Strategies for Optimised Management of Electric Energy Obtained via Photovoltaic Conversion (Case Study: Solar Racing Vehicle for Very Long Distances)

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Abstract. The main objective of this paper is to show how viable is the utilisation of the solar energy. That is accomplished by the optimal utilisation of the electric energy (obtained via photovoltaic conversion) in a solar racing vehicle. Two distinct steps corroborate to that: minimising the electrical, chemical and mechanical losses and optimising the energy management via racing strategy.

A program has been written in order to achieve the stated above. It uses Simulated Annealing and a rules-based expert system. What the program does, based on instantaneous inputs (available solar energy, wind velocity and fractional slope of the track), is calculate the instantaneous velocity that is ideal to save as much energy as possible during the entire race. Thus, the vehicle can go as fast as possible, using as little energy as possible.

Simulated Annealing is an optimisation process that is suited for large, multivariable, combinatorial optimisation problems such as this one: finding an optimal racing strategy, by optimising the parameters of the expert system. Our proposal, then, is to use it to plan a minimum-time (thus maximum average speed) race, using the best way possible the scarce energy converted by the photovoltaic panel.

Keywords --- Energy management; Photovoltaic; Solar Energy; Optimisation; Simulated Annealing; Variational Calculus; Simulator.

1 Introduction

The main objective of this paper is to show how viable is the utilisation of the solar energy and to give guidelines to those who wish to use it on small-sized vehicles, houses, geographically-isolated machines and communities etc. Showing how a reliable and feasible racing vehicle can cross an entire continent only relying in solar power – and its careful usage management – is much more than the necessary to achieve that goal.

Many improvements to every single part of the vehicles have been done since the first WSC, in 1987, won by the GM Sunraycer at an average speed of 67kph (or 67km/h). Nuna won the last edition of that event, the WSC 2001, at an amazing average speed of 92kph. And all that using less power than a hair dryer does. Two distinct steps of optimisation corroborate to that high efficiency: minimising the electrical, chemical and mechanical losses (design optimisation) and optimising the energy management via racing strategy (race optimisation).

That is where mankind must head to this century: finding new, clean, renewable ways to provide power to its essential needs such as hospitals, lighting, heating and industry.

There are two steps to achieve this: <u>optimisation of the racing strategy</u> and <u>optimisation of the design</u>. The first will be addressed using a robust optimising technique called Simulated Annealing. The second will not be addressed here, for the parameters of the vehicle have already been defined: low aerodynamic drag coefficient, low weight, low rolling resistance coefficient, one person (there could be two), what causes the car to be “short”, i.e., have around 4500mm of length. The two-people vehicles have around 6500mm of length. Even knowing that the performance will decrease, the design team has chosen to use four – instead of three – wheels, for the sake of safety, for the estimated maximum speed of the vehicle is approximately 100kph (kilometres per hour), considered by the team too high to a three-wheeled vehicle.

Before proceeding to the racing strategy optimisation study itself, we shall introduce each part of the problem.

The first thing to be known is the <u>fundamental relation of power balance (usage and obtaining)</u>. **Mr. Eng. Chester Kyle**, General Motors Engineer, wrote it (Kyle, 1990). He was the one of the designers and the team leader of the 1987 *World Solar Challenge* (*WSC*) GM entry, the *Sunraycer*, which has won the race that year and turned to be the paradigm for the following editions of the event.

