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Development of Energy Efficient Battery Electric Car for Shell Eco-Marathon Competition - Qatar University Experience

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Abstract - **The paper reports on the participation of Electrical Engineering students of Qatar University students in Shell Eco Marathon (SEM) competition, which aims at designing and racing energy efficient vehicles. This participation has multiple objectives both for improving student technical and soft skills. Details of the design of a three-wheel car for SEM Asia 2014 race in Manila are given. Additionally, a dedicated computer-controlled test bench is developed for testing and optimizing the car design, and for training the drivers for optimum driving strategy that minimizes energy consumption. The process of car and test bench design has gone through various phases of study, modeling and simulation, optimization, and testing. Both mechanical and electrical parts of the test bench as well as the car are designed in-house. The design has to meet SEM technical and safety requirement, which guided the team till the ultimate design. The testing was done on the designed car, which was shipped to Manila/Philippines to participate in the SEM Asia 2014 competition February 3-9, 2014 in Manila. In Manila, the team planned to record so many data from different runs with different driving strategies on the real track circuit. These data will be compared to those that will be obtained using the designed test bench for same conditions for further tuning and improvement of the car model and car design**.

Keywords-Car design, EV (electric Vehicle), Simulation.

I. INTRODUCTION

Interest in electric, solar and hybrid electric vehicles and even motorbikes has been steadily increasing in recent years. Giant oil and gas multinational companies are investing in research and development in renewable energy, and some are challenging engineering students to design and race energy-efficient vehicles. The well-established Shell Eco marathon (SEM) competition [1] is now running annually in Americas, Europe and Asia, and is attracting participation of university student teams from all over the world, as well as corporate teams (e.g. from Honda and Toyota). This competition includes two main categories: urban concept and prototype; each of these two categories includes a number of subcategories that depends on the type of energy used. Each year, SEM competitions enforce a number of rules; many of these rules change from year to year and from racing track to another. Hence students are challenged with set of new criteria in every competition; something that is beneficial to experienced participants and new comers alike as the design constraints change for each race offering new learning opportunities. The rules may be divided into three categories: technical, safety, and race rules; the comprehensive list is available online [2]. The competition is open to students from schools and universities, and is designed to challenge them in the design and racing of cars under stringent constraints. Such participation allows students to sharpen engineering, technological, and teamwork skills, and reinforces awareness of contemporary issues, including environment and energy efficiency [3]-[7]. Qatar University (QU) has identified this competition as a learning platform for engineering students, and decided to participate in the SEM race starting from 2011 in Lausitz, Germany. The motivation for this participation is to enable engineering students to compete with their peers at international level for multiple student and educational programs benefits. The ultimate goal is to embed the design of the car in the program as a learning platform that serves various courses including Electric Machines, Sensors and Instrumentation, Power Electronics, Communications, Renewable Energy, Control, Electronics, Embedded Systems, etc.

In this paper, we report on the work done by QU Electrical Engineering students in preparation for participation in the solar/electric prototype category of the upcoming SEM Asia 2014 competition in Manila, Philippines. The overall experience, challenges, achievements and future plans are discussed.

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II. CAR DESIGN AND IMPLEMENTATION

The primary design constraints are driven by the competition rules described above and by the racetrack and race conditions. The racetrack of SEM Asia 2014 is set in the roads of Manila (Figure 1) does not have step slopes and sharp turns. This relaxes electric motor and battery sizing constraints and allows a nearly constant driving strategy for maximum energy efficiency.

