Simulation and Analaysis of Battery Performance of a Solar Car Using a Model Implemented in Simulink

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Abstract—Battery performance of a proposed solar car has been investigated under different road and weather conditions while the car makes a trip in one of the longest routes in Dhaka city, using a model of the solar car developed in Matlab Simulink. It is observed that the solar power alone is sufficient to feed the car during summer days, where in other seasons x% to y% additional energy is needed. A significant reduction in energy consumption is observed when the car runs at lower speed, which is attributed to lower air drag at lower speed. Energy consumption further reduces with the increase in number of stoppages. Thus the solar car will be an ideal mode of transport for a city like Dhaka, where traffic congestion is a daily occurrence.

Index Terms—Solar car, SIMULINK, Solar panels, Batteries, Battery modelling, State of charge.

I. INTRODUCTION

THE unsustainable nature of fossil fuel and its horrendous effect on our environment create concerns to find an environment friendly alternative energy source. This quest leads us to the renewable energy sources like sun, wind, tides, hydropower and biomass which are safe and clean. Considering economic issue, another major driving force behind renewable energy, solar energy comes out as the most suitable one. It is the most sustainable as our sun will provide this solar energy for another billion years. Beside this, photovoltaic cell, which converts solar energy to electrical one, also increases every year as new ideas with new technology keep emerging and improving and production of photovoltaic panels is now more than ever before by doubling its production in every two years. So, considering the improvement, growth, efficiency and effectiveness of solar technology we should implement this eco-friendly and economic technology.

In Dhaka city, a major mode of transportation for daily office commuters is fuel driven cars. However, emissions from such cars pose serious environmental and health hazards, especially during office hours when cars are caught in traffic congestion causing more and more toxic emissions. Solar powered clean cars can be of great advantage to the public and environment and can go a long way to alleviate this problem. On these premises, a solar powered light-weight economically affordable clean car for the daily office commuters of Dhaka city was proposed in [1] which is able to run on solar power alone during sunny days of summer and spring, and with complementary charging of the batteries from other sources during winter and under overcast sky.

Batteries are the indispensable and critical part of the electric drive system of a solar car. A healthy battery will ensure a longer battery life and a safe driving of the car. Further, unlike fuel driven car, there is no rapid recharging system for solar car. Therefore, it is imperative to have a prior understanding of how the battery will perform on the road under different road and weather conditions. With this objective, this paper aims to investigate the battery performance while the car is making a trip from home to office in Dhaka city, considering one of the longest trips, Uttara to Motijheel, which is about 18 km long, under different traffic and weather conditions.

Performance analysis is carried out using a model developed in Simulink assuming the batteries to be 80% charged. The simulation has been conducted using the specifications of the solar car that is being built in the Robotics Workshop of BRAC University [2]. In this study, the simultaneous charging and discharge characteristics, mainly the variation in the state of charge (SOC) and the terminal voltage (V_t) of the battery with travel distance and time under different traffic conditions in different seasons of a year are observed and analyzed, where the aging effect of the battery is ignored.

Environmental and economic aspects of the battery are discussed and compared to a fuel driven car of similar type. It is estimated that the solar car, in the long run, costs much less than a petroleum or even a gasoline car with a negligible effect on the environment.

In the subsequent sections, sections II and III, models used for the solar panel, battery, charge controller and the motor power are described, followed by their implementation in Simulink. Section IV provides the simulation results on the battery performance under different road and weather conditions along with the environmental and economic aspects of using solar car. Finally section V concludes the findings of this work.

II. MODELING OF SOLAR CAR

A solar car is an electric car where the electricity is supplied by solar panels, though sometimes additional source may be required. Sun radiates light energy falling upon the surface of solar panels as direct, reflected and diffused beams. Solar
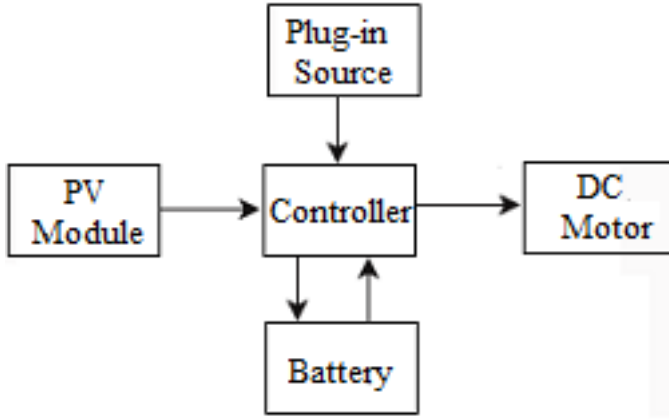
Fig. 1. Block diagram of electric drive system of solar car

panels converts that light energy into electricity and stores the charge in a battery or in a set of batteries. The battery then supplies power to a DC motor which provides mechanical power to rotate the wheels of a vehicle platform. A charge controller is used to control the dissipation of energy to the motor to ensure healthy battery life. Fig. 1 depicts the electric drive system of a solar car in block diagram. Following subsections discuss the modeling of different modules of the electric drive system.

