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Solar vehicles – a feasibility study toward optimization of energy consumption based on regional insolation and traffic data

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چکیده

The concept of energy optimization in vehicles is typically regarded as reducing the fuel consumption. Designing vehicles running on clean, free solar energy is a novel approach that can fulfill all necessities considered in this idea of optimization. Utilization of solar energy in transportation industry particularly commuter urban vehicles may seem impractical due to low efficiency and output of solar cells in comparison with other power sources. Therefore, performing feasibility studies based on technological limitations, regional insolation data and traffic status is absolutely essential. This paper, besides introducing solar vehicles, describes the general equation of power in terms of insolation, resistances and losses. Based on real solar irradiation and traffic information related to the city of Mashhad, the second biggest city in Iran, the feasibility of designing a solar commuter vehicle is investigated. The results clearly state that the idea can provide reasonable annual range of urban traveling. In addition, the environmental effects of utilizing these zero-emission vehicles for reducing hidden ecological costs are studied.

Solar vehicles – a feasibility study toward optimization of energy consumption based on regional insolation and traffic data

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Abstract – The concept of energy optimization in vehicles is typically regarded as reducing the fuel consumption. Designing vehicles running on clean, free solar energy is a novel approach that can fulfill all necessities considered in this idea of optimization. Utilization of solar energy in transportation industry particularly commuter urban vehicles may seem impractical due to low efficiency and output of solar cells in comparison with other power sources. Therefore, performing feasibility studies based on technological limitations, regional insolation data and traffic status is absolutely essential. This paper, besides introducing solar vehicles, describes the general equation of power in terms of insolation, resistances and losses. Based on real solar irradiation and traffic information related to the city of Mashhad, the second biggest city in Iran, the feasibility of designing a solar commuter vehicle is investigated. The results clearly state that the idea can provide reasonable annual range of urban traveling. In addition, the environmental effects of utilizing these zero-emission vehicles for reducing hidden ecological costs are studied.

Keywords – Feasibility study, Insolation, Power cycle, Solar vehicle, Traffic data

1- Introduction

Since the outset of automobile industry, internal combustion engines have been employed as the most popular mechanical drivers and hydrocarbons as the most important fuels. After the oil crisis in the late 1970’s and beginning of the environmental concerns in 1980’s, efforts were started to find an alternative source of energy for power generation in general and automobiles in particular.

Electric vehicles, once being the counterpart of fuel-consuming vehicles in 19th century and then just recognized for research or recreational intentions, have been the most promising ideas receiving considerable attention. Batteries, fuel cells and hydrogen are the main proposed power sources in theses vehicles. Solar energy absorbed by solar cells and stored in batteries is another supply of energy that was introduced in solar vehicles.

Solar vehicles technology was firstly introduced by Hans Tholstrup and Larry Perkins who crossed Australia in 1983 just to show the practicability of an electric vehicle mainly dependent on solar energy. The idea was soon welcomed by many other groups from universities and automobile companies attending competitions held in many different countries. These races have been acting as exhibitions for introducing the newest technologies of electric motors, solar cells, batteries, composite structures and many other novel ideas. During these two decades, as the vehicles designed demonstrated promising performance, the idea of employing solar energy in urban vehicles has turned to a practical concept currently investigated by several groups especially in Australian universities.

In conventional fuel-consuming automobiles, the designer is not concerned about providing enough power to run the vehicle; but in solar vehicles, the balance between generated and consumed electric energy is marginally satisfied and that is just the point where the concept of optimization of energy consumption is well meant. Thus, the feasibility of a design founded on climatologic parameters and vehicles systems specifications must be carefully studied. Such studies have been presented in a number of technical reports but just in a few conference or journal articles [1-6]. This paper proposes a model for doing the feasibility design of solar commuter vehicles based on real solar data in the city of Mashhad and then discusses whether the results are satisfactory or not. Environmental effects of employing these vehicles are also briefly investigated.

2- Solar vehicles technology

A solar vehicle, as mentioned earlier, is an electric vehicle which supplies all or most of its required power by converting solar radiation into electricity with the help of solar cells. Based on the real time balancing of power cycle, electronic devices designed for these vehicles store the energy in the batteries or make use of batteries. Electric motors are the drivers of solar vehicles which are of great advantage in comparison to the internal combustion engines as they are much more efficient, have no emissions and need less supplementary elements such as cooling, fuel injection and power transmission systems. The structure of these vehicles is also made of light materials such as glass or carbon composites which considerably reduces the overall weight. All these benefits are exactly the factors that are important in optimization of automobiles attributes and particularly the energy consumption.

