VEHICLE PROFILE DESIGN VERSUS SOLAR ENERGY COLLECTION: STYLING CONSIDERATIONS FOR SOLAR-POWERED PERSONAL COMMUTER VEHICLES

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Abstract

While current photovoltaic (PV) efficiencies limit the feasibility of a solar-powered personal commuter vehicle similar in size and shape to current gasoline powered automobiles, research into developing a hybrid design has been growing. The present focus of PV technologies in the automobile industry is directed towards creating a hybrid using a small gasoline motor in conjunction with PV cells. Sole use of solar energy for powering automobiles can be seen in several solar-car racing events, but the dominating designs tend to focus on maximum energy harvest/utilization efficiencies and streamlined designs, which results in a flat vehicle profile. This study looked at altering the profile to emulate the curved design of today's civilian automobiles. Using two different profiles, this study simulated a car being parked in a random orientation during a given period of time. The results were examined to determine the effect that altering the profile will have on overall solar energy collection under different weather conditions.

Introduction

Photovoltaic (PV) technology has been around for over a 150 years, but it was not until the successful demonstration of a silicon P-N junction solar cell in 1954 that its widespread usage was realized [1]. With the increasing need of alternative energy, and the continuous improvement of PV performance, it is likely that solar power will become cheaper and more prevalent. From its use in consumer devices, home and grid power generation, lighting, to stand-alone communication, warning, and monitoring systems, the pervasive use of PV is imminent [2].

While using solar energy in transportation is becoming more of a reality, little evidence exists that major automobile manufacturers are showing interest in full-scale production of solar-driven vehicles. As a result, the development of solar cars is mainly led by participants in events such as the American Solar Challenge and other solar races worldwide [3]. In this type of competition, many of the vehicles with similar designs were able to successfully finish the race. The vehicle design is bound by a certain set of rules, which limit items such as motor size, area of solar panels, amount of batteries, and type of battery. With a goal of traveling up to 1,500 miles across the country solely on solar power, the design is mainly governed by variables such as weight, energy-harvest capability, and wind resistance. The PV cells are usually oriented almost parallel to the earth. This is primarily done to enlarge energy harvest and reduce wind drag.

Bound by such limitations and being focused on maximum efficiencies results in solar vehicles with flat profiles that travel close to the ground and allow just enough space for one human driver, as shown in Figure 1. Designing the car in this manner allows for the PV cells to achieve a direct beam radiation at almost 0^o angle of incidence (AOI) during peak sunlight hours, resulting in less radiation loss from scatter [4]. In other words, the vehicle is able to collect a substantial amount of energy at peak irradiance hours, or when AOI is very small. In such a design, nevertheless, energy harvest in the morning and afternoon hours is not maximized due to large AOIs.

Figure 1. The solar car by University of Michigan, which took the first place in 2010 American Solar Challenge [5]

Minimizing AOI is crucial to achieving maximum power output, but in doing so the race vehicles sacrifice space and comfort because of their flat and compact design. Considering the practicality of a solar-powered personal commuter vehicle, the vehicle design would have to sacrifice some of the optimal AOI to create more cargo space. Furthermore, such a vehicle would need to have adequate head space for the driver to sit in an upright position, use a steering wheel, and even have space for safety features. While such a personal commuter vehicle would not have to adhere to the same set of rules established for various solar car races, the technologies used in these races provide a good baseline, and certain design considerations used in constructing these racers apply. Thus, the goal of this study was to investigate the influence of vehicle profile on its solar-energy harvest capability in order to determine the feasibility of a solar-powered personal commuter vehicle.

Related Research

The energy-harvest capability of solar panels can be affected by factors such as cell operation temperature [2], dust accumulation [6], and environmental aspects of vehicle deployment regions including altitude, weather patterns and shadowing of landscapes [7]. Cloud cover during the harvest of solar energy also has an impact on the amount of spectral irradiance reaching the PV cell. Spectral irradiance, comprised of both direct and diffuse components, is measured in watts per square meter (Watt/m^2). In addition to absorbing visible (380-780nms) and near-infrared (780-4000nms) solar radiation, local cloud cover might reflect up to 70% of the direct radiation [8]. With varying weather patterns throughout the world, environmental attributes of each location must be carefully taken into account in order to maximize the module output, and keep associated hardware and operation costs to a minimum.