A. Calculation of Solar irradiance

The model used to portray total solar irradiation on a solar panel, G_{TP}, considers direct solar beam on the panel G_{BP}, diffuse radiation G_{DP}, and ground reflected irradiance G_{RP} [3]. The general equation of G_{TP} is given by,

$$G_{TP} = G_{BP} + G_{DP} + G_{RP} \qquad (1)$$

1) Direct solar beam radiation: If G_B is the direct beam radiation at the surface of the earth and θ is the angle of incidence between the normal to the panel face and the incoming direct beam, the direct beam radiation G_{BP} is given by,

$$G_{BP} = G_B cos\theta \qquad (2)$$

If n is the day number (1-365) of the current day of a year, G_B is calculated as,

$$G_B = G_0 exp\left(-\frac{K}{sine\beta}\right) \qquad (3)$$

where G_0 is the extraterrestrial radiation and β is the altitude (zenith) angle of the sun, the angle between the sun and the local horizontal beneath the sun [3]. They are determined by,

$$G_0 = 1150 + sin\frac{360\left(n - 275\right)}{365} \qquad (4)$$

$$K = 0.174 + 0.035sin\frac{360\left(n - 275\right)}{365} \qquad (5)$$

If the latitude of the region where the solar panel is placed is L, angle of declination is δ and the hour angle is H, β can be found using the following equations,

$$sin\beta = cosLcos\delta cosH + sinLsin\delta \qquad (6)$$

$$\delta = 23.45sin\frac{360\left(284 + n\right)}{365.25} \qquad (7)$$

$$H = \frac{15°}{hour} \ (hours\ before\ solar\ noon) \qquad (8)$$

The hours before solar noon is positive before noon and negative after noon. $cos\theta$ of (2) is determined by (9) where φ is the slope of the panel, ϕ_P is the azimuth of the panel.

$$cos\theta = cos\beta cos\left(\phi_S - \phi_P\right) sin\varphi + sin\beta cos\varphi \qquad (9)$$

The azimuth of the sun ϕ_S is given by,

$$\phi_S = sin^{-1}\frac{cos\delta sinH}{cos\beta} \qquad (10)$$

2) Diffuse Radiation: The model of diffuse component of radiation on a flat solar panel is given by,

$$G_{DP} = SG_B\frac{1 + cos\varphi}{2} \qquad (11)$$

where the sky diffuse factor S is computed as follows,

$$S = 0.095 + 0.04sin\frac{360\left(n - 100\right)}{365} \qquad (12)$$

3) Reflected Radiation: The reflected radiation term on a surface of any direction is modeled as,

$$G_{RP} = \rho G_B\left(sin\beta + S\right)\frac{1 - cos\varphi}{2} \qquad (13)$$

where ρ is called the ground reactance or albedo; for concrete of the road, the value of it is estimated as 0.55 [4].

B. Electrical Model of Solar Panel

A solar cell is the unit component of a solar module. When there is no sunlight, a solar cell is not an active device; it works as a diode. If it is connected to an external supply it generates a current I_D, called diode current. That is why the electric circuit model of solar cell is like Fig. 2, which contains a current source I_{PH}, a diode and a series resistance R_s representing the internal resistance of a cell. The net current I is therefore the difference between I_{PH} and I_D as (14).

$$I = I_{PH} - I_D = I_{PH} - I_0\left[exp\left(\frac{V + IR_S}{V_t}\right) - 1\right] \qquad (14)$$

where V is the voltage across the load. I_0 is the dark saturation current and it strongly depends on temperature [5]. The thermal voltage of cell V_t is calculated as (15),
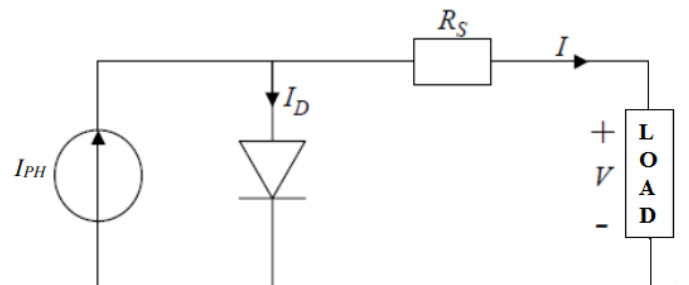

Fig. 2. Electric equivalent diagram of a solar cell.

$$V_t = \frac{mkT_C}{q} \tag{15}$$

where m is idealising factor, k is Boltzmanns gas constant, T_C is the absolute temperature of the cell, e is electronic charge. T_C depends on both the ambient temperature T_a and irradiance G_a as given by the following empirical relation,

$$T_C = T_a + C_2 G_a \tag{16}$$

Where C_2 is a constant computed approximately as 0.03 Cm²/W.

An equation to calculate the series resistance of a cell is deduced as (17).

$$R_S = \frac{V_{OC,0}}{I_{SC,0}} - \frac{\frac{(V_{OC,0})^2}{V_{t,0}} - V_{OC,0} \ln\left(\frac{V_{OC,0}}{V_{t,0}} + 0.72\right)}{P_{max,0}\left(\frac{V_{OC,0}}{V_{t,0}} + 1\right) V_{OC,0} (I_{SC,0})^2} \tag{17}$$

Here, V_{OC}, I_{SC} and P_{max} are the open circuit voltage, short circuit current and maximum power respectively; the added subscript '0' indicates that the parameters are measured under standard temperature $(298K)$ and irradiance $(1000W/m^2)$. The values of these parameters for standard condition are collected from the manufacturer's data-sheet.

Cells are grouped in series or parallel or both to create module to supply higher current or voltage at the module terminal. A generalized figure of the module is shown in Fig. 3, where N_{PM} number of parallel branches and N_{SM} number of series brunches are connected.