Solar vehicles have been designed based on two distinct strategies. The first type includes those which are to attend in competitions. Therefore, it is tried to achieve higher speed and longer driving duration utilizing the finest available technology. The cost of such designs frequently exceeds a hundred thousand dollars and the finally assembled car, like the one shown in Figure 1 is rather suitable for research activities than driving on urban streets.

Figure 1: Nuna II, the solar car designed in university of Delft, the best and most expensive one ever built

The other type of solar vehicles is designed to be used as a commuter car being an urban vehicle with characteristics in compliance with safety regulations and automobile standards regarding the dimension, seating layout and visibility domain, etc. Different teams from universities and automobile manufacturers around the world are currently working on this idea to obtain a design with reasonable cost and performance. A prototype of the vehicle Toria is shown in Figure 2.

Figure 2: Toria, an electric vehicle equipped with solar cells

Here in this paper, the second type that is the solar commuter vehicle is investigated based on regional climatologic and traffic information. Doing such an analysis is absolutely necessary to make sure about the practicability of the idea of running a car on solar energy which seems idealistic at the first look.

3- Governing power equation

In solar commuter vehicles, in analogy to any other vehicle, the electric power supplied by solar cells or batteries is consumed due to resistances and losses. The overall power equation can be stated as:

$$P_{motive}.\eta_e.\eta_m.\eta_t = mg\,C_{rr}\;V + \frac{1}{2}C_d A\rho V^3 + mg\,V\sin(\theta) + ma\,V_{ave} \qquad (1)$$

The left hand term is related to input power where P_{motive} is the power generated by solar cells and is always affected by weather conditions. The three other parameters are efficiency coefficients which correspond to electrical system, electric motor and power transmission mechanisms, respectively. On the right-hand side, the main four terms of energy losses are rolling resistance, aerodynamic resistance, road gradient and acceleration. Introducing the remaining parameters, m is the mass of vehicle, g is the gravity constant, C_{rr} is the rolling resistance coefficient mostly related to tires. In addition, C_d is the drag coefficient, A is the frontal area of the vehicle, ρ is the density of the air, V is the velocity of vehicle and V_{ave} is the average velocity during vehicle acceleration. All these parameters are subjected to varying in each possible design, giving the designer the flexibility to balance Equation 1 according to driving strategy and urban necessities.

4- Numerical results of the feasibility study

To perform a reliable feasibility study for utilizing solar commuter vehicles in a certain region, daily solar insolation and urban traffic information should be available. For the city of Mashhad, these data are taken from [7] and [8], respectively and then placed in Equation 1 in terms of input power, velocity and urban traveling range.

Figure 1 illustrates the amounts of insolation measured and recorded for the city of Mashhad in the year 2000, but as its variation is negligible during different years, it can be considered as the averaged monthly insolation for this city. The other parameters related to systems technical specifications are assigned based on some prototypes and also technological limitations in Iran, all stated in Table 1.

Table 1: Design parameters of the proposed solar car

m (kg)	Array area(m^2)	C_{rr}	C_d	A (m^2)
300	2	0.01	0.25	2
η_e	η_m	η_t	η_{cells}	V (km/h)
0.8	0.8	0.8	0.15	36, 50, 55