Before writing the equation of the required instantaneous <u>power</u>, we shall write the equation of the required instantaneous <u>force</u> required by the car to ride at a given instantaneous velocity, given the other parameters just cited:

$$\text{Force}_{\text{Kyle}} = \text{Force}_{\text{SLOPE}} + \text{Force}_{\text{ROLLING RESISTANCE}} + \text{Force}_{\text{AERODINAMIC DRAG}} \quad (1)$$

but:

$$\text{Force}_{\text{SLOPE}} = W*\sin(\text{atan}G) \quad (2)$$
$$\text{Force}_{\text{ROLLING RESISTANCE}} = W*C_{RR}*\cos(\text{atan}G) \quad (3)$$
$$\text{Force}_{\text{AERODINAMIC DRAG}} = ½*C_D*A*\rho*(V-V_W)^2 \quad (4)$$

in which:

- **W** is the vehicle weight, calculated by multiplying mass **m** and the local gravity acceleration **g** (W = m*g);
- **G** is the fractional slope of the track, which tells how much the track rises for each meter travelled in the horizontal plane;
- $\mathbf{C_{RR}}$ is the rolling resistance coefficient. It shall be used Michelin Solar value, which has been thoroughly tested an has turned to be a canonical value;
- $\mathbf{C_D}$ is the aerodynamic drag coefficient, which is a shape-only value. It represents the ratio of the forces (forces of the fluid, resisting the progress of the car immersed in it) between the given shape and a sheet placed normally to the fluid flow (that is, normally to the heading of the car, for no-wind conditions);
- **A** is a characteristic area, usually the frontal area, for this kind of problem;
- **ρ** is the air density or specific mass;
- **V** is the car velocity relative to the ground and
- $\mathbf{V_W}$ (also relative to the ground) is the projection of the wind velocity on the direction of the car movement. As $\mathbf{V_W}$ is measured on the same heading of the car, a positive $\mathbf{V_W}$ is tail wind, helping the car, while a negative $\mathbf{V_W}$ is head wind, which tries to push the car back.

The product of $\mathbf{C_D}$ and **A** is usually referred to as $\mathbf{C_{DA}}$ and this work will use it.

Thus the total force that the car must exchange with the ground in order to ride at velocity **V** is:

$$\text{Force}_{\text{Kyle}} = W*\sin(\text{atan}G) + W*C_{RR}*\cos(\text{atan}G) + ½*C_D*A*\rho*(V-V_W)^2 \quad (5)$$

The power the car must transfer to its motor wheel is thus:

$$\text{Power}_{\text{Kyle}} = \text{Force}_{\text{Kyle}} * V \quad (6)$$

or

$$\text{Power}_{\text{Kyle}} = \text{Power}_{\text{SLOPE}} + \text{Power}_{\text{ROLLING\_RESISTANCE}} + \text{Power}_{\text{AERODINAMIC\_DRAG}} \quad (7)$$

or

$$\text{Power}_{\text{Kyle}} = W*V*\sin(\text{atan}G) + W*V*C_{RR}*\cos(\text{atan}G) + ½*C_D*A*\rho*V*(V-V_W)^2 \quad (8)$$

This equation makes the power balance: $\text{Power}_{\text{Kyle}}$ yields the necessary power that must be transferred to the motor wheel in order to propel the vehicle at instant velocity **V**, given the car parameters **W**, $\mathbf{C_{RR}}$ and $\mathbf{C_{DA}}$ and the external variables **G**, **ρ** e $\mathbf{V_W}$.

Actually, only m is a car parameter, because g is of course an external variable, but it changes so little along the track (less than 0.1%) that it can be considered constant, making the vehicle weight – and not only its mass – a "car" parameter.

Rearranging equation 8 to a polynomial form:

$$\begin{aligned}\text{Power}_{\text{Kyle}} = {} & V^3(½*C_D*A*\rho) + V^2(-C_D*A*\rho* V_W) + \\ & V^1(W*\sin(\text{atan}G) + W*C_{RR}*\cos(\text{atan}G) + ½*C_D*A*\rho* V_W^2)\end{aligned} \quad (9)$$

2 Understanding the Power Balance

Analysing each term of the equation 7:

2.1 $\text{Power}_{\text{Kyle}}$

PowerKyle has already been explained above.