An equation for the module current I_M having a voltage V_M at its load terminals is derived in [6] as (18) where the subscript 'M' indicates that the corresponding parameter belongs to an entire solar module.

$$I_M = I_{SC,M}\left[1 - exp\left(\frac{V_M - V_{OC,M} + R_{S,M}I_M}{N_{SM}V_{t,M}}\right)\right] \tag{18}$$

The parameters $I_{SC,M}$, $V_{OC,M}$, $R_{S,M}$ and $V_{t,M}$ of a module having N_{SM} number of series branches and N_{PM} number of parallel branches can be calculated using the following equations,

$$I_{SC,M} = I_{SC}N_{PM} \tag{19}$$

$$V_{OC,M} = V_{OC}N_{SM} \tag{20}$$

$$R_{S,M} = R_S \frac{N_{SM}}{N_{PM}} \tag{21}$$

$$V_{t,M} = V_t N_{SM} \tag{22}$$

The short circuit current basically proportional to the irradiance of the sun G_a as,

$$I_{SC} = C_1 G_a \tag{23}$$

Here C_1 is a constant defined by (24). G_a is the irradiance of the sun on the surface of the earth and $G_{a,0}$ is the standard irradiance$(1000W/m^2)$.
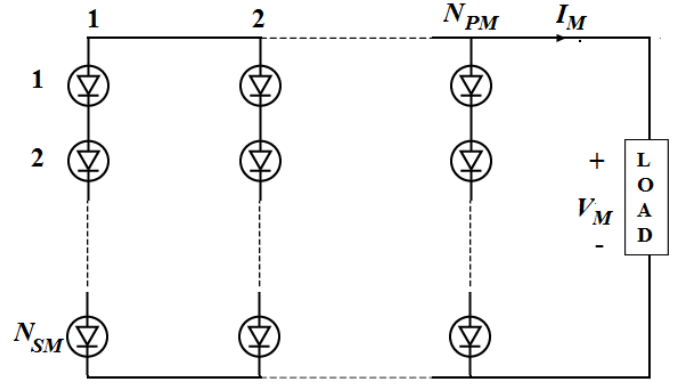

Fig. 3. Photovoltaic cells in series and parallel in a photovoltaic module

$$C_1 = \frac{I_{SC,0}}{G_{a,0}} \tag{24}$$

The open circuit voltage of the cell depends on the temperature of the solar cells as,

$$V_{OC} = V_{OC,0} + C_3 (T_C - T_0) \tag{25}$$

The constant C_3 is usually considered to be $-2.3\ mV/C$ [6] and T_0 is the standard temperature $(298K)$.

C. Modeling of Battery

The model used for battery is based on Thévenin battery model [7] as shown in Fig. 4, where R_0 and C_0 are the resistance and capacitance between electrodes of the battery, R_B is the series resistance, V_B is the open circuit voltage and I_L is the load current. All of the three parameters namely V_B, R_B and V_d in Fig. 4 are functions of SOC and have been evaluated experimentally for our batteries [8].

The load current, I_L for a load which draws out Power P can be calculated using (26) as in [7].

$$I_L = \frac{(V_B - V_d) - \sqrt{(V_B - V_d)^2 - 4R_B P}}{2R_B} \tag{26}$$

In case, battery is being charged by I_{CH} current, it flows opposite to I_L and the overall current flowing through the battery is reduced to $(I_L - I_{CH})$.

With I_L known, the terminal voltage V_t and the total charge dissipated from battery Q_{dis} in time t can be calculated as,
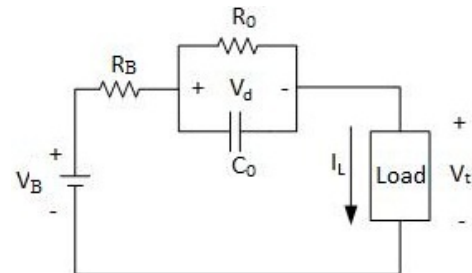

Fig. 4. Thévenin Battery Model

$$V_t = V_B - I_L R_B - V_d \qquad (27)$$

$$Q_{dis} = I_L t \qquad (28)$$

The new SOC of the battery after time t is then given by,

$$SOC\,(new) = SOC\,(old) - \frac{Q_{dis}}{C(T_a)} \qquad (29)$$

where $C(T_a)$ is the capacity of the battery which also depends on the ambient temperature T_a. According to [9], a relationship between the battery capacity and the ambient temperature is derived as, using a linear fitting approximation,

$$C(T_a) = C_0(0.0082T_a - 0.77) \qquad (30)$$

where C_0 is the discharge capacity at $25°C$.

With the new SOC calculated as in (29), V_B, R_B and V_d are re-evaluated according to the following relations which were determined experimentally in [8].

$$V_B = 1.4667SOC + 11.0233 \qquad (31)$$

$$V_d = 0.086SOC \ - 0.011 \qquad (32)$$

$$R_B = -0.0531SOC + 0.066 \qquad (33)$$

D. Power Calculation of DC Motor

Power required by the motor to drive the car can be estimated by adding together individual force components that arise from different physical effects. The major three forces are the force of acceleration F_A, aerodynamic drag force F_D, force exerted by the air against the movement of the car, and the frictional force F_R, force required to overcome the frictional resistance between the wheel and the road [10]. Summing up, total driving force, F_T is obtained as,

$$F_T = F_R + F_D + F_A \qquad (34)$$

The car will have a force of acceleration only when it is accelerating, otherwise it will be zero when running at a constant velocity. All of the three major forces are calculated using the following equations,

$$F_R = \mu_R mg \qquad (35)$$

$$F_D = \frac{1}{2}C_D\rho A_{CROSS}v^2 \qquad (36)$$

$$F_A = ma \qquad (37)$$

Here, m is the mass, A_{CROSS} is the frontal cross sectional area, v is the velocity, a is the acceleration of the car, ρ is the air mass density, C_D is the coefficient of aerodynamic drag force, g is the gravitational acceleration, and μ_R is the coefficient of rolling resistance.