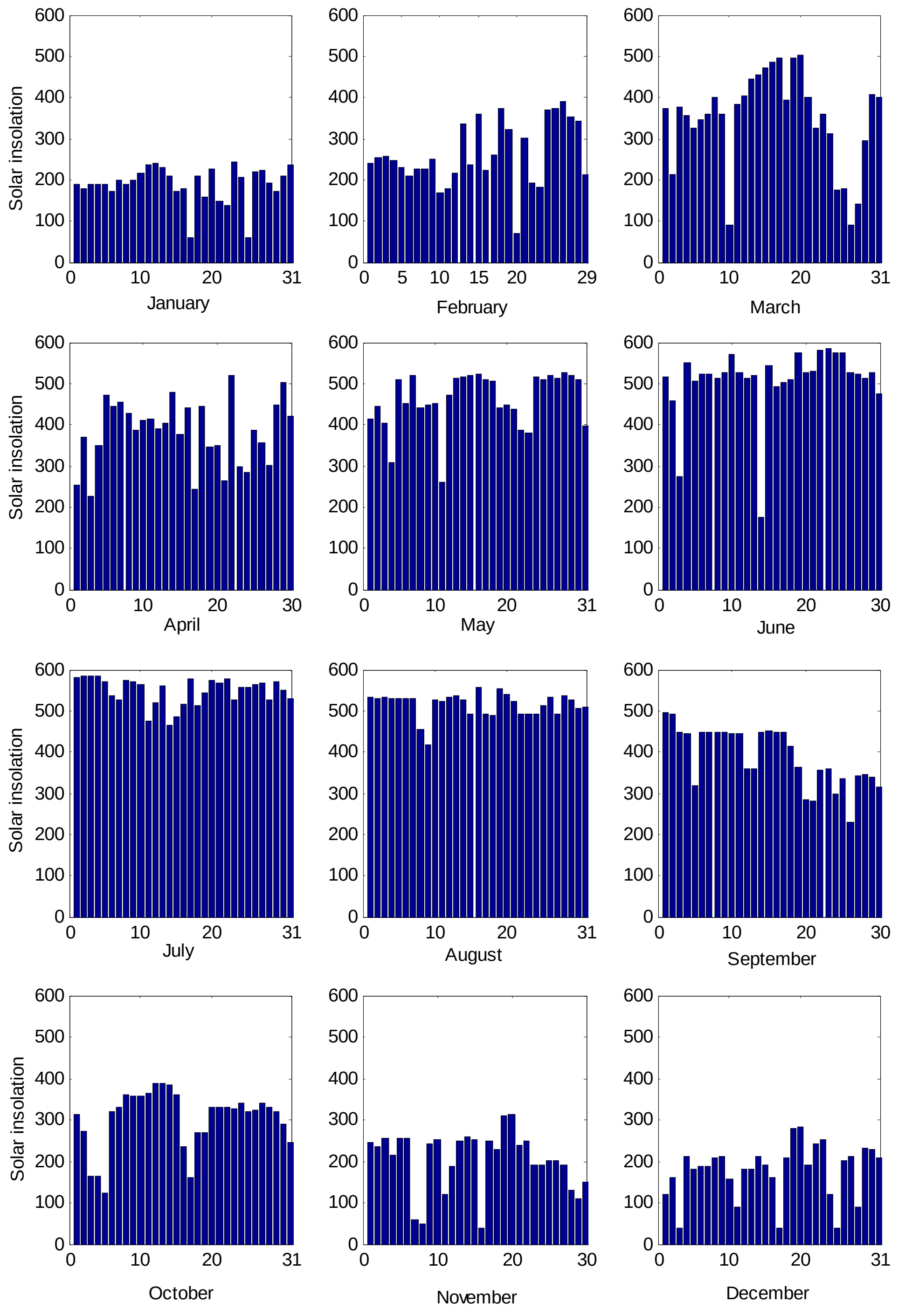

Figure 1: Daily solar insolation in cal/cm^2 measured in the city of Mashhad in the year 2000 [7].

For a race car, that is not supposed to be analyzed here, the most important riding parameter is the maximum speed of the vehicle. However for solar commuter vehicles, due to maximum speed limit in urban areas and also the traffic status in mega cities, the driving range turns out to be more critical.

To improve this driving range, utilizing a battery pack, which is requisite to the concept of solar vehicles, is the easiest approach. Using the input data in Table 1, the daily insolation (firstly converted to metric scale) presented in Figure 1 and a 1.5 kWh pack of lead acid battery which is proper in size and cost for a solar commuter vehicle, the daily driving range is calculated. The results are demonstrated in Table 2 considering two different conditions. The battery being full in the morning or just being charged during the day, are the two different assumptions. It is obvious that a battery pack imposes extra weight to the vehicle, about 30 kilograms for each kilowatt-hour capacity; however, the results shown in Table 2 are beyond expectations.

The assumed velocities are also meaningful based on the research reported in [8]. The velocity of 36 km/h is the average velocity of vehicles on streets except downtown. 50 km/h is the average velocity measured in highways and 55km/h is the maximum allowable velocity of automobiles in urban areas.