2.2 PowerSLOPE

$\mathbf{Power_{SLOPE}}$ (**W*V*sin(atanG)**) is the required power to raise – or lower - the car on slopes: if the car is going upwards, $\mathbf{Power_{SLOPE}}$ is positive; if downwards, negative. PowerSLOPE is function of **m**, **g**, **V** and **G**. Among these variables, the only one that can be controlled by the designer is car mass. It is strongly recommended that it is minimised, that is, a great effort must be made to achieve a car weight that is as low as possible, for high mass increases $Power_{ROLLING\_RESISTANCE}$ as well, as we shall soon demonstrate. To keep motor power below an upper limit – to avoid overheating, which leads to efficiency loss and even failure – the car should be kept below a safe velocity (that velocity decreases with the increase of the positive **G**).

A very interesting feature of the permanent magnet, DC brushless motor that will be used is that it works in all the four quadrants. That means it can regenerate the wheel power that potentially exceeds the required power $Power_{Kyle}$ for a given velocity **V**. Per example, if the wind is helping the car (and/or there is a steep slope downwards), the power available to it may easily exceed the power needed to proceed at the desired velocity. Then the pilot can break the car using regenerative breaking – to keep it at that velocity - and the energy can be regenerated and used to recharge the set of batteries.

The possibility of regenerating the exceeding energy can lead one to a wrong conclusion: that the energy used to climb a hill will, sooner or later, be regained during the respective downwards part of the track. That part will certainly come, for the race start and finish points are at the same level (Darwin and Adelaide are both shore cities, thus are at sea level).

You will waste energy due to regenerating and charge/discharge inefficiencies or due to varying speed of the car. Or due to a combination of both; it depends on your racing strategy.

The first of the two phenomena just described has already been explained. We shall now explain the latter.

When the $Power_{Kyle}$ equations are examined, it is easy to realise that the power increases with V^1, V^2 and V^3. We shall see that a large part of that power is represented, in the majority of the race situations, by $Power_{AERODINAMIC\_DRAG}$, whose value is $½*C_D*A*\rho*V*(V-V_W)^2$. One can realise that $Power_{Kyle}$ is approximately proportional to V^3.

Calculations with real numbers of the car to be sent to the WSC2003 shows that it is expected to have an average velocity of about 65kph (approximately 18m/s), and we shall use that number for this explanation. If the car rides at constant speed – 65kph -, it shall consume a motor wheel power proportional to 18^3. If it changed from 15m/s to 21m/s all the time, its average velocity would still be 18m/s, but its required power would be proportional to 15^3+21^3 (which equals 12636). That value is greater than 18^3+18^3 (which equals 11664, a value of about 92.3% than that of the varying velocity strategy). Receiving and converting so little energy from the sun, the designer cannot afford to waste eight percent of the converted energy.

It is easy for one to realise that only the energy that is not lost on breaking noise, grinding and heat will be available to regeneration. Of course, beyond the noise, grinding and heat losses, there are losses in the regenerating itself and in the charge/recharge cycle in the batteries (the regeneration/recharge/discharge cycle is about 70% efficient, and the recharge/discharge cycle alone, without regeneration, has an efficiency of about 80%). That is why a car riding on an ever-horizontal track needs less energy to proceed at a given velocity than a car that is on a track full of slopes.

If the velocity were kept constant, the car would use – ideally, and still using the numbers above - as little as 92.3% of the required power for the variable-velocity strategy. Thus constant velocity seems the best strategy, but to achieve the goal of keeping constant velocity when travelling across regions with irregular topography (i.e. with lots of slopes), one must do two things: use power from battery pack during ascending parts of the track (for sun power alone would not be able to keep the car at desired, constant speed) and recharge it during the descending parts. As stated above, the overall efficiency of the regeneration/recharge/discharge cycle is far less than 92.3%. Now it might seem more appropriate to allow the velocity to vary and avoid using this cycling, what proves the first statement (constant speed is better) wrong. This will be further discussed in this text.