If the car is running at a velocity of v then the power exerted by the shaft of the motor can be expressed as,
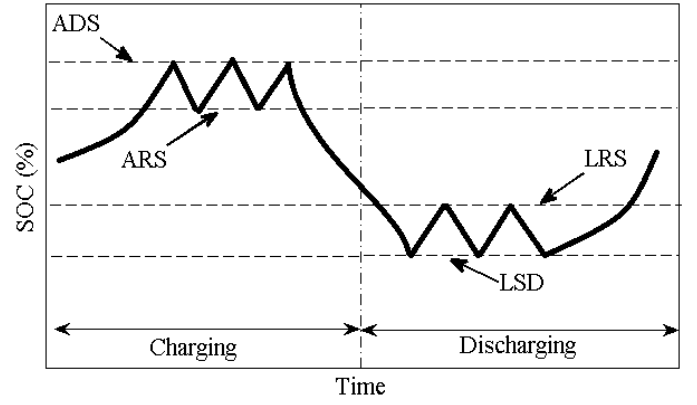
$$P_T = F_T v. \qquad (38)$$

Fig. 5.   Charge Controller set points

If the efficiency of the motor is η_m, the power required to be supplied by the battery to the motor is given by,

$$P = \frac{P_T}{\eta_m} \qquad (39)$$

E. Mechanism of charge controller

There are four set points in a charge controller, two to avoid overcharge and two for overdischarge as in [10]. The maximum SOC the batteries are allowed to reach and above which solar panels are disconnected from the battery is array disconnect SOC (ADS). Then the battery may discharge to a SOC level low enough to start charging again; the level is array reconnect SOC (ARS). Similarly, the load is disconnected at the minimum SOC, namely low SOC load disconnect (LSD), after which more discharging may damage the battery. Then the battery may charge for some time, the SOC rises and the load is connected again at a level of load reconnect SOC (LRS). The points are depicted in Fig. 5

III. IMPLEMENTATION IN SIMULINK

The implementation of the aforementioned models of solar panel, battery, motor power and charge controller are described in the following subsections.

A. Implementation of solar panel

The aforementioned algorithm of calculating module current is implemented in the graphical programming language of Simulink where the inputs are ambient temperature T_a, solar irradiance G_a and the terminal voltage of the load V_t, and it gives I_{CH} as output as Fig. 6 shows. The algebraic constrain block the figure is used to solve the nonlinear equation of (18). The numbers of different equations used in the model of are imprinted on the corresponding function blocks.

B. Implementation of Battery Model

Fig. 7 shows the battery model in Simulink where the power required P and charging current I_{CH} are the inputs to battery. It calculates I_L, V_t and SOC after dissipating power for a certain time and gives out as outputs. Eq(1), Eq(2) etc. labeled
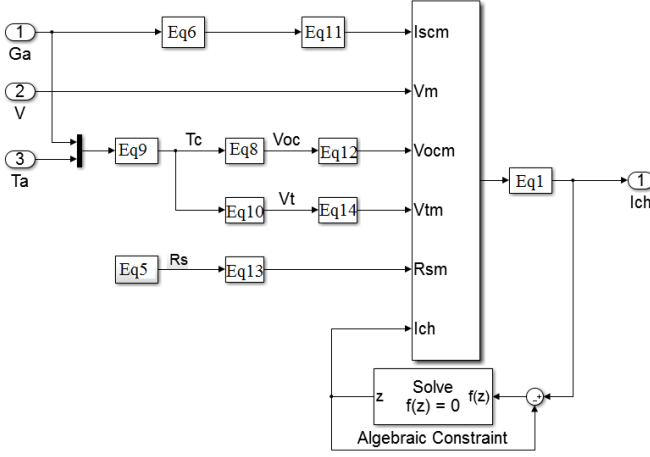
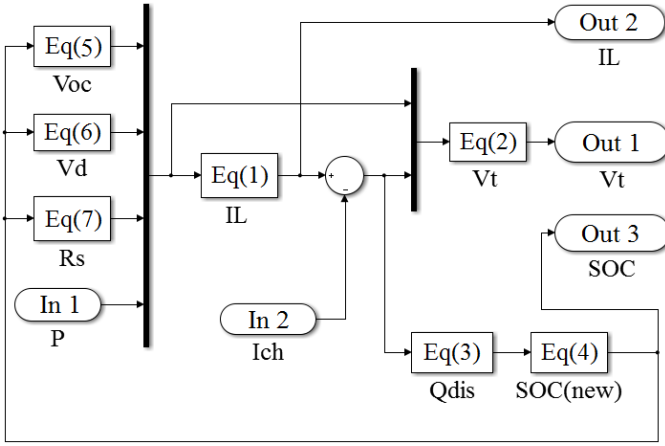Fig. 6. Inside view of the mask of the PV module model

Fig. 7. Implementation of Battery model in Simulink

Fig. 8. Implementation of charge controller model in Simulink

variables or the users may produce a set of value according to their concern.

D. Implementation of Charge Controller

Fig. 8 implements the charge controller in SIMULINK. There are two if blocks in the diagram; upper one is controlling the discharging state and lower one the charging state. If the SOC goes below the given level to turn off discharging, and the discharging process is not switched off yet, the upper if block commands the Discharge off block to disconnect the load. On the other hand, if the SOC is high enough to turn on discharging, the same if block triggers Discharge on action block to connect the load and deliver input power to the output. Same mechanism applies for the charging state controller if block except, this time, the input charging current flows to output when charging is turned on.

E. Combining the Components

All the components portrayed in earlier sections are packed inside subsystems and combined together to build a complete model of vehicle as in Fig. 9. All data found by the simulation are transfered to the MATLAB workspace to plot and analyze the results.

IV. RESULTS AND DISCUSSIONS

An itinerary is assumed for a Dhaka city dweller from his home to office, which is 18 km long. For the sake of convenience, it is assumed that the person leaves his home in the morning with his car fully charged and reaches his office by driving 10% of the distance at 10 kilometer per hour (kph) and rest of the road either 30 kph or 60 kph depending on the road condition. In the afternoon, he returns by the same route with same speed characteristics.

