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Tradeoffs in the Design of Solar Powered Vehicles

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Abstract. *The University of Puerto Rico-Mayaguez (UPRM) has many past efforts in developing alternate energy vehicles. Due to our lack of fossil fuels, the island has to import all of its energy producing fuels. Furthermore, our limited land area has stressed the need for clean renewable energy sources for the island's future well being. The automobile has the greatest potential due to its central role in today's society. Past efforts include projects such as electric, hybrid and solar powered vehicles (SPVs). In 1990 "The Shining Star of the Caribbean", Puerto Rico's first SPV participated in GM Sunrayce, the first solar powered vehicle race across the United States. The UPRM also participated in Sunracye 1993 (USA) and The World Solar Cup (Australia) with it's second generation SPV, "Discovery" and in Sunrayce 95 with the third generation SPV, "The Shining Star II". These projects were developed by students in an interdisciplinary environment. This paper describes the evolution and design tradeoffs of our solar powered competition vehicles during the past decade. The most important design considerations are its overall efficiency, low cost, design for serviceability, and design for shipping. Experiences learned from the competitions are also presented.*

Keywords: *Solar powered vehicles, engineering education*

1. INTRODUCTION

In the 1970's the energy crisis sparked interest in alternate energy systems for everyday use. Today's environmental considerations have renewed this interest further. The automobile has the greatest potential due to its central role in today's world. From the first known electric vehicle, Thomas Davenport 1834, to the first solar car trip, Hans Tholstrup 1982-83, the solar car concept has become an interest to many car manufactures today. This concept has developed to the point of having international solar car races.

The University of Puerto Rico has been looking for alternate energy extensively. Research efforts for renewable energy sources has lead to projects such as human powered, electric and hybrid vehicles in the past. One of the most challenging projects is the development of technology for solar powered vehicles. SPVs are developed as part of the course INME 5015 Special Topics at the Department of Mechanical Engineering, University of Puerto Rico, Mayaguez Campus. The solar powered vehicle program is based mainly on the work of undergraduate students.

The objectives of this project are threefold. First, education of students in the underlining principles of vehicle design, construction and testing subject to various constraints in particular environmental and energy considerations. Secondly, provide a means for students to acquire practical, “hands on” experience in their field of choice. Lastly, build a competitive solar powered competition vehicle capable of participating in national and international events such as the Sunrayce and the World Solar Challenge.

The design and construction of a solar car is not a trivial exercise. The students are required not only to design, manufacture, test and race their solar powered vehicles but to raise the funding required complete the project. The funds required to enable an endeavor of such activity are significant. The students must face "real world" challenges such as competing for limited funds, writing proposals, presenting and selling their project to possible sponsors, meeting deadlines and teamwork in addition to applying state of the art technology.

2. VEHICLE CONSIDERATIONS

Not only producing a vehicle that has efficient power capabilities and outstanding aerodynamics is important, but adhering to the Sunrayce and World Solar Challenge rules is of vital nature. Considerations such as the solar collector volume space of 1.6 x 2 x 4 meters, braking distance of 22 meters at a velocity of 30 Km/hr, stability considerations, and drivers safety (seat belts, vision, collision safety) are required. In addition, the Sunrayce classification (1993 and after) requires the use of lead acid batteries and terrestrial grade solar cells. These restrictions influence a great extent influence the weight, power consumption, and overall design factors of the vehicle. In addition the rules have evolved since the first competition therefore requiring reevaluation of the design tradeoffs for each event.

Figure 1 shows a typical solar vehicle configuration. The solar panels capture the solar energy and convert it to electrical energy. The peak power tracker matches the impedance between the solar panel and the load to optimize the power efficiency under varying atmospheric and road conditions. Energy from the power tracker is fed to the motor/controller subsystem. Any excess energy not used for propulsion is stored in the battery modules. Energy recovered during braking is also fed back to the batteries.

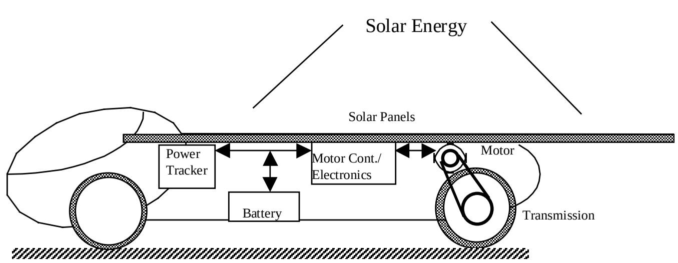


Figure 1 Typical Solar Vehicle Configuration

During the concept generation phase alternate configurations for the vehicle are studied and used to obtain comparative data on the tractive force delivered, power required, solar area available, aerodynamic shape and vehicle stability (center of mass location) for each vehicle configuration. The basic three alternative configurations studied are listed below.