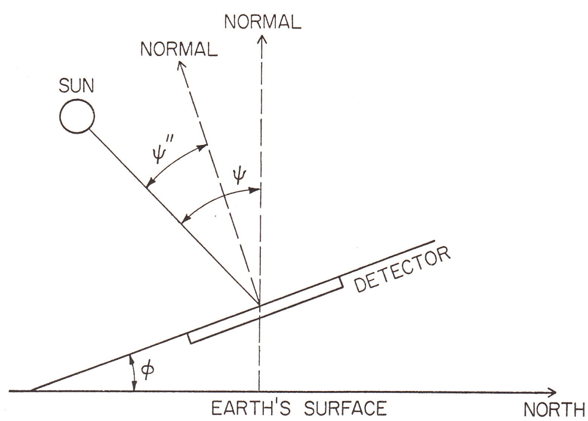

Figure 2. A diagram of the angle of incidence: The angle of incidence is represented by ψ'' and is referenced with the normal of the detector (solar panel). The actual tilted angle of the detector is denoted by φ [7]

Angle of incidence (AOI) of the PV panels, as illustrated in Figure 2, also influences the solar-energy harvest ability. An AOI above 45^o greatly reduces the absorption of the sun's direct radiation and must be considered when attempting to minimize reflectance on the cell itself [9], and thus is often considered undesirable for use on a solar-powered vehicle. In addition, the yearly orientation of the PV cell in relation to the sun is another crucial parameter to optimize power generation. The glass used on solar panels also causes reflectance, which is associated with an optical loss. When using a glass-covered module, the reflectance increases dramatically above an AOI of 60^o [10]. Such loss in diffuse spectral irradiance is important to note, and makes analysis of this factor crucial when setting up a fixed module. The study performed by King et al. [9] points out that while annual loss caused by a low AOI is small, it can have a significant monthly effect.

A study by Ahmad, Hussein, and El-Ghetany [11] used a computer model to predict optimal tilt angles for yearly power generation in Cairo, Egypt. The study concluded with the optimal tilt angle (20^o to 30^o) about solar power generation specifically in Cairo, and confirmed the importance of AOI and the tilt angle on the overall performance of the PV array. Using a mathematical model, Tang and Wu [12] created a table and map for optimal tilt angles in China. Considering that China's territory covers many climates and latitudes, such a model proved beneficial to this emerging country. Tang and Wu's study pointed out that different months of the year have different optimal tilt angles based on the change in the sun's angle to the fixed PV module and their mathematical model successfully predicted actual diffuse radiation values in 182 different locations throughout China where pollution levels were low [12]. This study can serve as a guide for PV module installation in China, and once again confirms the effects of both diffuse solar irradiation and AOI on a solar module's efficiency in any location.

Martin and Ruiz [6] discovered that angular losses due to AOI are generally not taken into account when estimating the energy production of PV systems. The resulting effects are inaccurate corrections to current systems, and the potential neglect of increased productivity of the cell. Their model, developed to analyze optical losses for silicon PV modules, uses reflectance and AOI as major contributors to overall decreased cell performance. Upon completing their study, Martin and Ruiz confirmed the effectiveness of their model, and noted that the type of solar technology used has no significant impact on the angular loss, but AOI and reflectance are significant contributors.

Recent research has looked into developing a hybrid solar car that reduces the consumption of gasoline. A study conducted by Arsie et al. [13] developed a model for optimizing a solar hybrid design. Using a calculator developed by the US National Renewable Energy Lab to determine optimal tilt angle in both the horizontal and vertical directions, they reported that panels aligned 90^o to the road (vertical direction) on an automobile would generate about only one third of their capable power, and about 45% to 65% of those placed horizontally. They also noted that the feasibility of these panel orientations is questionable. Such studies are beneficial as they look at aspects such as weight, aerodynamics, optimal solar tilt angle, power generation and energy storage. Investigating the design of solar hybrids is important as it allows many problems to be uncovered prior to attempting the build and full-scale production of a commuter vehicle powered solely by a PV system. By adopting technologies such as multi-junction panels with efficiencies of nearly 35% could eventually result in an all-solar powered car [14].

Solar-powered Personal Commuter Vehicle

Positioning a solar array to minimize AOI and reduce reflectance results in better utilization of the available solar irradiance. A majority of PV technology is used for generating electricity for buildings and houses. These applications tend to rely on either fixed or tracking systems; the former is generally set between 20^{o} and 30^{o} of AOI (depending on latitude), while the later follows the sun and uses the most efficient AOI to maximize the conversion of direct spectral irradiance. Such knowledge can be applied to other technical areas such as automobiles by choosing angles that will reflect the best efficiencies for specific geographic locations.

Little research has trained on creating a solar-powered personal commuter vehicle, however. Every day, people commute to work; once they arrive, they proceed with their car parked outside. Given a parking area exposed to the sun, the commuter vehicle's PV cells could charge a set of batteries over the course of the day while sitting outside, and may collect enough electricity for its owner to commute to and from work. Once home, the automobile would then be hooked into either a standard 110V or 240V outlet to trickle charge during the night. This would ensure the user with enough electrical power in the batteries to commute back to work, thus restarting the cycle. With the shape of the car being curved instead of flat, as discussed previously, it would provide the driver more comfort and cargo space. With a proper design, such a vehicle may be able to offer a practical application for commutes up to a 30-mile round trip.