A. Performance Analysis

Fig. 10 shows the plots of power required P and car speed v as the car travels at different velocities from its origin to destination. The top most plot shows the different velocities of the car during its trip which starts with 10 kph at its origin covering 5% of the distance, goes at after that for 15% of the road, then goes at 60 kph for 60% of the

in the diagram refer to the corresponding equation numbers in this paper. The time interval after which the model calculates dissipated charge and records a new SOC can be fixed by the mask parameter dialog box along with the nominal capacity of the battery, initial state of charge, temperature and the number of batteries in series.

C. Implementing Load Block in Simulink

The Simulink block of Load, named Load in Fig. 9, takes inputs of variable velocity on different time frames and some invariants related to the car e.g. its weight, frontal area. If the car moves at velocity v_1 kilometer per hour (kph) for t_1 minutes, comes to a halt and rests for t_1^r minutes, and then starts again at v_2 kph at which it runs for another t_2 minutes, the input format is $v = [v_1 0 v_2]$ and $t = [t_1 t_1^r t_2]$. Time t_1 consists of the time at which the car accelerates from static position to reach v_1, the time it runs at constant v_1 kph, and fall time when the car decelerates to halt. The inputs are transferred to a MATLAB program which gives a timeseries variable P using the equations (34) to (39). The signal building block of load has some presets e.g. Busy road, Highway, Empty road etc. to select easily some preloaded values of the
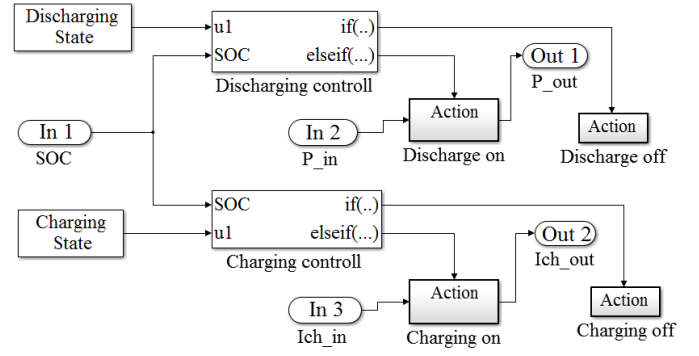
Fig. 9. The model of the solar car combining all individual components

TABLE I
PROPERTIES OF SOLAR CAR

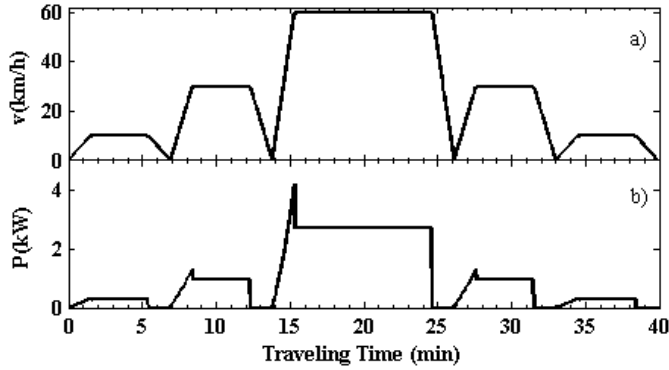| Components	Parameters	Value
Panel[2]	Maximum Power, P_{max} (W)	50
	Open circuit voltage, V_{OC} (V)	18
	Short circuit current, I_{SC} (A)	3.11
Battery[8]	Capacity of a battery, C (Ah)	70
	Number of batteries in series, N	5
Charge controller	Array disconnect SOC, $ADS(\%)$	100
	Array reconnect SOC, $ARS(\%)$	85
	Low SOC load disconnect, LSD (%)	25
	Load reconnect SOC, $LRS(\%)$	50
Vehicle platform[2]	Mass of the car, m (kg)	500
	Maximum velocity, v_{max} (kph)	60
	Time to reach max. velocity, t_{max} (min)	1.5
	Frontal area, A_{CROSS} (m^2)	1.1
Environment[10]	Coeff. of rolling resistance, μ_R (W)	0.025
	Coeff. of aerodynamic drag force, C_D	0.035
	Air density, $\rho(kg/m^3)$	3.11

Fig. 10. Variation in (a) car speed, and (b) motor power of the battery during one full trip as the car travels from origin to its destination.
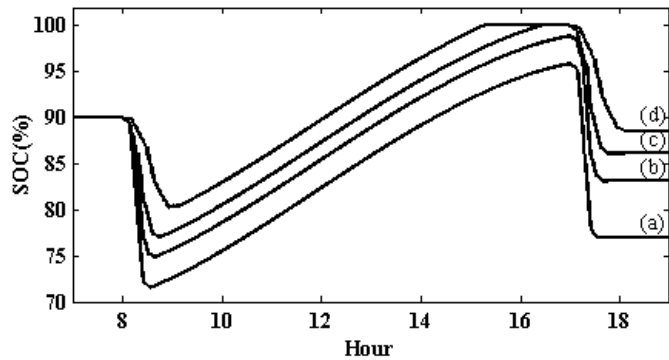

Fig. 11. Variation in SOC in spring with the car traveling (a) 90%, (b) 60%, and (c) 30% of the road at the top speed. Plot (d) is that for 30% with 20 number of stoppages.

road, after which it goes at 30 kph and 10 kph for the rest of 15 and 5 of the road, respectively, before it reaches the destination. For the sake of simplicity we assumed a constant acceleration with which the car reaches the maximum speed from its rest position and a constant deceleration with which it comes to a halt from its maximum speed. For higher speed higher acceleration and deceleration are assumed than those at lower speed. The required power increases gradually with the increase in car speed as can be seen from the power plot below the velocity plot in Fig. 10. The power drops abruptly whenever the velocity reaches target speed because the driver releases the accelerator at that time, and hence force of acceleration becomes zero requiring less power to drive.