1. Four-wheeled vehicle

2. Three-wheeled vehicle (one fore tire and two aft tires)
3. Three-wheeled vehicle (two fore tires and one aft tire)

The design starts with the energy management considerations in order to size the power components: solar panel, energy storage and motor/controller. In addition the preliminary energy management study is used as a guide to establish performance goals and other design parameters such as target weight, aerodynamic coefficients, tire characteristics, etc.. Component selection is based on the following criteria:

1. Cost
2. Ease of manufacturing parts
3. Ease of obtaining supplies
4. Reliability and Safety
5. Vehicle Performance Characteristics
6. Maintenance and Emergency Repairs
7. Ease of transportation (was overlooked in the first generation)

2.1 Energy Management

An energy balance Eq. (1) on the system states that the all the solar energy that enters (**Ein**) minus the expended energy (**Eout**) equals the energy stored in the batteries (**ΔE**). The expended energy includes both that used for propulsion and mechanical/electrical losses.

$$\Delta \mathbf{E} = \mathbf{Ein} - \mathbf{Eout} \qquad \textbf{(1)}$$

Given that the amount of energy available is limited (the solar collector area must be 8 m^2 or less) losses, must be kept to a minimum in order to maximize performance. Losses are due to the inefficiencies of the electrical and mechanical components used and are a function of the operating point of these. The solar panel, battery module and motor/controller are areas where most electrical losses occur. The selection of both the solar cell type and battery type greatly affect the overall efficiency of the vehicle but their selection was primary based on budget constraints. In both cases efficiency is directly proportional to cost. For example aerospace grade cells with higher efficiencies than terrestrial grade cells usually cost an order of magnitude more then the later. Similarly Silver Zinc battery cells have one of the highest energy recovery efficiencies and capacity/weight ratio but are also an order of magnitude more expensive than lead acid batteries. Aerodynamics, rolling resistance and friction in the mechanical systems account for the greatest mechanical losses *Just and Serrano* (1990), *Serrano* (1991). Figure 2 illustrates the energy flow in the solar powered vehicle.

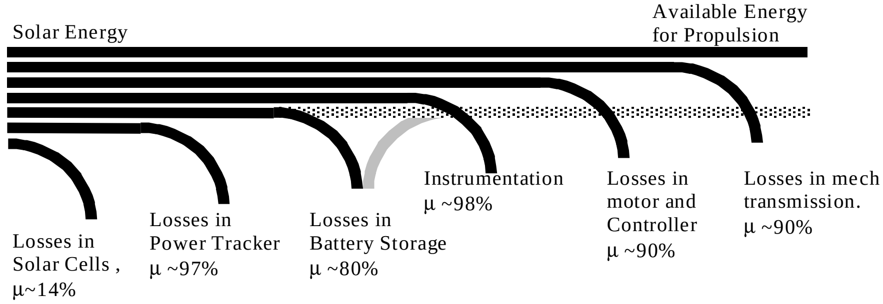


Figure 2 Energy Management in a Solar Vehicle

Once a motor/controller combination is selected the peak operating efficiencies vary depending on the power and speed of operation.. Motor controllers generally have a high efficiency. Brushless DC motors suitable for solar powered vehicle applications usually have a peak efficiency ranging from 75 to 85 percent but may exceed 90%. The cost for such motor/controller combinations exceed $4000. In order to determine the motor's rpm it necessary to determine the transmission ratio between the motor and the wheels. A three speed bicycle transmission has an efficiency of 95% and a transmission consisting of a deralleur has an efficiency of 98% , *Whitt and Wilson* (1983). Once the type of transmission is selected the transmission ratio must be determined that will provide the optimum cruise velocity at a the highest efficiency for a given power input *GM* (1989).