In addition to weather pattern and AOI, another factor that would affect a vehicle's solar harvest capability is parking orientation. Once arriving at work, the driver will face a multitude of parking options, and must make a choice as to the most efficient parking orientation (which way the front, rear, or side of the car will face). The user could be parking in a North/South orientation, an East/West orientation, or anything in between. Each of these orientations will offer users differing amounts of solar radiation over the course of their 8-hour workday, with the East/West and North/South orientations representing the potential extremes. The commuter, however, may have few parking options from time to time due to parking-lot configuration or space availability. This could result in a parking orientation that is less than optimal for overall solar-power generation.

To better understand the proposed vehicle profile and its performance of solar-energy harvest under various parking orientations and weather conditions, this study investigated the total amount of electricity collected by two different vehicle profiles, namely flat and curved profiles. Based on the previous discussion, the dependent and independent variables used in the study were identified. Independent variables included vehicle profile (flat or curved), parking orientation (North/South or East/West), peak solar irradiance, and daily high temperature; data for the latter two independent variables was retrieved from online public records. The dependent variable was actual energy collected in watt-hours. Each profile's daily output in wattage was compared on a daily basis, and the total energy collected was the area under the power or wattage curve. The hypotheses of this research are listed as below:

H_1: During an 8-hour interval, there is a significant difference in the amount of total daily power produced by the curved and flat profiles.

H_2: During an 8-hour interval, there is a significant difference in the amount of total daily power produced between curved profiles parked in East/West and in North/South orientations.

H_3: During an 8-hour interval, there is a significant difference in the amount of total daily power produced between flat profiles parked in East/West and in North/South orientations.

H_4: During an 8-hour interval, there is a significant difference in the amount of total daily power produced by the solar profiles between different weather patterns.

Experimental Design

Figure 3. Flat (top) and curved profiles with five solar panels wired in series

This study looked at a scaled-down version of this possible solar commuter vehicle's profile. While not using as many angles as the envisioned vehicle, it examined the difference between a flat and curved profile of equal surface area. Each profile consisted of five equal-sized solar panels. Shown in Figure 3, the flat profile was built to position the PV panel in parallel with the earth's surface. The curved profile was made up of 5 sections. Four of the sections were tilted 15^o, 30^o, -30^o and -15^o, with respect to ground, while the fifth section was at a zero-degree orientation, much like the flat profile. The combination of panel tilt angle and corresponding area coverage percentage (in this case 20% for each tilt angle) could be used to describe the potential profile of a solar commuter vehicle. To simplify this study, the focus was on those profiles that were symmetrically flat or curved.

In addition to examining the energy collection pattern of different profiles, this experiment also investigated whether parking orientation or weather patterns would change the amount of electricity harvested by specific vehicle profiles. The specific curved profile chosen could provide a good baseline for future investigations for several reasons: It could still effectively handle changes in irradiance through the day (and utilizing peak irradiance at midday); it resembled a realistic design for a personal commuter vehicle; and it was significantly different from the control (the flat profile). Based on the findings from this profile, future designers can decide whether to increase or decrease the tilt angles, change the percent coverage of certain angles, or revert back to a flat design.

Table 1. 2-way factorial design showing four treatments

Profile	Parking Orientation	
	East-West	North-South
Curved	Power/Day	Power/Day
Flat	Power/Day	Power/Day

A two-way factorial design, shown in Table 1, was used to assess two different profiles at two different parking orientations. For the purposes of this study, the profiles acted as fixed arrays while they are exposed to daily sunlight. The North/South and East/West orientations represent the extreme possible parking scenarios. An East/West orientation was exposed to sunlight through the course of the day with an unfavorable AOI. Being oriented in a North/South orientation allowed for an optimal AOI for the part of the curved profile facing south. The other half faced north and had to rely on midday solar radiation as well as diffuse radiation.

An additional copy of each profile was used, resulting in a replicate for each treatment. This was done so that both the curved and flat profiles were facing both orientations during each blocking period resulting in a complete randomized block. There were four total structures (two flat and two curved), which were randomly assigned to either of the orientations. A complete randomized block was used (see Table 2), which assigns two profiles to the North/South orientation and two to the East/West orientation. Each orientation had to have both a curved and a flat profile when testing during each two-day time interval. In other words, there cannot be three profiles facing one direction and one profile facing the other. Such an arrangement of the profiles was tested for two consecutive days to account for day-to-day changes in weather.