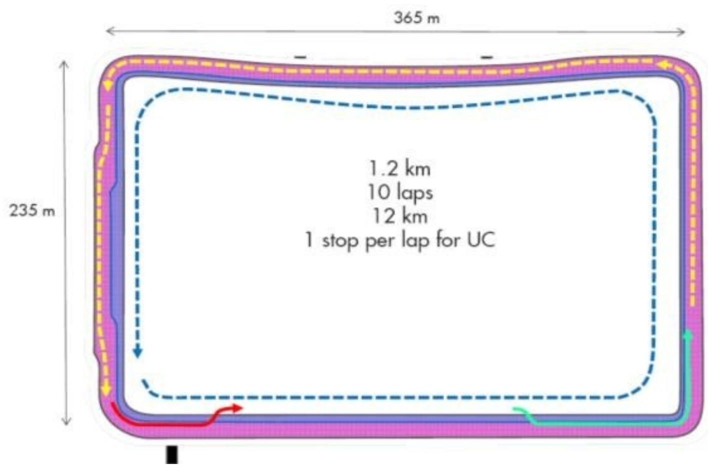
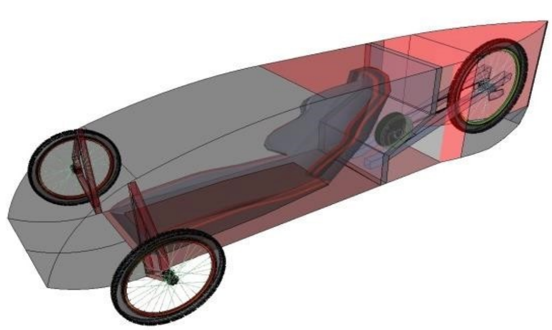


Fig. 1: Manila track to be used in SEM–Asia 2014

III. MECHANICAL ASPECTS

According to the rules and constraints of the race, the speed limit of the car should be around 45 km/h. After considering various concept designs, the team of students decided to opt for "teardrop" shape (Figure 2) that may be manufactured fully at the university; this was a challenging task for electrical engineering students. The teardrop has round, smooth sides that taper off and the shape has the lowest drag coefficient rather than other shapes; this makes the teardrop an aerodynamic shape. The car has two front wheels, used for steering, and one rear wheel, used for propulsion.



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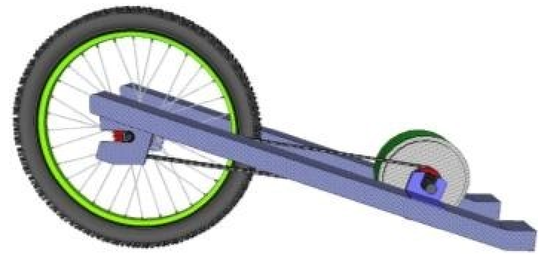

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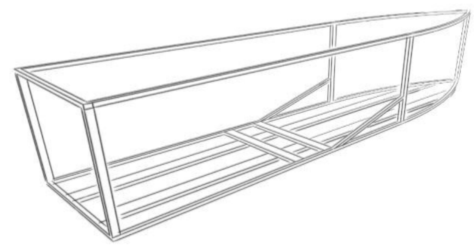

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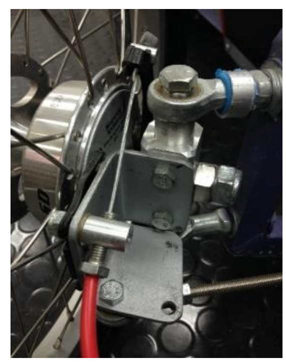
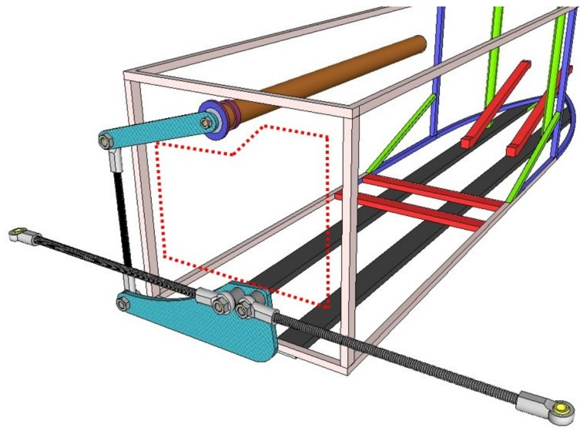


(d)

Fig. 2: (a) Adopted design concept of the car and details of some of its components (rear wheel and motor mounting (b), chassis-frame (c), and (d) in-wheel wire tensioned braking system with custom made knuckle).