The expended energy is a function of the load and the speed. The load may be expressed as:

$$\mathbf{P_{Tractive} - ma - F_a - F_R = 0} \qquad \textbf{(2)}$$

Where $\mathbf{P_{Tractive}}$ is the tractive force produced at the tire ground contact; **ma** is the inertial acceleration force; $\mathbf{F_R}$ is the sum of the first order magnitude forces contributing to rolling resistance and $\mathbf{F_a}$ is the aerodynamic resistance force. Equation (2) may be expressed as a function of the reduction ratio, characteristics of the motor (rpm), available acceleration, wheel and tire used. In addition to the transmission efficiency, the vehicle's weight is also important as it affects the rolling resistance, gradeability and energy expenditures in accelerating the inertia. A mathematical model useful for simulation is generated using the energy balance Eq. (1), Eq. (2) and the vehicle's desired characteristics. With the model the effect of design decisions are tested, for example the selection of the transmission ratio, the rolling resistance data of various tires, motors (power, torque, speed, efficiency) and total solar area required, energy storage (capacity and weight tradeoffs) and aerodynamic coefficients.

2.2 Solar Panel and Energy Storage Selection

The solar panel array for the Shining Star was selected based on the number of facets the custom power tracker could handle. Aerospace grade silicon cells from Solarex were selected for the design of the Shining Star. Over 8000 cells were carefully hand mounted on Nomex™ honeycomb panels using an adhesive from Dow Corning. The result was an array with 6 facets, arranged such that they had a maximum power output of 1200 W. A computer program was developed to compare the power output for various solar array configuration alternatives and their effect on the vehicle's aerodynamic coefficient.

Silver Zinc battery cells manufactured by Eagle Pitcher were used with 30 Ah each as the energy storage device. The total weight of the energy storage system was only 27.7 kg compared to over 115 kg if lead acid batteries would have been used.

The second generation SPV, "Discovery 500", used a tilting flat panel to accommodate better angles of solar incidence. This design trades off aerodynamic efficiency for power input. The flat panel is less aerodynamic but it is more efficient as it can be adjusted to capture solar energy. This important tradeoff was due to the fact that the solar cells used in the "Discovery 500" were less efficient than those used in the "Shining Star". Another advantage of the flat panels was the ease with which it could be disassembled for transportation, in addition the electronics were simpler as it requires fewer power trackers. Aerodynamics become a dominant factor over 48 kph, but the vehicle was designed to cruise at the breakeven point therefore it was preferred to capture a larger amount of energy. The fact that the winner of the GM Sunrayce 1990 averaged 27 kph which is below the design point where the aerodynamics become the key factor was also taken into consideration in the tradeoff. Solectria terrestrial grade solar cells were used in the “Discovery 500”. The cells were purchased as modules therefore no need for mounting the individual cells, reducing manufacturing time and cost.

Lead acid batteries were used as required by the Sunrayce regulations. A 10 pack battery module was developed using DieHard deep cycle marine batteries weighing 10.4 kg each for a total of 104 kg and approximately the same capacity used in the Shining Star but over three times as heavy.

The third generation SPV, “Shining Star II” used a fixed panel design rather than a tilting panel as in our second generation vehicle due to the new race route. Previous competitions were held on a south to north direction, therefore a tilting panel offered an advantage in tracking the sun throughout the day. The 1995 route was a in the east west direction therefore the tilting panel design offered no power advantage. A flat panel configuration for the solar array was selected for its simplicity and low weight. The panel consisted of 800 laminated cells producing 92 volts and an average of 600 watts during the competition. In addition due to higher average cruising speeds the aerodynamics was among the key factors considered. The vehicle’s body aerodynamics included wind gust effects studied using CFD software and wind tunnel tests on scale models. Temperature effects in solar cell performance were considered in our energy management program. Extensive testing was performed to obtain accurate models of solar cells, batteries and vehicle performance in order to develop an effective energy management strategy. Wheels and suspension elements were contained within the body shell to reduce drag and a low center of gravity was used for higher stability. The “Shining Star II” energy storage system consisted of six Delco-Remy lead acid batteries, totaling 120 kg.

2.3 Motor and Transmission Selection

Primary concerns, in the selection of the transmission ratios, is operating the motor at it's highest efficiency possible. Various electric motors were studied by the students. Series DC , Shunt DC , and Compound Wound motors were examined. The Shining Star used an experimental 20 Hp 160 V Brushless DC motor from Unique Mobility. It was selected due to its torque, speed, current, and efficiency in the various operating ranges considered. The operating point of the motor is a function of the available power and the velocity of the vehicle. Therefore a primary concern, in the selection of the transmission ratios, is operating the motor at it's highest efficiency possible. Automatic and continuously variable transmissions were discarded in favor of a chain drive mechanism with efficiencies of up to 98.5% ,*Whitt and Wilson* (1983). Gradeability was determined from the maximum acceleration permissible from the vehicle configuration. The “Shining Star” used a chain drive mechanism with a 3.7 to 1 speed reduction.