Table 2. Assignment of profiles to East/West (EW) or North/South (NS) over the two-day intervals (blocks). Each profile is randomly assigned to be profile one or two

Profile	Days 1-2 (Block 1)	Days 3-4 (Block 2)	Days 5-6 (Block 3)	Days 7-8 (Block 4)
Curved 1	EW	NS	EW	NS
Flat 1	EW	NS	EW	NS
Curved 2	NS	EW	NS	EW
Flat 2	NS	EW	NS	EW

These directions were chosen to represent the extreme cases of a potential parking situation. With each of the profiles being fixed in one of the orientations for a two-day interval, they simulated many fixed-plate collectors. A fixed array that is aligned in a North/South/south direction has access to the highest yearly average solar irradiation in the Northern hemisphere. This is due to that fact that during the winter months when the sun is lowest on the southern horizon it is more beneficial to be facing south. An East/West orientation is exposed to a different quantity of solar irradiation. Initially, the flat profiles were randomly assigned to one of the two orientations. By default, the curved profiles were placed in the alternate direction. During each day of the two-day interval, measurements of power were taken with the data logger that was connected to and powered by a laptop computer. Following this two-day interval, the profile orientations were reassigned and the same measurements were taken over the same two-day period.

Shown in Figure 4, each of the four profiles had five total solar modules, and the five different sections were wired in series. Sized in 50x16.5x3 cm^3, the amorphous solar panels used in this experiment could operate between -40° and 176°F and had a maximum output of 1.8W. All entry points were sealed using clear silicon to prevent moisture. The PV panel-holding structures were constructed in 2x2 and 2x3 Douglas fir. The series wiring of these solar panel resulted in each of the profiles having a maximum voltage rating of 80 volts (16V x 5) and a maximum current rating of 125mA. It must be pointed out that while each panel was rated for 12V, they actually produced between 13V and 16V, depending on the amount of solar irradiation available and the temperature.

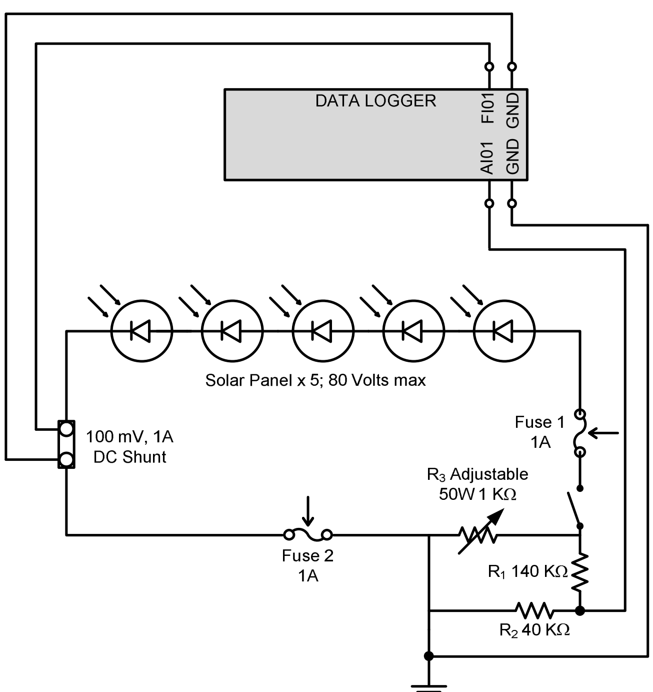

Figure 4. Schematic diagram for the measurement system

Measurement of both current and voltage was accomplished with the use of a Labjack data logger and a Dell laptop. The laptop used the software provided by Labjack called DAQ Factory to record both the current and voltage. The data logger is comprised of 16 channels. Four of these channels are high voltage channels (0 – 20V) and were used for measuring the maximum 80V generated by each profile. Because these channels can only handle a maximum of 20V, a voltage divider circuit was used to reduce the voltage entering each channel. The voltage was reduced from the 80V generated by each profile to below the 20V maximum specified on the data logger's channel. This did not, however, have an effect on the readings generated by the data logger; it only changed the scaling of what was entering each channel to avoid component failure.

Four of the remaining twelve low-voltage channels (0 - 2.5V) were dedicated to measuring current. This was done by the use of an electrical shunt. The shunt (a very precise resistor) was wired in series with each profile before it reached the data logger. The data logger then received a voltage reading based on the voltage drop across the shunt and recorded it on the laptop. The voltage reading was then converted into a current reading and corresponding energy collection was calculated in watt-hours. Both the data logger and computer were housed in a sealed plastic box to protect them from weather. Four of these circuits were constructed, one for each profile. Attribute measurements showed these four circuits performed very similarly with the largest difference of less than 0.5%. Thus, no variation was associated with the measurement circuit.