The chosen design is based on an aluminum frame (Figure 2) made by aluminum square tubes of 2x2 cm and reinforced at the bottom by 2x4 cm rectangle aluminum bars. This choice was made after doing extensive comparison of carbon fiber, steel and aluminum by creating an evaluation matrix of these materials based mainly on weight, reliability, strength, and ease of assembly. The frame was designed to comply with safety rules of SEM, in particular with respect to the requirement of having an effective roll bar that extends 5 cm around the driver's helmet and protects the driver's shoulders when seated in normal driving position. Using 1 mm-thick polycarbonate sheets makes the exterior shell. The suspension system and wheels have been chosen to have a 10 cm clearance between chassis and ground. One of the most challenging tasks was the design of the two-wheel steering system as the small height and width of the vehicle frame are 50cm and 45cm. The custom designed steering mechanism shown in Figure 3 was good for a comfortable driving position and clear view for the driver as per the SEM rules. A sprocket chain system is used to couple the electric motor to an in-wheel gear that provides multiple gear ratios allowing suitable torque to be generated by the motor at low car speeds. A base was made in which both the motor and wheel are aligned very precisely to avoid any accident that may occur due to slip off the chain from the sprocket. The design allows easy wheel and motor removal. In-wheel-Drum-type brakes are used for all three tires; these are cable-activated from the steering.



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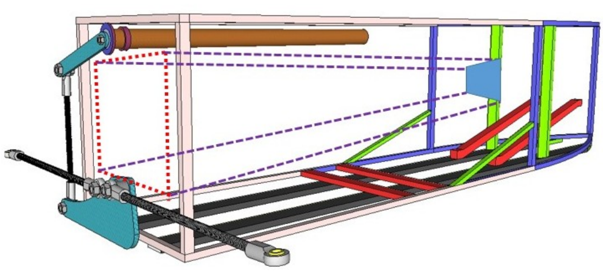

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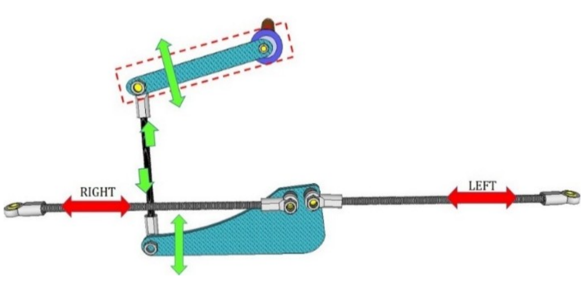


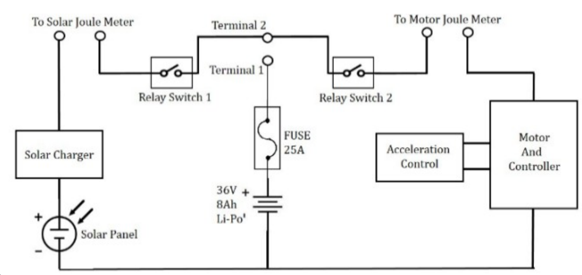
(c)

Fig. 3: The adopted steering mechanism. (a) Viewing space (RED DOT) from the top front view; (b) View (RED and VIOLET DOT) from the sitting position of the driver ; (c) the working mechanism of the steering system

As the design of the vehicle limits the view of the diver, the steering system was designed in a manner that the driver can have a good view from his sitting position. In Figure 3, the red dotted spot is marked as the viewing space for the driver. The whole steering system was manufactured in the university lab and the materials used for manufacturing were aluminum sheet 4mm, rod end's and aluminum threaded bars of 6mm. standard bicycle handle was used for the steering handle. The working mechanism of the steering system is very simple. From Figure 3, when the Upper part [red dotted] is pushed down, the vehicle moves to the right side and when it is pushed upward, it moves to left side.

