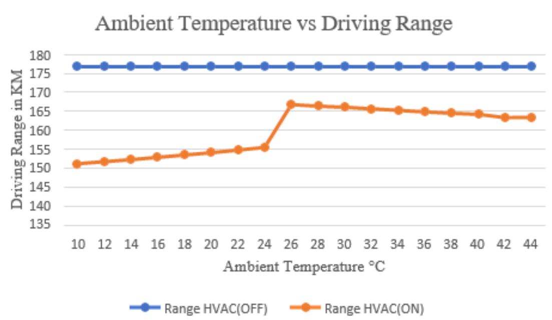

Fig. 21: Ambient Temperature vs Driving Range

The Ambient Temperature is plotted against the driving of the E-Bus. Both the OFF and ON conditions of the HVAC system are considered.

The off condition also represents the driving range when the battery supplies energy only to the powertrain of the E-Bus. This is a constant value of 176.8 Km and does not vary with the ambient temperature. The nature of the graph for the range when HVAC is turned ON deduces that lower the ambient temperature, lower would be the driving range of the E-Bus. This is due to Heater utilizing more battery power compared to the AC.

V CONCLUSION

HVAC provides thermal comfort for the passengers by controlling the maintaining the desired cabin temperature inside the vehicle i.e., 24℃. The battery pack of the electric bus supplies all the require energy for transmission as well as for the auxiliary units, HVAC loads consumes half the energy supplied by the battery for the auxiliary system. From the simulation results we came to know that the Heater of the HVAC unit consumes a lot of power more than the AC and it drastically reduce the driving range of the electric bus so by using an optimised HVAC heating unit the driving range of the vehicle can be extent to some distance.

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