The observatory at La Lomita Ranch (35.24, -120.62) was used for testing. This site was chosen because it has access to power, which is necessary for running the laptop computer and data logger. It also provides exposure to sunlight during the 8am – 5pm testing period. The experiment was conducted from April 14 to May 7, 2009. Each day after testing was complete, the computer was shut down and the components were covered with a tarp until the next day. In the mornings, all of the materials were once again uncovered for data collection.

The four profiles at the two orientations were analyzed using a two-way factorial design, as presented in Table 1. The statistical method of blocking was used to account for potential variations in weather during each of the two-day testing intervals. Both peak solar irradiation and daily high temperature were used as covariates in the analysis. Each block consisted of each of the possible treatments. Both variables were recorded and could be used as covariates in the analyses if they were deemed significant.

An 8-day pilot study was done prior to the primary experiment. The purpose of this study was necessary for two reasons: To find out any unforeseen problems, as well as to determine the sample size needed to make the analysis statistically powerful. It examined the following potential problems: Robustness of the solar panels, the measurement circuits, the laptop's ability to record measurements, the data recording software and functionality of the wooden structures. This pilot study also provided enough data to do an initial analysis of the first 8 days in Minitab. A significance level of 5% was chosen in the analysis. With the results from the pilot study, issues such as voltage and current measurement as well as equipment resolution were fixed by modifying the measurement system.

With these issues fixed, the primary experiment proceeded for sixteen days. Data from the 16 days was then analyzed. Based on the data, it was clear that the sample size was large enough, because the independent variables were indeed significant at the 5% significant level. An indicator of insufficient sample size would have been that the majority of independent variables were insignificant. Because this was not the case, a power analysis was not necessary.

Prior to analysis, the raw data had to be converted into usable numbers for two reasons: (1) A voltage-divider circuit was used and (2) the data was collected solely in voltage. To get the correct current reading, the equation ((raw voltage number – 0.4)*10)/201 was used. The amplifier's default offset quantity was 0.4. The multiplication of 10 was done based on the 1–amp, 100mV rating of the shunt. The gain factor of the LJ Tick Amplifiers was 201. The voltage numbers were converted based on the voltage-divider ratio of 0.222 (e.g. 40/180) between the true number of volts and the reading on the computer. Total energy collection can be represented in watt-hours, which was the area under the power curve.

Results and Discussion

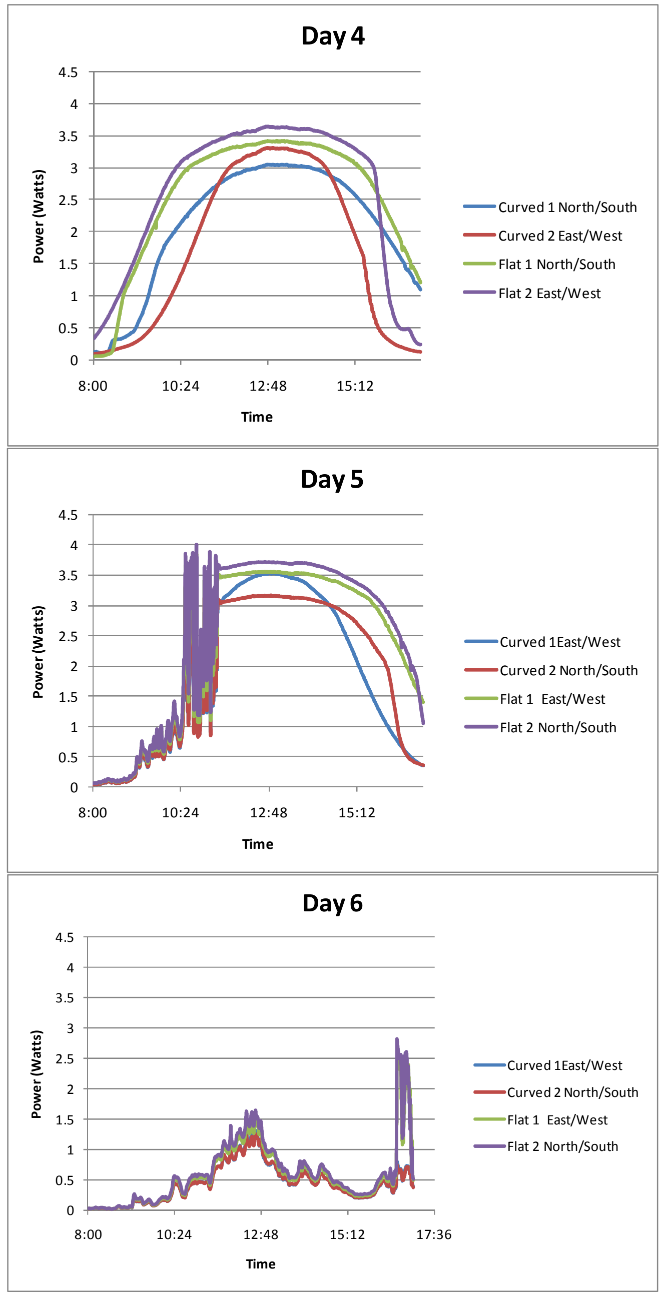

Figure 5. Graphs of time vs. power from days 4, 5, and 6. Solar irradiation was 974, 835, and 346 watts/m^2 respectively, and the high temperature was 72.5, 70.0, and 60.1 °F respectively