IV. ELECTRICAL ASPECTS

The car was originally designed for SEM Asia 2013 in Malaysia (July 2013) where the track was characterized by steep hills and sharp turns. The race was canceled because of forest fires in neighboring Indonesia, which resulted in hazardous clouds of fumes over Malaysia. The organizers decided to report the team's participation to SEM Asia 2014 in Philippines (February 2014), which has a much different track (Figure 1) that requires less propulsion power. The motor power is at 210 W would have been adequate to overcome the slopes of Malaysia racetrack. The same motor will be oversized for Philippines track, but the decision was not to change it given time constraints. The detailed electrical circuit and wiring diagram is shown in Figure 4.



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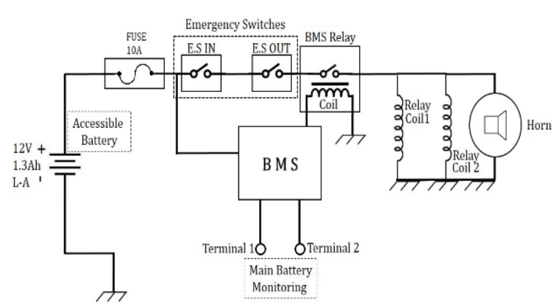


(b)

Fig. 4: (a) Main Electrical circuit diagram of the car; (b) Auxiliary circuit

The motor we have used has the following ratings: 48V 15A and 750 Watt. The motor parameters such as current are programmable to adjust for different scenarios. During the vehicle test, we have programmed the motor in different ratings to get the best results. For the peak-to-peak current we have programmed the motor for a maximum current of 7A while the continuous current was set within 12-15A. The motor and control system are powered from a 48V-Lithium-Polymer battery used as an energy storage device. The battery has a 5Ah /35A constant discharge current and is protected by a Battery Management System (BMS) as enforced by SEM safety rules. The BMS, protecting against over current, over voltage and excess temperature, was designed and tested in-house. The battery is charged through a solar charger, which is based on a boost converter enhanced with a Maximum Power Point Tracker (MPPT). The solar system provides 36V at a solar irradiance of 1kW/m2 by combining two 18V-10W-polycrystalline solar cells in series, due to the limited surface area of 0.17m2 allowed for solar panels. The boost converter boosts the 36V to around 55V in order to charge the battery. Despite the small contribution (estimated at 7 to 10%) of this solar power to the propulsion power, it was decided to include it so as to challenge the students in designing MPPT and battery charging system that makes most of the available solar power.

V. TEST BENCH DESIGN AND IMPLEMENTATION

Maximizing energy efficient is the ultimate objective of the SEM competition. It is clear that this efficiency is determined by performance of the vehicle and by the equally important driving strategy that should take into consideration the characteristics of the racetrack. In order to test different scenarios, it is important to have a dedicated computer-controlled test bench that can reproduce conditions similar to the race. Such a tool can help in assessing and improving vehicle performance and in educating the driver about the best possible driving strategy for maximization of energy efficiency. This test bench is designed to simulate all kinds of forces such as friction and air drag forces, which are applied by the test bench as load. The main objective of building a test bench is not only to improve driving strategy having a clear view of the track before the competition, but also to optimize the car drive train design for minimizing power consumption. Figures 5 and 6 show the basic diagrams of the test bench hardware and software respectively.