The Discovery 500 uses an 8 Hp brushless DC motor by Solectria with timing belt drive mechanism. The speed reduction is 6 to 1. The motor has two windings therefore it may be used in low for high torque or in high for high speeds. With this reduction the Discovery is capable of 50 kph in low and over 80 kph in high. The Solectria motor was selected due to its lower cost.

The Shining Star II used the same motor/controller and transmission design as the Discovery 500, except that the gear ratio was sized accordingly to the performance and vehicle characteristics. The brushless DC motor with timing belt drive had proven to be reliable in the past experience and its lower cost were the key factors in the design decision of the third generation SPV.

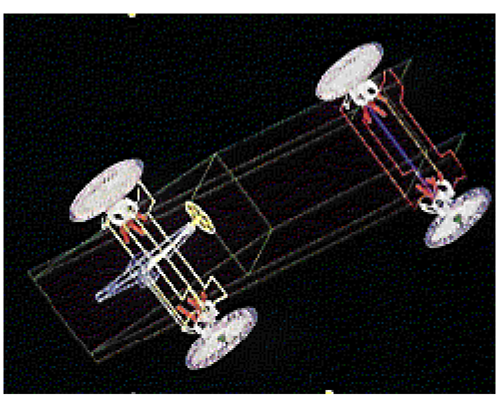
2.4 Chassis And Body Selection

Various configurations for the chassis were considered including that of a four-wheeled vehicle and two for a three-wheeled vehicle. The three wheeled configurations offers greater efficiency (lower rolling resistance at the cost of more instability) yet require greater care in design and weight distribution in order to produce a stable vehicle.

The "Shining Star" had a more traditional four wheeled configuration, shown in Figure 3. In four wheeled vehicles the stability is only a function of the height of the center of mass. This design allowed freedom of locating components along the vehicle's longitudinal position.

For the second and third generation solar powered vehicles a three wheel configuration; two fore tires and one aft tire was selected. The decision was based on simplicity, reduced number of components which has a positive impact on reliability in a design and reduced weight. A mathematical model was developed in order to predict stability, critical in three wheeled vehicle design, *Cole* (1971). By application of Routh's stability criterion, information about the critical velocity (which will produce instability) and the center of mass position required for stability are obtained. The equations of motion are solved numerically to simulate the behavior of the vehicle. To predict rollover stability, the vehicle configuration was represented by a three-dimensional model. An overturn analysis was performed for the conditions of accelerating in a steady turn, braking in a steady turn, and performing a steady turn. From this analysis the critical rollover velocity for the center of mass can be obtained. This procedure was also performed for incline plane motion. The critical rollover velocities were graphed versus the center of mass position and these results were used to determine dimensions for a stable vehicle.

Due to the geographical location of Puerto Rico transportation costs are very high. The original design used in the Shining Star was too expensive to air freight therefore various chassis alternatives were developed and studied for the following generations . A tubular space frame was selected over the rectangular parallelepiped structure used for the "Shining Star". The final design selection was made based on the ease of manufacture, safety factor, ease of repair and low cost of transportation. The chassis for the "Discovery 500" consists of two main parts, a space frame which protects the driver and a beam section which carries the batteries, electronics, solar cells and rear suspension. These two components may be easily separated in order to reduce the size of the vehicle for transportation. The "Shining Star II's" chassis although one piece uses modular (removable) sections to sustain the body/solar panels therefore reducing its packaging factor. The location of the heavy components were determined by stability considerations. Figure 5 shows the Shining Star II's chassis structure.