Figure 5 illustrates examples of the typical energy collection patterns of the profiles studied during the test period. The vertical axis represents the power in watts for a specific time period between 8am and 5pm. Day 4 depicts completely sunny conditions. This graph is very smooth, with each of the profiles exhibiting unique power generation sequences over the course of an 8-hour exposure. Day 5 exhibits a different scenario. The early morning shows a very undulated and uneven pattern, which was a result of morning clouds ultimately burning off leaving sunny conditions. When compared with Day 4's result, it is obvious that there was much less solar irradiation available on Day 5. Finally, Day 6 offers the most unique power-generation sequences. Day 6 is graphed on the same scale as previous days, which highlights how much less total daily power was generated. This entire day was cloudy and only offered roughly a third of the total solar irradiation of a completely sunny day.

The main effects and interactions between independent variables were determined by examining group means of different treatments. Table 3 indicates that there were main effects of profile, orientation, and set toward the daily power collection. During the 16-day experiment, flat profiles on average collected more energy than curved profiles. In the mean time, profiles parked in North/South orientation on average collected more energy than profiles parked in East/West orientation. Finally, set 2 on average collected more energy than set 1.

Table 3. Group means of power (Watts) collected per day: Main effects of Profile, Parking Orientation, and Set

Profile	Parking Orientation		Group Average
	EW	NS	
Curved	1891.74	2088.98	1990.36
Flat	2606.23	2624.02	2615.12
Group Average	2248.99	2356.50	

Profile	Set		Group Average
	1	2	
Curved	1999.58	1981.15	1990.36
Flat	2547.11	2683.14	2615.12
Group Average	2273.34	2332.15	

Figure 6 illustrates the interaction between profile and orientation, and between profile and set. In examining the profile*orientation plot, it is clear that there was a difference in total daily power generation between curved profiles parked in East/West and curved profiles parked in North/South orientations. There was much less difference between the total daily energy generated by flat profiles parked in either orientation. In both orientations, flat profiles generated more total daily energy than curved profiles. As seen in the Profile*Set interaction plot, there was a difference in the amount of total daily energy collected between different profiles within both set 1 and set 2. Profiles in set 1, however, had much less difference in daily energy collection than profiles in set 2.

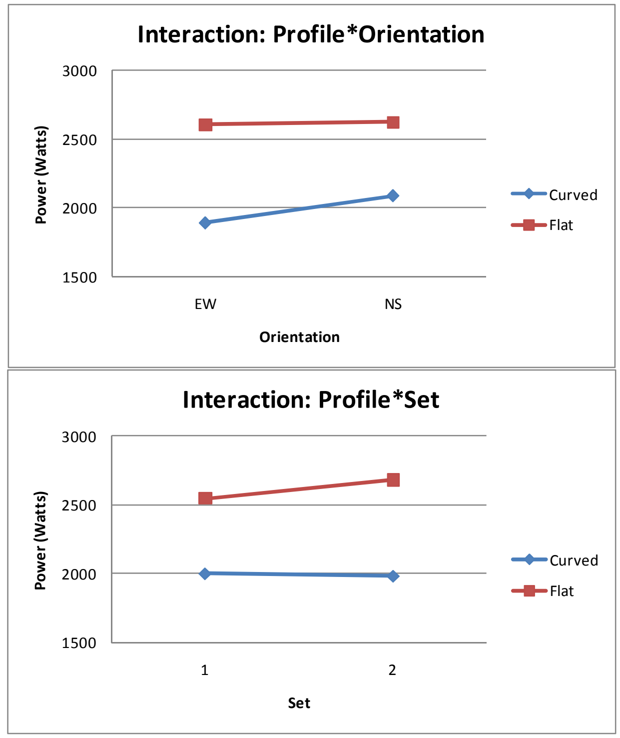

Figure 6. Interaction between Profile and Orientation (top) and interaction between Profile and Set

To determine the significance of main effects and interaction between independent variables, experimental data was analyzed in a two-way ANOVA, shown in Table 4. According to the comparative statistical results, at the 5% significance level the main effects profile, orientation, and day all have significant main effects on total power collection. Nevertheless, there was no significant main effect of the set (e.g. curved 1/flat 1 vs. curved 2/flat 2) on the daily total energy collection at the 5% level. At the 5% significance level, both interactions, profile*orientation and profile*set, significantly affected the daily total energy generation. According to the r-squared adjusted, 94.59% of the variation in the total power output could be explained by the profile, orientation and day. This shows a good linear relationship between the dependent and independent variables used in the study.