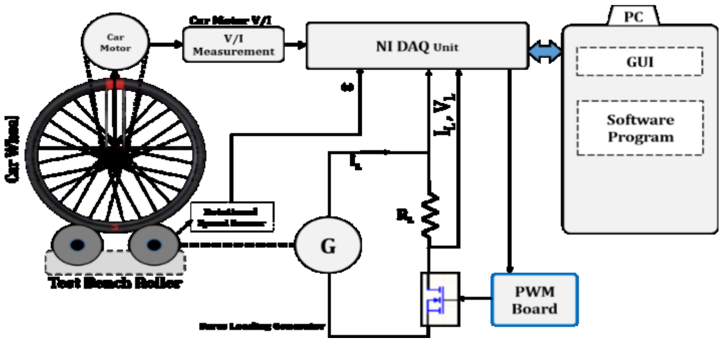
The test bench consists of two steel rollers where the rear wheel of the car under test will be placed. One of these rollers is directly coupled to a PM DC machine (rated 48V, 26.5 A, 3000 rpm) that will function as Motor or Generator according to the loading needs (i.e. in case of accelerating and cruising it will work as a generator to generate opposite loading forces and in case of coasting it will work as a motor to compensate for vehicle inertia). Based on previous experience in competition, drivers coast rarely and mostly try to maintain a constant speed in all track sectors. Therefore, the DC machine in the test bench is used as generator (loading mode) for simplicity. The generator output power is dissipated in a resistive load controlled by a PWM-driven electronic switch (MOSFET) for varying the average load acting on the car wheel. The force acting on the car wheel (determined by the PWM signal duty cycle) will simulate the total traction force or tractive effort calculated by the software program (LABVIEW environment). Communication between the PC and hardware is done through a 12-bit NI-DAQ. The various parameters (car motor Voltage and current, car speed, and load current and voltage) are collected in real time via sensors. Emulating a certain track can be implemented by creating the same real tractive force (F_{load}) through the test bench. From [8], only two forces needed to emulate the track on the test bench; namely and the aerodynamic drag force due to air (the first term in equation (1)) and the rolling resistance force (second term).

$$F_{load} = \frac{1}{2} * \rho * C_d * A * v^2 + \mu_{rr} * m_{front} * g \quad (1)$$

$$m_{front} = m_{total} - m_{rear} \quad (2)$$

where is the air density, A the frontal area, v the car velocity, C_d the drag coefficient, μ_{rr} the coefficient of rolling resistance, m the mass of the vehicle, and g the gravitational force. It is worth mentioning that the density of air varies due to humidity and temperature. Wind also plays a vital role for aerodynamic drag force.

During testing the car on the test bench, only rear part is placed on the bench's roller and the frontal part is placed on the ground, which dictates ignoring the weight of the frontal part. Therefore, only the frontal weight (equation (2)) was considered for the tractive force model. In order to generate the necessary PWM signal that results in the appropriate load on the car which emulates track conditions, the LABVIEW program performs the necessary calculation using equation (1) to simulate driving and track conditions by processing data from the test bench, car constant parameters (frontal area, air drag coefficient, total vehicle and driver mass and the rolling resistant coefficient that depends on the tire type and road surface roughness), track model (track sectors distances and gradient slopes), and time and speed (Figure 6). All the collected and calculated system variables are saved and displayed in real time using the GUI (Figure 7).



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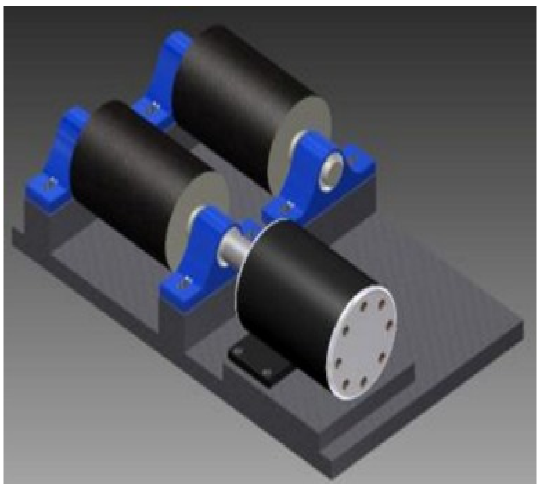

(b)

Fig. 5: (a) Bloc diagram of the test bench simulating cruising or accelerating; (b) Test bench Roller and Motor/Generator