For now all we can do is realise the importance of things like the capacity given by the set of batteries, the use of highly-efficient batteries, the energy regeneration via regenerative breaking and the minimising of vehicle weight.

2.3 PowerROLLING_RESISTANCE

PowerROLLING_RESISTANCE (**W*V*CRR*cos(atanG)**) is the power necessary to overcome the rolling resistance due to contact tires-track and keep the cat ate velocity **V**. It is not clear at a first glance, but PowerROLLING_RESISTANCE depends on **V**, for $\mathbf{C_{RR}}$ has two components: a low-velocity one, $\mathbf{C_{RR1}}$ and a $\mathbf{C_{RR2}}$, a corrector of $\mathbf{C_{RR1}}$, based on velocity. That is because the tires and wheels hysteresis and inertia forces grow with velocity. The formula that calculates it follows:

$$C_{RR} = C_{RR1} + N*C_{RR2}*V / W \qquad (10)$$

Where:
N is the number of wheels;
$\mathbf{C_{RR1}}$ is low-speed rolling resistance coefficient and
$\mathbf{C_{RR2}}$ is rolling resistance coefficient corrector.

The equation above shows where the car wastes supposedly unnecessary energy: using a fourth wheel. As mentioned above, the team has chosen to pay that price instead that of little safety.

Just like happened with $Power_{SLOPE}$, the car weight is a factor that matters to this power: it should be minimised as much as possible – as long as still guaranteeing strength and rigidity – in order to minimise wasting energy both in $Power_{SLOPE}$ and $Power_{ROLLING\_RESISTANCE}$.

2.4 $\mathbf{Power_{AERODINAMIC\_DRAG}}$

$\mathbf{Power_{AERODINAMIC\_DRAG}}$ ($\mathbf{½*C_D*A*\rho*V*(V-V_W)^2}$) is the power that the vehicle must overcome to keep itself at velocity relative to the ground V, while riding immersed in a fluid of specific mass – or density – ρ. That fluid is flowing with a speed - relative to the vehicle itself – equal to V-Vw.

As one can see, $Power_{AERODINAMIC\_DRAG}$ depends not only on the external variables above, but on the following car parameters: $\mathbf{C_D}$ and **A**. As already mentioned, $\mathbf{C_D}$ and **A**, together, multiplied to form $\mathbf{C_{DA}}$. That value has a very meaningful participation on the car's overall characteristics: $\mathbf{C_{DA}}$ is the only car parameter that influences on $Power_{AERODINAMIC\_DRAG}$. It should then be minimised above all costs, even above car mass (but not above car safety!), for $Power_{AERODINAMIC\_DRAG}$ is, as previously discussed, by far the largest portion of $Power_{Kyle}$ considering the whole race.

The functioning of this resistance is: the air flow encounters the car and has to avoid it; depending on how this avoidance is made, the car will be more or less "resistive" to that flow. This resistance can be lowered or augmented by enormous amounts only by changing a tiny part of the car body: it is by far the most sensible part of the design. A rear-view mirror, little as it is, per example, can make $\mathbf{C_{DA}}$ 50% higher. A canopy enhancement can decrease $\mathbf{C_{DA}}$ from 0.14 to 0.11 etc. Of course, when one speaks of $\mathbf{C_{DA}}$, he or she is talking exactly of $Power_{AERODINAMIC\_DRAG}$, for the relation is direct, linear. That saved power is gained "for free": little or no mass is added, no rolling resistance either. The only precaution that must be taken is not to change the photovoltaic panel shape in a way that it could receive less insolation.

The other effective way to lower $\mathbf{C_{DA}}$ is using wheel dressings and/or wheel fairings. The vehicle *Honda Dream* has been reported to gain significant 5kph – from 70kph to 75kph - in 1990 WSC only by doing it. That is, with no additional energy usage. To give an idea of the saved power, let's estimate a power ratio, remembering the approximated cubic relation between power and velocity:

$$Power_{energy\_saving} / Power_{no\_saving} = V_{saving}^3 / V_{no\_saving}^3 = 70^3 / 75^3 = 0.8130 \quad (11)$$

that is, an economy of 18.70% of energy was obtained, only by using wheel fairings, which weighted, together, about only 1 kg.