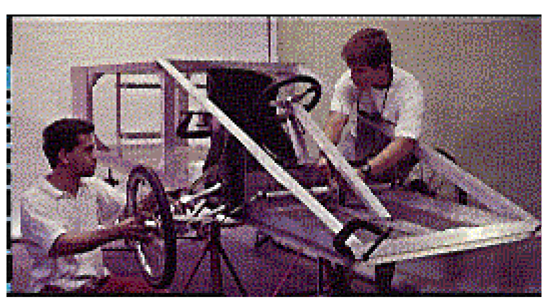


Figure 3 Shining Star Chassis Configuration

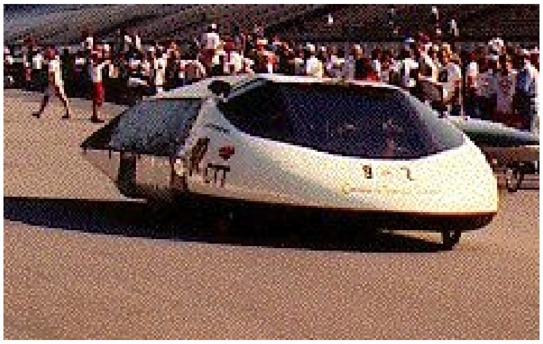


Figure 4 The Shining Star,
GM Sunrayce 1990

Figure 5 Shining Star II Chassis

The body of the "Shining Star" had fiberglass and foam sandwich construction which was required because the body was designed to support the load of the solar panels due to it's streamline design, see Fig.5. In the "Discovery 500" the body carries no load therefore was created using only a fiberglass shell which was lighter and required no reinforcements in the fiberglass., see Fig. 6. The "Shining Star II" incorporated a streamlined wing shaped body, see Fig. 8, manufactured with a foam core and laminated with fiberglass. Most of the body is covered with solar cells in order to minimize surface, body and supporting structure weight. The body is designed in modules in order to allow disassembly and reassemble for transportation with a high packaging factor. The disadvantage of the modular design is that the body is not as strong as a single piece element and requires additional ribs for stiffness which increases its weight.

Figure 6 The Discovery 500, Sunrayce 93

Figure 7 The Shining Star II, Sunrayce 95

2.5 Other Systems

The safety of the solar car drivers is of utmost importance Effects such as tire construction (traction force, and cornering properties), and energy dissipation (brake design and selection), will be investigated thoroughly. A minimum braking distance, 22 meters for a speed of 30 Km/h, was set as the target goal in the "Shining Star". The car was equipped with three braking systems. The first system was part of the motor/controller and allowed regenerative braking as a means of reducing speed and recovering kinetic energy lost. A second system consisted of four disk brakes. An independent hydraulic system governed the emergency braking system. The “Discovery 500” used mechanically actuated disk brakes, in the front and rear. The rear brake as two independent actuating mechanisms for safety. In addition the vehicle used a regenerative brake on command, in contrast with the “Shining Star” which had regenerative brakes activated automatically. On command regenerative braking allows the vehicle to better utilize potential energy in down hill situations because the regenerative brake may be completely disabled. The “Discover 500” and the “Shining Star II” were equipped with disc brakes in the front and with regenerative braking. .

The part of the chassis supporting the driver and surrounding the driver was designed to resist an impact of at least 8 km/hr for the “Shining Star”. For the second and third generation vehicles a maximum of 5g’s frontal and rollover impact scenarios where used. Finite element analysis was performed as part of the structural design using programs such as ANSYS and WeCAN, *Serrano* (1999). The driver has a five point racing seat belt system.

The “Shining Star” used double A-arm suspension mechanisms with conventional springs and shocks. The “Discovery 500” used a novel suspension system based on rubber straps in tension. This suspension system was very light weight and simple reducing both manufacturing and maintenance costs. An arm and strut suspension was used in the “Shining Star II” for its handling characteristics, low cost, good ride, compact packaging and low weight. Once again rubber straps were used in the suspension design.

All three design shared twenty inch bicycle tires, wheels with wide rims, heavy duty spokes and hubs fitted with disc. The “Shining Star” and the “Shining Star II” used rack and pinion steering whereas the “Discovery 500” used a cable steering linkage in order to reduce weight.

Air circulation for driver was provided by forced convection produced by the vehicle’s movement and supplemented by battery operated clip on fans. All three designs protect the driver against possible emissions from the batteries by providing a separate source of ventilation. All rules and regulations concerning safety on electrical systems were designed according to Sunrayce regulations.

3. LESSONS LEARNED

Special efforts should be dedicated to system optimization in order to increase performance while maintaining low vehicle cost, modularity, and reduced number of parts (for lower weight, increased reliability, shorter manufacturing time, facilitate transportation logistics, ease of serviceability and reduction of spare part inventory).