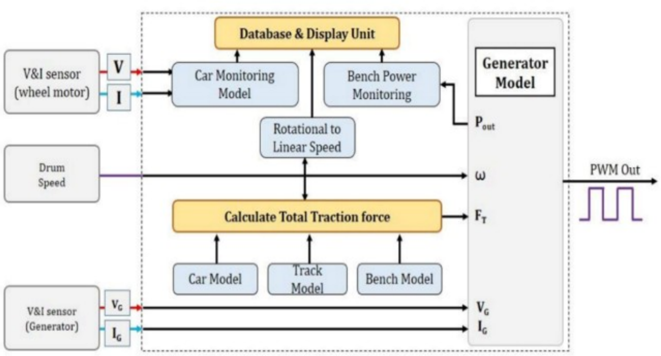

Fig. 6: Test bench software

In order to test the test bench, three runs of different scenarios are being tested on the car. In the first scenario, the electric car has to cruise at 25km/h for two minutes. It took 18 seconds to reach the cruising speed and the cruise control of the electric car is engaged. Using a wattmeter, which is connected with the car, the power for each second is measured. Energy consumption is measured by integrating all the powers over time. The obtained results are depicted in Figure 8.

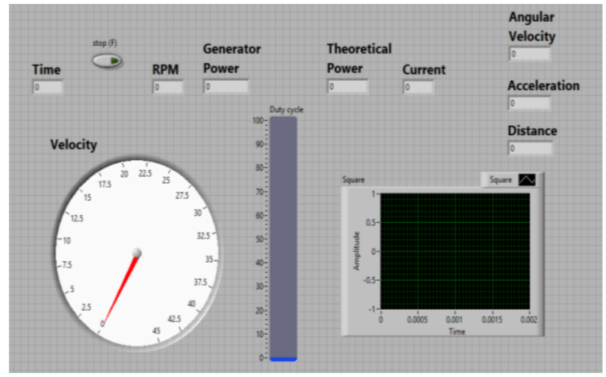

Fig. 7: Display view of test bench model using LABVIEW

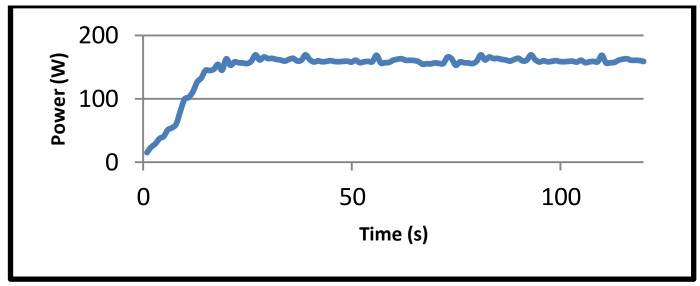

Fig. 8: Power vs time graph at 25km/h (high acceleration)

From Figure 8, it is obvious that the power of the electric vehicle is increasing until 18 seconds and after reaching the cruising speed, the power remains almost constant. The electric vehicle consumes equal amount of power if the speed does not change, which agrees with the theoretical power computed by the LABVIEW model. On the other hand, the small and localized fluctuations in the power curve are due to the sensitivity of the current sensor upon the automatic adjustment of the duty cycle by the LABVIEW program in order to maintain the load (air drag and rolling forces) power. For that reason, the duty cycle increments and decrements in order to keep the theoretical and test bench-emulated load power matched.

In the second scenario, the electric car has to cruise at 25 km/h with slower acceleration for two minutes. It took almost 40 seconds to reach 25km/h and after that the electric car cruises to 25 km/h. The results are shown in Figure 9.

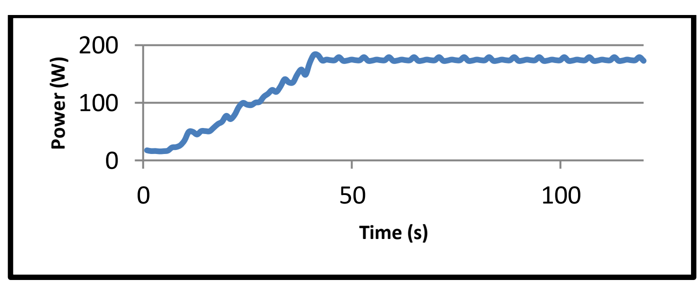

Fig. 9: Power vs time at 25 km/h (slow acceleration)