Table 2: Annual range of traveling based on the proposed solar commuter vehicle

Velocity (km/h)	Annual traveling range (km)
36 (empty battery)	13944
50 (empty battery)	9443
55 (empty battery)	8278
36 (full battery)	28600
50 (full battery)	19804
55 (full battery)	17642

It is obvious that the amount of solar irradiation varies in different months of the year. Consequently, the monthly traveling range is different being maximum in summer and minimum in winter. Figure 2 shows this range in the same year calculated for the speed of 50 km/h and in the case of empty battery in the morning.

With the free driving speed of 50 km/h, the vehicle has a driving range of about 9500 km which is nearly doubled to 19800 km considering a 1.5 kWh pack of lead acid battery. This obtained traveling range with such a vehicle is nearly identical to the average annual traveling range of a commuter in Mashhad [8] and therefore proves the practicability of solar commuter vehicles. It is also notable that the proposed design has still considerable potentials for improvement especially regarding the efficiencies stated in Equation 1.

In both these calculations, it is assumed that the vehicle is always subjected to solar radiation during sunlight hours. This is due to the fact that a commuter vehicle is parked in most of these hours and therefore can be easily subjected to solar rays. An off-line off-board solar module mounted at the parking roof, being always oriented toward the solar rays can also be an interchange to this concept. In the latter case, no solar cell is mounted on the vehicle and the vehicle batteries are charged not with network electricity but with solar energy absorbed by the module and stored in off-board batteries.

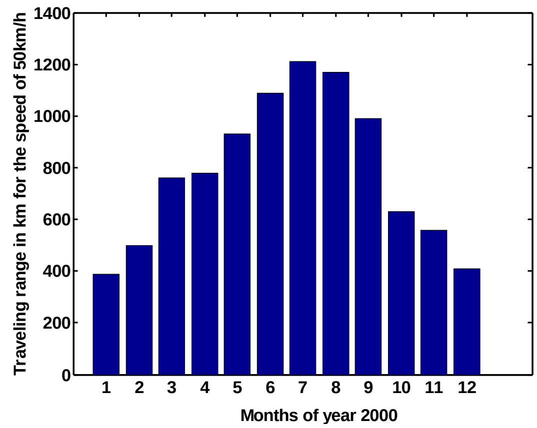

Figure 2: Monthly traveling range (in km) for the proposed vehicle with the velocity of 50 km/h.

It is noteworthy that Mashhad can be considered a typical benchmark for other mega cities in Iran because of its climatologic and traffic status. Hence, the results can be safely extended and confirmed.

Optimization of energy consumption in vehicles, whether by reducing fuel burning or employing other sources of power, normally results in economical advantages in the view of vehicle owner or optimization of energy utilization in the global aspect. However, the other important side that is mostly neglected is the environmental benefit. Employing the clean energy of solar radiation instead of the fossil fuels which produce pollutants such as CO_2, CO and NOx can undoubtedly decrease the intensity of air pollution in big cities. It also helps to eliminate the unnecessary costs imposed to the society due to health and ecological problems. Results in Table 3 confirm the environmental benefits of using such green vehicles as an alternative to conventional automobiles.

Table 3: Annual ecological costs due to automobiles fuel consumption in Mashhad (2002)

Type of pollutant	Ecological costs ($)
CO_2	29,000,000
CO	96,000,000
NOx	48,000,000

The costs are calculated based on the information derived from [8] and the costs imposed by the emission of greenhouse gases estimated and reported by U.S. Environmental Protection Agency (EPA) [9].

5- Conclusion

In this paper, the technology and history behind solar vehicles were briefly introduced. Then, to ensure the feasibility of an urban vehicle being totally or to a great extent relied on solar energy, a simple equation for balancing generated and consumed power was reported. Regarding realistic consideration of available technologies in Iran for manufacturing a light-weight passenger car, real daily solar irradiation and traffic information of the city of Mashhad, the equation was solved for different driving strategies during a given year. The results clearly demonstrate that the idea can be practical and fulfill the minimum commuting requirements in such a mega city. In addition, a considerable amount of money can be saved because of the ecological and health benefits in the case of using zero-emission vehicles, such as solar commuter vehicles, as a replacement for fuel consuming automobiles.

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