Fig. 11 shows how the SOC varies when the car moves at the top speed of 60 kph for different lengths of the road. As can be seen from this figure, SOC drops to almost 67% when the car runs 90% of the road at the top speed, indicating about 13% additionally required charge at this speed. However, SOC drops to only 78% when the car runs only 30% of the road at the top speed with 60% at half the top speed and the rest 10% at 10 kph, indicating more that 40% reduction in energy consumption at this slower speed and almost no necessitiy of additional charge. The higher energy requirement at higher speed is due to the higher aerodynamic drag force which increases as the square of the velocity according to (36). Energy requirement is further reduced if the trip is accompanied with frequent breaks (topmost plot in Fig. 11) during heavy traffic congestion which is a common phenomena in the city of Dhaka.

Fig. 12 shows how the SOC varies when the car travels at the speed described earlier in different seasons of the year. The car can not only travel solely on solar power during summer seasons but also store some more energy at the end of the day. However, in spring and winter some additional energy will be required. However, if the car mass increases, the required energy will also be increased. If the mass of the car doubled from 500kg to 1000kg, the SOC in the end of the day decreases by 25% as in Fig. 15.
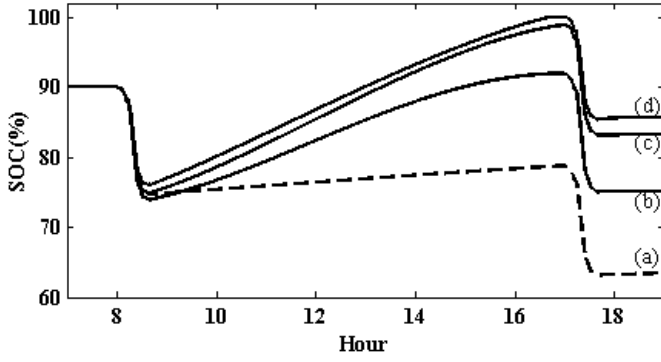
Fig. 12. Variation of SOC in (a) cloudy summer, (b) winter, (c) spring, and (d) summer throughout a day with the car traveling at 60% of the road at top speed.
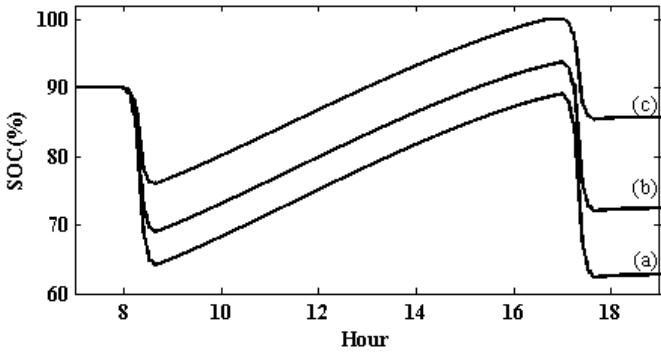

Fig. 13. Variation of SOC for a car with mass (a) 1000kg, (b) 800 kg and (c) 500 kg with the car traveling 60% of the time at top speed in summer.

B. Environmental Impact

While there are no global warming emissions associated with generating electricity from solar energy, there are emissions associated with other stages of the solar life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. Most estimates of life-cycle emissions for photovoltaic systems are between 26 and 60 grams of carbon dioxide equivalent per kilowatt-hour (CO_2eq/kWh) [11].

In addition to that, the proposed solar car needs different amount of additional energy to be supplied from national grid in seasons other than summer. In Fig. 14 the bars represent the average amount of energy supplied by the solar panels in a day for each month of a year while the car travels 30% of the road at top speed. The gap between the top of a bar and the dashed line of required energy is the measure of energy drawn from national grid. Apart from April and May, where the supplied energy is in excess of what required, the additional energy differs from month to month depending on the sun's position and the cloud factor of that month. The term cloud factor stands for the ratio of solar irradiance available on the surface of a solar panel to the ideal irradiance if the sky is clear. In January, for instance, about 60% of ideal irradiance falls on a solar panel due to excessive fog, but in April a panel can get excess to almost 80% and hence, the respective cloud factor of January and April is 0.6 and 0.8. Considering this factor a more pragmatic estimation of additional energy is calculated for each month having 25 working days. The total additional energy for an entire year is found by summing up the data of each month is around 55 kWh.

Generally, the electricity of national grid is produced by fuel driven power plants emitting a considerable amount of carbon dioxide which should also be attributed to the solar car while computing its environmental impact. The grid electricity emission factor is taken as 0.637 kg-CO_2eq/kWh [12]. Fig. 15 shows the average emission of CO_2eq gas in grams in a day for each month of a year. The effect of varying weight of the car on the greenhouse gas emission is also depicted in the figure. The total amount of CO_2eq gas emission over a year for a 500 kg car is 34 kg and for a 1000 kg car 134 kg.

On the other hand, petrol produces 2.7 kilograms of greenhouse gas emissions per liter combusted [13].

When it comes to calculating how a fuel driven car affects the atmosphere, the result is highly alarming. To travel from Uttara to Motijheel, a fuel driven car may burn 2 to 6 liters of petrol depending on the traffic condition and the type of the engine of the car. According to [13] petrol produces 2.7 kilograms of greehous gas per liter combusted leading to an emission of 11 kilogram of CO_2eq gas to the atmosphere per day if an average of 4 liters of petrol is assumed for the trip. The harm a fuel driven car does to the environment in a week is higher than that of a solar car in an entire year.