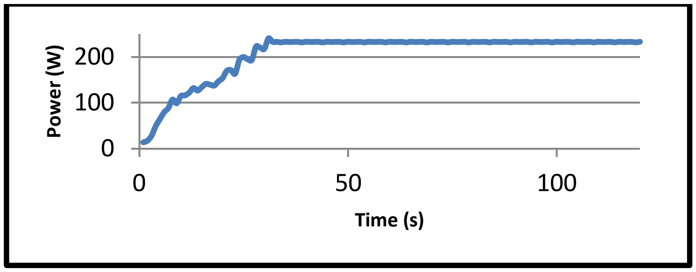

Fig. 10: Power vs time at 35 km/h

In the third scenario, the electric car has to cruise to 35km/h with medium acceleration. It took 31 seconds to reach 35 km/h and after the electric vehicle runs into cruising speed. The results are depicted in Figure 10.

Typical numerical results are summarized in Table 1 for the three above scenarios. From the Table 1, one can conclude that if the electric vehicle is cruising at a same speed, but with different accelerations, the one with higher acceleration will consume more energy than the one with slower acceleration. Moreover, increasing the velocity will consume more energy. Also time is an important factor for emulating the track, because in the competition the driver should finish the lap within a certain limit (28 min). From the several test runs over the developed test bench, the electric car consumes power without connecting any electrical load to the generator due to the inertia of the permanent magnet DC motor (used as a generator) as well as the inertia of the roller. It's worthwhile to mention that the roller was manufactured twice to reduce its inertia.

TABLE 1: ENERGY CONSUMPTION TABLE OF DIFFERENT SCENARIOS

Scenario	Time to reach velocity (s)	Energy consumption (Wh)	Distance (m)	Time (s)
Speed at 25km/h	18	4.966	715	120
Speed at 25km/h	40	4.752	682.5	120
Speed at 35km/h	31	6.921	903	120

The test bench enabled the team to devise a better driving strategy for SEM ASIA Manila completion in 3-9 February 2014. Nonetheless, the team is working on improving the test bench and fine-tuning the theoretical model.

VI. CONCLUSION

An electric car has been designed for the Shell Eco Marathon Asia 2014 competition. This has been implemented and successfully tested. A test bench emulating real track conditions has been designed, implemented and tested successfully. The test bench considered all forces (e.g. air drag and rolling resistance) that would be practically involved in real scenarios. Therefore, this set up enables optimizing the driving strategy indoors, optimizing the design of the car, training the driver on the best driving strategy, and hence minimizing the energy consumption.

The test bench comprises three main parts: a mechanical roller, a load emulating all the forces acting upon the car, and a control system that controls the test bench. The control system consists of a Labview program acquiring readings from appropriate sensors. A mechanical roller made of steel was designed and manufactured to the width of the tire so that the rear tire of the car rests safely on the roller. In order to emulate the real track a computer-controllable electronic resistive load (2.2 Ohm total) was designed. This load consists of a permanent magnet DC motor that can be used as a generator loaded with a variable resistance. The electronic load emulates the forces, which are not available in labs such as air drag and rolling resistance forces. This load, hence its power, is controlled by adjusting the duty cycle of chopper circuit put in series with the variable resistance. The Labview program has to match the real power being measured using the sensors with the power calculated by a car theoretical model by adjusting the chopper duty cycle. At the matching condition, an extra load is being added to the car (running on the roller), which is equal to the power needed to account for the drag force and rolling resistance. The theoretical model was validated using the data obtained during QU team participation in SEM Asia Malaysia 2012. As the car speed changes the forces involved should change accordingly. A speed sensor was then used in order to measure the real speed of the car running on the test bench, which is needed by the model. Also, the speed-readings allow the model to calculate the distance being covered and hence displaying next values for speed and power requirement for the next track sector. The whole set up was tested successfully on the car, which will participate in SEM Manila 3-9 February 2014. In order to find the best driving strategy three different scenarios were tested using two main parameters, namely the car speed and the way gears are shifted (slow and fast). The results showed that the energy consumed by the car is less when the speed is less, when gear is changed slowly and when the acceleration is slow. This indicates that the test bench is emulating real scenarios. It is planned to use the SEM Manila data to scrutinize further the car model and the test bench.

VII. ACKNOWLEDGEMENT

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