Further analysis was done using Tukey pairwise comparisons to minimize both Type I and Type II errors. The following outlines the results from the study:

Table 4. ANOVA General Linear Model results for 16 full days of testing. Daily total power outputs were used in the analysis, which did not look at individual time intervals during the day

Source	Degrees of freedom	Type III sum of squares	Mean square	F Value	*p* Value
Profile	1	6245245	6245245	279.81	0.000
Orientation	1	184931	184931	8.29	0.006
Profile*Orientation	1	128818	128818	5.77	0.021
Set	1	55328	55328	2.48	0.123
Profile*Set	1	95436	95436	4.28	0.045
Day	15	18312885	1220859	54.7	0.000
Error	43	959734	22319		

- When looking at all pairwise comparisons among levels of profile, a level of 95% confidence can be used to state that flat profiles produce between 549.4 and 700.1 more watts per day than the curved profiles.

- When looking at all pairwise comparisons among levels of orientation, a level of 95% confidence can be used to state that a North/South orientation produces between 32.2 and 182.8 more watts per day than an East/West orientation.

The interaction between profile and orientation was also analyzed using Tukey pairwise comparisons:

- When looking at all pairwise comparisons among levels of profile*orientation, a level of 95% confidence can be used to state that a curved profile in a North/South orientation produces between 56.1 and 338.4 more watts per day than an curved profile in an East/West orientation.

- When looking at all pairwise comparisons among levels of profile*orientation, a level of 95% confidence can be used to state that a flat profile in an East/West orientation produces between 573.3 and 855.7 more watts per day than an curved profile in an East/West orientation.

- When looking at all pairwise comparisons among levels of profile*orientation, a level of 95% confidence can be used to state that a flat profile in a North/South orientation produces between 591.1 and 873.5 more watts per day than an curved profile in an East/West orientation.

- When looking at all pairwise comparisons among levels of profile*orientation, a level of 95% confidence can be used to state that a flat profile in an East/West orientation produces between 376.1 and 658.4 more watts per day than an curved profile in a North/South orientation.

- When looking at all pairwise comparisons among levels of profile*orientation, a level of 95% confidence can be used to state that a flat profile in a North/South orientation produces between 393.9 and 676.2 more watts per day than an curved profile in a North/South orientation.

- Finally, there is no significant difference between in the total power generated by flat profile in an East/West orientation, or flat profile in a North/South orientation.

The test of hypotheses is discussed in the following:

H_1: During an 8-hour interval, there is a significant difference in the amount of total daily power produced by the curved and flat profiles.

a. **H_o: $\mu_{curved} = \mu_{flat}$**
H_a: $\mu_{curved} \neq \mu_{flat}$

b. At the 5% significance level, H_o is rejected and, therefore, the profile shape is associated with a significant difference in the amount of total daily power produced.

H_2: During an 8-hour interval, there is a significant difference in the amount of total daily power produced between curved profiles parked in East/West and in North/South orientations.

a. **H_o: $\mu_{east/west} = \mu_{north/south}$**
H_a: $\mu_{east/west} \neq \mu_{north/south}$

b. At the 5% significance level, H_o is rejected and, therefore, the orientation is associated with significant difference in the amount of total daily power produced by the curved profile.

H_3: During an 8-hour interval, there is a significant difference in the amount of total daily power produced between flat profiles parked in East/West and in North/South orientations.

a. **H_o: $\mu_{east/west} = \mu_{north/south}$**
H_a: $\mu_{east/west} \neq \mu_{north/south}$

b. At the 5% significance level, H_o is not rejected and, therefore, it is not fair to conclude that orientation impacts significantly the amount of total daily power produced by the flat profile.

H_4: During an 8-hour interval, there is a significant difference in the amount of total daily power produced by the solar profiles between different weather patterns.

a. **H_o: $\mu_{day} = 0$**
H_a: $\mu_{day} \neq 0$

b. At the 5% significance level, H_o is rejected and, therefore, day is associated with a significant difference in the amount of total daily power produced

Limitations and Implications

Three major limitations of this study, namely weather pattern, angle of incidence, and parking location, are discussed in this section.