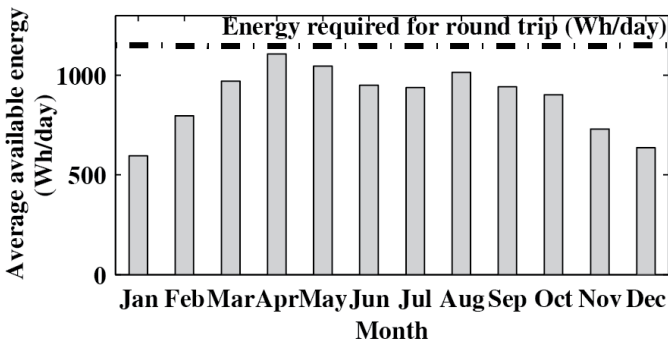Apart from their feature of pollution free drive, the feature

Fig. 14. Additional energy required by the car throughout a year with the car moving at 60% of the road at top speed with 10 number of stoppages.
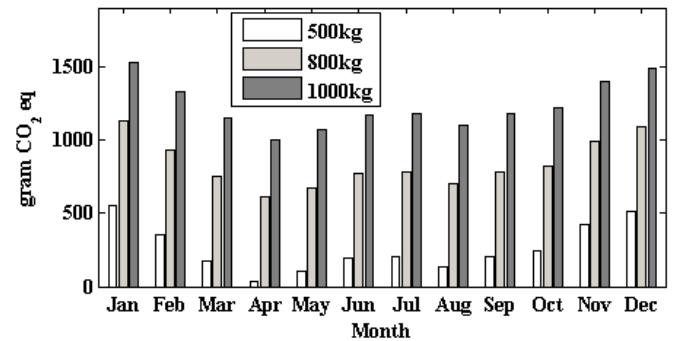

Fig. 15. Emission of CO_2eq gas for every month with a mass of 500 kg, 800 kg and 1000 kg with the car moving 60% of the road at top speed

TABLE III
OPERATION COST ANALYSIS OF A FUEL-BASED CAR

Component	First year (BDT)		Present worth for 25 years (BDT)	
	Without traffic congestion	With traffic congestion	Without traffic congestion	With traffic Congestion
Fuel	55,870	89,185	12,98,312	20,72,491
Annual Maintenance				
Engine Oil, Filter Replacement	30,000		697,142	
Servicing, Fitness Test, Tax	18,000		418,285	
Total Operation Cost			1,995,454	2,490,777

TABLE II
LIFE CYCLE COST ANALYSIS OF A SOLAR CAR

Component	Number of Units	Unit Cost (BDT)	Initial Cost (BDT)	Present Worth (BDT)
Solar panel	250W	140 per Watt	35,000	35,000
Battery	5	7,500	37,500	37,500
Battery 5 Yrs	5		37,500	36,360
Battery 10 Yrs	5		37,500	34,183
Battery 15 Yrs	5		37,500	31,160
Battery 20 years	5		37,500	27,541
Charge Controller	1	25,000	25,000	25,000
Charge Controller 10 Yrs	1		25,000	23,503
Charge Controller 20 years	1		25,000	22,096
DC motor	1	40,000	40,000	40,000
DC motor 10 Yrs	1		40,000	37,605
DC motor 20 years	1		40,605	35,354
National grid utility bill			620	14,407
Annual Maintenance			2,000	37,740
Life Cycle Cost				437,050

of solar car of requiring less energy at slower speed will be a big advantage over the fuel driven cars which consume more fuel at slower speed to cover the same distance due to inefficient burning of the fuel. Furthermore, fuel driven cars will keep buring fuel thus producing more pollution whenever in traffic congestion or waiting at a traffic signal, while the solar car, instead of consuming energy, will harness energy from the sun.

C. Economic Aspects

Life cycle cost (LCC) analysis is a way to determine the economic impact of current and future costs comprised of the cost of operating an item over its entire lifetime, starting from the time of initial acquisition till purchases made later [14].

The LCC of the solar car includes the cost of the solar panel and the expenses related to the operation and the maintenance of the panel and the battery. Solar panels are expected to serve for no less than 25 to 30 years without requiring any major replacement. It is considered that with cautious taking care of, monocrystalline panels may even last till 40 years [15]. The initial cost of setting up a panel is quite high, but this investment is compensated by its long life of 25 to 30 years. Electric lead-acid batteries also have a high life cycle of 5 years and therefore will not require frequent replacements [15]. Manufactured three stage charge controllers usually have a factory warranty of 5 years, but they have an expected lifetime of 15 years [16]. Brushless DC Motors usually have a life span of more than 10000 hours that corresponds roughly to 10 years

of operation with a car with a maximum of 4 hours of daily usage [17].

In order to find the LCC, the present worth (PW) of all the components needs to be determined and then summed. Present worth of any item is the amount of money that needs to be invested at the present time in order to purchase the item 'n' years later, assuming an inflation rate of 100i% and an interest or discount rate of 100d%, and is given by,

$$PW = \left(\frac{1+i}{1+d}\right)^n \times C_0 \tag{40}$$

where C_0 is the initial cost of the item at the time of investment[18];

For recurring expenses, which adds up to the total cost every year of operation, the individual PW of each element in the series can be added up to find the cumulative PW. Thus expenses such as the fuel cost and maintenance cost can be calculated using the following equation [18],

$$PW = \frac{1-x^n}{1-x}C_0 \tag{41}$$

where

$$x = \frac{1+i}{1+d} \tag{42}$$

The values of the average inflation and interest rates of Bangladesh have been found to be 6.59% and 7.25%, respectively.

We can further add the cost of electricity when the solar car will also be powered through main line electric supply during days of insufficient solar energy. The tariff of electricity supplied by Dhaka Electric Supply Company (DESCO) to home and business consumers with an average consumption over 400 units is BDT 11.25 per kWh of usage for residential use [19]. For 55 kWh calculated in the previous subsection the cost is BDT 620 a year, and BDT 15,500 for 25 years.

Considering the costs of each component and their corresponding life span, the LCC of a solar car is found BDT 190,000 over a period of 25 years, considering 280 days of office commuting [1].