3 Relation Between the Three Parts of PowerKyle

To understand how those parts of the total used power coexist, how much each of them is important, and when, a Race Simulator has been implemented in MATLAB 6.1. It not only helped comprehension, but also helped give the initial steps towards energy management optimisation. The Simulated Annealing procedure that shall soon be described has also used the Simulator.

4 Energy Wasted Outside the Car and Energy Wasted Inside the Car

As the energy that is wasted outside the car has been thoroughly explained, we shall now study the energy that is wasted inside the car, no matter what the external conditions are.

As one will see, this kind of energy waste is one that is, at certain level, easy to minimise, and an approximate, significant 5% of the available sun energy can be saved if some precautions are taken.

The solar power that is available at a certain time is $Power_{SUN}$, and the power that the car manages to transmit to the ground is $Power_{WHEEL}$. How much of the initial $Power_{SUN}$ power will be delivered to the ground? And thus how much of it will be lost due to internal – mechanical, electrical and chemical - losses?

The following equation answers the above questions:

$$Power_{WHEEL} = Power_{SUN} * eta_{SUN\_TO\_WHEELS} \quad (12)$$

Where:

$$eta_{SUN\_TO\_WHEELS} = eta\_coverage * eta\_cells * eta\_MPPT * eta\_driver * eta\_motor * \\ * eta\_transmission \quad (13)$$

and the estimated values are (taken from the MATLAB Simulator):

eta_coverage = 0.96;
eta_cells = 0.17;
eta_MPPT = 0.98;
eta_driver = 0.98;
eta_motor = 0.94 and

eta_transmission = 0.98.

"Eta" is the way that the Greek letter **η** (usually associated to efficiency) was represented in the MATLAB Simulator.

Thus:

$eta_{SUN\_TO\_WHEELS} = 0.1444$

That is, only 14.44% of the solar energy that is insolating the panel wheel be delivered to the ground, and thus be transformed into kinetic energy, being used to counterbalance the three types of external losses ($Power_{Kyle}$).

If precautions were not taken, that number could be lowered to as much as 10%. The top teams, such as *Honda*, *General Motors*, *Aurora* and *Biel* achieve numbers close to an amazing 20%. These numbers show how important is internal energy management. Important note: lowering $\mathbf{C_{DA}}$ and **W** – that is, **m** – is called external energy management.

Both types of management, based on optimisation of each part, each system, are equally important to achieve this work's objective of saving clean, nearly infinite power. And, in this case study, propelling the car faster, to achieve better race placement.

It is important to remember that $Power_{WHEEL}$ is, at each moment, due not only to direct solar power conversion, but due to batteries discharge, that is, the complete formula is:

$$Power_{WHEEL} = (Power_{SUN} * eta_{SUN\_TO\_WHEELS}) + (Power_{BATT} * eta_{BATT\_TO\_WHEELS}) \tag{14}$$

where:

$$eta_{BATT\_TO\_WHEELS} = eta\_batt\_discharge * eta\_driver * \\ * eta\_motor * eta\_transmission \tag{15}$$

where (value taken from the MATLAB Simulator):

eta_batt_discharge = 0.95.

5 The Racing Strategy Optimisation Approaches: Short and Long-term Optimisation

Simulated Annealing is responsible for the optimisation of the expert system parameters, that is, it shall yield as results:

- the amount of total battery charge that is to be left at the end of each race day (when the car must stop, at 17:00);
- the threshold velocities: lower bound velocity and upper bound velocity; the algorithm will try to keep the car between these two velocities, according to GM's "Lambda Strategy" (Kyle, 1997);
- the threshold batteries charge: lower bound charge and upper bound charge; the algorithm will try to keep the set of batteries between these two states of charge;
- the threshold batteries discharge rate: lower bound discharge rate and upper bound discharge rate; the algorithm will try to keep the set of batteries between these two discharge rates (i.e., currents).