The design and component selection should rely extensively on off the shelf components whenever possible in order to reduce costs, facilitate procurement, maintenance and repair. Safety and reliability should have a high priority when selecting components. Proven technology in a well developed design generally translates into reduced cost, higher reliability, shorter development time, lower repair cost and maintainability, available manufacturing facilities, known quantities, and easier testing procedures. Testing and predicting vehicle performance characteristics play an important part in the system optimization from the onset of vehicle development. Allow enough time for testing and practice before the competition, and know your vehicle (energy management). It is best to optimize the system not necessarily individual components, therefore testing is a key factor in fine tuning and optimization.

Other tradeoffs in vehicle design constraints and performance should be considered to optimize the design. For example, our geographic situation requires that our vehicle be transported air freight therefore increasing our costs to and from the competition.

Therefore a modular design easily disassembled and reassembled for transportation with a high packaging factor is important. The use of a minimum number of tools in the design (for maintenance) should also be considered.

The following table summarizes the characteristics of the three generations of solar powered vehicles:

Table 1. Summary

	Shining Star	Discovery 500	Shining Star II
Weight w/o driver	365 kg	240	385
Cost	$250,000	< $25,000	< $35,000
Solar Cells (eff)	Space grade (16%)	Terrestrial (11%)	Terrestrial (14%)
Batteries	Silver Zinc	Lead Acid	Lead Acid
Configuration	4 wheels	3 wheels	3 wheels
Chassis	aluminum	aluminum	aluminum
Steering	Rack and pinion	Linkages w/ cables	Rack and pinion
Motor	20 Hp	8 Hp	8 Hp
Cd	< 0.3	~ 0.32	< 0.3
Vmax	63 kph	92 kph	108 kph
Transportation Cost	High	Low	Ave.
Serviceability	Ave.	Above ave.	Ave.
Competitions	GM Sunrayce 90	Sunrayce 93, World Solar Challenge 93	Sunrayce 95

5. CONCLUSIONS

The objectives of the project have been met. First, this approach to teaching engineering provides a “Just in Time” educational experience, students from various levels and disciplines are permitted to work together on the project. In many occasions students encounter engineering problem situations in the project laboratory shop before it is taught in their engineering courses as part of the regular curriculum. Therefore the students experience the need to acquire knowledge in order to apply it to the problem solving activities. This provides a sense of purpose to many topics which may not seem of use when taught under a traditional setting. Students with experience serve as mentors to the new students. This course has served as a catalyst for student awareness and participation in other National Design Competitions. The course structure has proved successful since it's implementation. Over eighteen student projects have been produced (three Solar Powered Competition vehicles, one Solar/hybrid Commuter vehicle, two Solar Powered Boats, five Formula SAE, two SAE Mini Baja, three SAE AeroDesign, one Propane Powered vehicle and one Human Powered Vehicle) during the last ten. These projects have stimulated undergraduate students to pursue graduate studies in science and engineering and the student chapters of professional societies have received a boost

Second, the design of solar powered vehicles is an excellent opportunity for a great hands on, learning engineering experience. And third, our school has demonstrated that it is capable of developing a reliable low cost competitive vehicles.

REFERENCES

Bergman W., " Critical Review of the State - of - the - Art in the Tire Force and Moment Measurements", SAE Trans., Vol. 86, pp 1436-1450, Paper No. 77033, 1977

Cole, ***Elementary Vehicle Dynamics***, Department of Mechanical Engineering, University

of Michigan, Ann Arbor, MI., 1971.
Houston J. C., " The Effect of the Normal Force Dependence of Cornering Stiffness on the Lateral Stability of Recreational Vehicles", SAE Trans., Vol 89, pp. 999-1005, Paper No. 800161, 1980.
GM, ***GM Sunraycer Case History***, volumes 1 and 2, General Motors, 1989.
Just and Serrano, " Selection of Reduction Ratios for a Solar Powered Vehicle ", SAE paper no. 901512 , Future Transportation Technology Conference and Exposition , August 13-16, 1990.
Serrano, D., ***Design of Solar Powered Vehicles,*** COPIMERA, San Juan P.R., April 19-20, 1991.
Serrano, D. and Perez, M., "Structural design of a Chassis for a Solar powered Vehicle", COINAR, Bayamon P.R., 1999
Whitt and Wilson, Bicycle Science, MIT Press, 1983