On the other hand, A 1500 cc car (e.g. Toyota Corolla X) which runs on gasoline on the streets of Dhaka can cover a maximum distance of about 17.24 km per liter without encountering any traffic congestions. If, however, there are heavy traffic jams on the road, the distance traveled per liter is reduced to a maximum of 10.8 km [20]. Thus, the amount of petrol required to travel a distance of 40km for 280 days of a year are 1050 and 650 liters with and without traffic congestion respectively.According to the current price chart

[21], the price of petrol is BDT 86 per liter, and hence BDT 2,305,500 with traffic congestion and BDT 1,445,500 without traffic congestion are the estimated cost of operating the car for a period of 25 years including other maintenance cost of the car as shown in Table III. These figures, compared to that of a solar car, are shockingly high.

On top of the value calculated, costs in terms of environmental and health hazards also needs to be taken into account. It can be clearly seen the long run cost of running a fuel-based car far exceeds the cost of using and maintaining a solar car, both quantitatively and qualitatively.

V. Conclusion

Battery performance of a propsed solar car has been investigated while the car makes a trip from home to workplace of an office commuter under different road conditions, using a model developed in Matlab Simulink. It has been observed that energy requirement decreases significantly when the car runs at a slower speed due to lower air drag force at lower velocity. Thus for a city like Dhaka, where traffic congestion is a daily occurrence, solar car will be a perfect mode of transportation as it is not only emission free but also consumes less energy under heavy traffic congestion, unlike the fuel driven cars which consumes more energy and emit more toxic gases under such condition.

References

[1] S. Ahmed, A. H. Zenan, and M. M. Rahman, "A two-seater light-weight solar powered clean car: Preliminary design and economic analysis," in *3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)*, May 2014, pp. 1–7.

[2] T. M. A. Khan, S. Rahman, M. K. Afgani, and K. E. Fahim. (2014, May) Solar car. 09221020.pdf. [Online]. Available: http://hdl.handle.net/10361/3228

[3] D. Dusabe, J. Munda, and A. Jimoh, "Modelling of cloudless solar radiation for pv module performance analysis," *Journal of Electrical Enginieering*, vol. 60, no. 4, pp. 192–197, 2009.

[4] L. Castaer, S. Bermejo, T. Markvart, and K. Fragaki, "Chapter iia-2 - energy production by a {PV} array," in *Practical Handbook of Photovoltaics (Second Edition)*, 2nd ed., A. McEvoy, T. Markvart, and L. Castaner, Eds. Boston: Academic Press, 2012, pp. 645 – 658. [Online]. Available: http://www.sciencedirect.com/science/article/pii/B9780123859341000180

[5] E. Lorenzo, *Solar Electricity: Engineering of Photovoltaic Systems*. Earthscan/James & James, 1994.

[6] A. Hansen, P. Srensen, L. Hansen, and H. Bindner, *Models for a stand-alone PV system*. Vindenergi og atmosfriske processer, Ris-R-1219, Ris-R-1219(EN), 2001.

[7] D. Sutanto and H. Chang, "A new battery model for use with battery energy storage systems and electric vehicles power systems," *IEEE Trans. Energy Convers.*, vol. 4, no. 2, Mar. 1995.

[8] R. Tariq, S. Sabbir, and S. Afrin, *Dynamic electrical model of sealed lead-acid battery for EV simulation*. Dhaka: BRAC University, Apr. 2014. [Online]. Available: http://hdl.handle.net/10361/3229

[9] M. Coleman, C. B. Zhu, C. K. Leel, and W. G. Hurleyl, "A combined soc estimation method under varied ambient temperature for a Lead-Acid battery," in *Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE*, vol. 2, Mar. 2005, pp. 991–997.

[10] S. Leitman and B. Brant, *Build Your Own Electric Vehicle*, 3rd ed. McGraw Hill Professional, Feb. 2013.

[11] NREL Laboratory, Alliance For Sustainable Energy LLC website, U.S. Department Of Energy, "Life cycle greenhouse gas emissions from solar photovoltaics," http://www.nrel.gov/docs/fy13osti/56487.pdf.

[12] M. Brander, A. Sood, C. Wylie, A. Haughton, and J. Lovell, "Electricity-specific emission factors for grid electricity," Ecometrica, Tech. Rep., 2011. [Online]. Available: https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf

[13] A. Kakouei1, A. Vatani1, and A. K. B. Idris, "An estimation of traffic related co2 emissions from motor vehicles in the capital city of iran," *Iranian Journal of Environmental Health Science & Engineering*, Nov. 2012.

[14] R. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, 2nd ed. CRC Press LLC, 2004.

[15] A. Celik, T. Muneer, and P. Clarke, "Optimal sizing and life cycle assessment of residential photovoltaic energy systems with battery storage," *Progress In Photovoltaics: Research And Applications*, vol. 16, pp. 69–85, Aug. 2007.

[16] E. Direct. (2013, Feb.) Comparison: Mppt versus pwm charge controllers. [Online]. Available: http://www.ecodirect.com/Charge-Controller-Comparisons/251.htm

[17] N. Minebea. (2013, Mar.) Brushless dc motors. [Online]. Available: http://www.nmbtc.com/brushless-dc-motors/

[18] R. A. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, 2nd ed. CRC Press LLC, 2004.

[19] Dhaka Electric Supply Company Limited, "Home consumers tariff rate, 2012 annual report," https://www.desco.org.bd/?page=tariff-rate, Jun. 2013.

[20] Toyota, "Toyota 2016 corolla: Features and specifications," http://www.toyota.com/corolla/2016/features, Mar. 2016.

[21] Bangladesh Petroleum Corporation, "Local selling price of petroleum products," http://www.bpc.gov.bd/contactus.php?id=39, Apr. 2016.