Note that optimising the first of the above items is the same as optimising the average discharge rate for each day, since the state of charge of the set of batteries is known before and after a day, and the total race time for a day is also known. We are working on both approaches.

The results listed above give to the team complete knowledge on velocity, batteries state of charge and batteries discharge rate along the race for the car to optimise its energy usage.

6 The Basic Energy Management Strategies Commonly Used in the WSC

There are two basic strategies of energy management used by the teams in the *World Solar Challenge*: constant velocity and constant batteries discharge. We shall now explain both of them: what they are and what pros and cons they have.

6.1 The Constant Velocity Strategy

The constant velocity strategy is based on the idea of keeping velocity constant as much as possible, as shown in Figs. 1 and 2. To accomplish this, there must be many batteries charging and discharging cycles, as shown in Fig. 3.

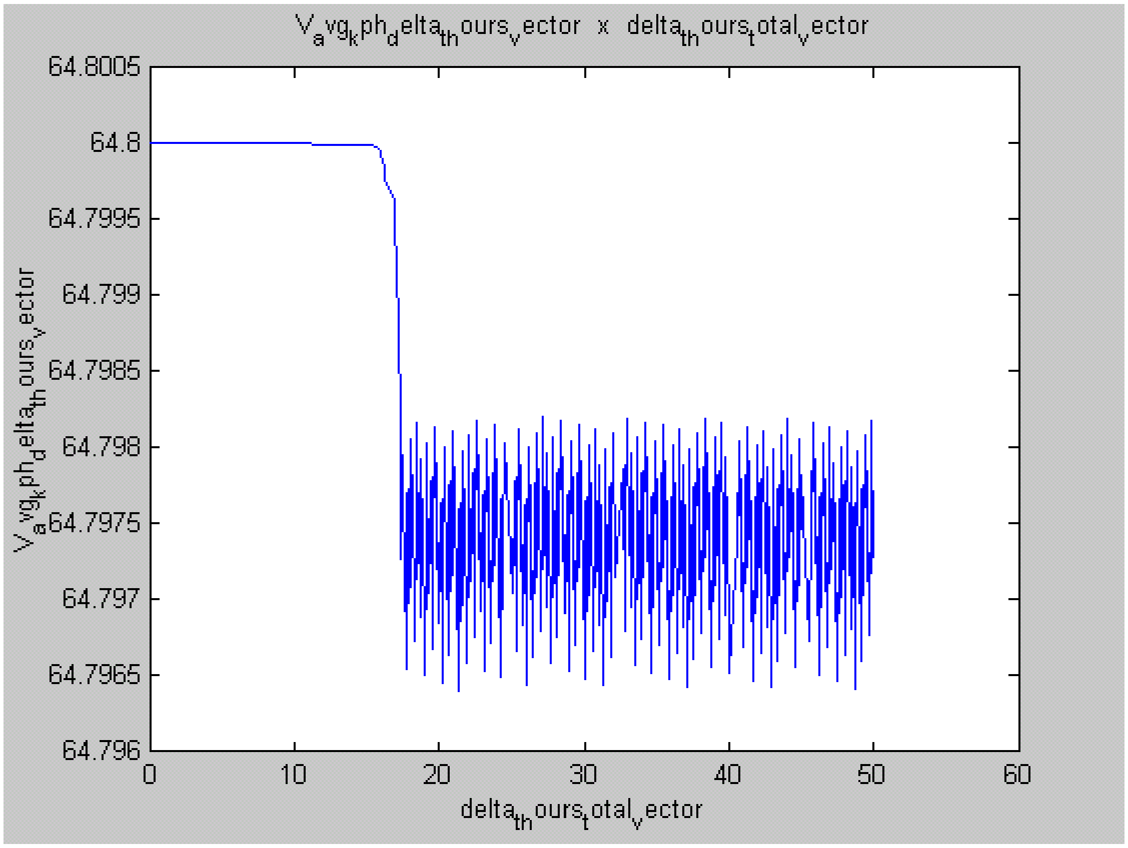

Figure 1: Speed (kph) *versus* time (h) when pure constant speed strategy is used. Note that the speed is practically kept constant during the entire race.