(1) The Change of Weather Pattern: There were many changes in weather during the experiment. While many of the days were sunny, there were a few days that started with early morning clouds. Since there were not many days that offered complete cloudiness over the course of 8 hours, definite conclusions cannot be drawn on how well different profiles performed in completely cloudy conditions. It also implies that the application of this research is limited by its geographic location and the time of operation. In addition to the weather conditions that may change from time to time, the daily solar energy collection by vehicles deployed will be quite different because solar irradiation will be different at different latitudes and in different months of the year.

While all components were sealed to prevent water destruction, they were not built to be waterproof. With the high cost of the materials, and a limited window of opportunity to complete the experiment, no data collection was done during rainy days; no conclusion can be drawn regarding the performance of different profiles during rainy conditions. Ideally, both cloudy and rainy conditions should be tested more thoroughly before a specific profile of a solar commuter vehicle can be determined.

(2) "Optimal" Angle of Incidence (AOI): As indicated in this study, for these two specific profiles, a flat shape is more effective in daily energy collection than a curved shape. The idea that the curved profile will have the best AOI at all times during the day is valid, but only applies to certain panels. As this study shows, the flat profiles still collected more power during the morning and evening hours. While having a less than optimal AOI during those two periods, the flat profile has the same light exposure on all of its panels. This appears to be superior in power generation to the curved profile where just one, two, or even three out of the five panels experienced optimal AOI, and the others having little to no solar exposure at all.

The curved profiles' weakness is visible during the middle of the day when peak solar irradiation is available. This is an important window of time that needs to be maximized to improve total daily power generation. With a proper tilt angle, the flat profile is able to fully utilize this time frame, making the curved profile inferior in power generation. It was the thinking that the curved profile could possibly make up for this inferiority during peak solar irradiation by maximizing morning and afternoon sunlight, as well as the direct and diffuse components of the solar irradiation during the course of a day. The finding of this study, however, was not able to confirm such thought.

(3) Parking Location: Parking the vehicle also becomes a critical element in determining the best profile. In order to collect solar energy, the proposed vehicle must be parked in a location that is directly exposed to the sun. In urban areas where such personal commuter vehicles might be deployed, parking structures usually do not provide large uncovered parking lots, not to mention that the shadow of nearby buildings could block the direct sunlight. Some may argue that commuters in such urban areas would take public transportation instead, but the low probability of always being able to park under the sun is a substantial limitation.

As the data shows, orientation has a significant impact on the curved profile's total daily power generation, with the extreme of North/South providing the best energy collection. While the flat profile did not exhibit any significant difference when parked in the two different extreme orientations, it is also known that avoiding a flat design is crucial to providing the comfort and cargo space sought after in a commuter vehicle. It appears that the ultimate solution lies somewhere between the two. Nevertheless, worrying about parking orientation is likely to be the last thing a daily commuter wants to be concerned with. Traffic and simply finding a parking spot are likely to be more serious concerns, especially in a highly-populated area. Thus, reducing the parking orientation's impact on the vehicle's ability to collect power should be seriously considered.

Conclusions and Future Research

While this specific combination of varying angles and coverage was not as efficient as one would have hoped, it has provided valuable insight as to the effects of creating a more curved profile shape. As stated previously, the half-egg shape is just one of the many combinations of angles and percent coverage possible. For this specific research, such a combination proved to be inferior to the flat shape that entrants into the solar car race strive for. Its inferiority does not mean a future solar commuter vehicle is unattainable. What it does suggest is that when increasing the tilt angle to allow for a more spacious commuter vehicle, the designer is sacrificing the vehicle's ability to generate power while it is parked. In recognizing this fact, the designer must try to maximize the flat area on the commuter vehicle that can be parallel with the earth.

Because of the restrictions on design, building an aesthetically pleasing solar commuter vehicle will be a challenge. While future research should investigate designs with solar panel tilt angles and percent coverage that fall in-between the two tested in this study, the designers should also consider other options to reduce the impact of AOI. Aside from changing the quantity of different angles used, the researcher should also consider changing the percent coverage of varying angles. This study used a symmetrically-shaped curved profile in an attempt to track the sun. Such a methodology did not prove as beneficial as one would have hoped. Because of this, future research should look at creating asymmetrical designs to test their effectiveness. While it may not address issues such as parking location or weather pattern, it could increase the overall energy collection making it a worthwhile tradeoff.

While future research should investigate designs with angles and percent coverage that fall in-between the two tested in this study, researchers should also consider other options for minimizing the effects of AOI. Using modular arrays or hidden panels that are deployed only during parking should not be ruled out. Such a design could allow for an aesthetically pleasing appearance while still being able to maintain high levels of power generation. Designers should keep in mind that focusing on functionality is the most important aspect to the success of such a vehicle. Building the ultimate solar commuter vehicle will require that the designer carefully balance the efficiency of the solar array, the comfort of the operator, as well as the safety of the vehicle on the road. The proper combination does exist and can only be exposed with further research.

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Biography

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