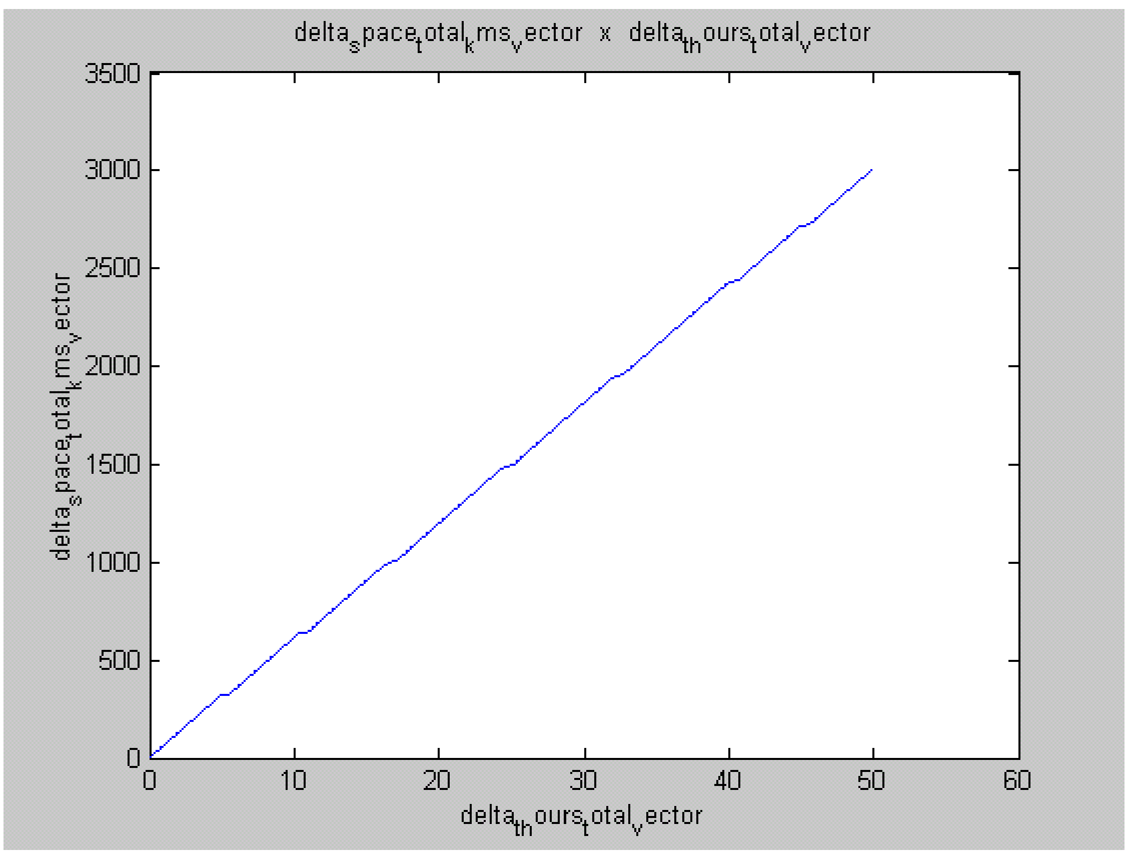

Figure 2: Total distance raced (km) *versus* time (h) when pure constant speed strategy is used. Note that the distance raced grows constantly during the entire race, showing that speed is really kept constant.

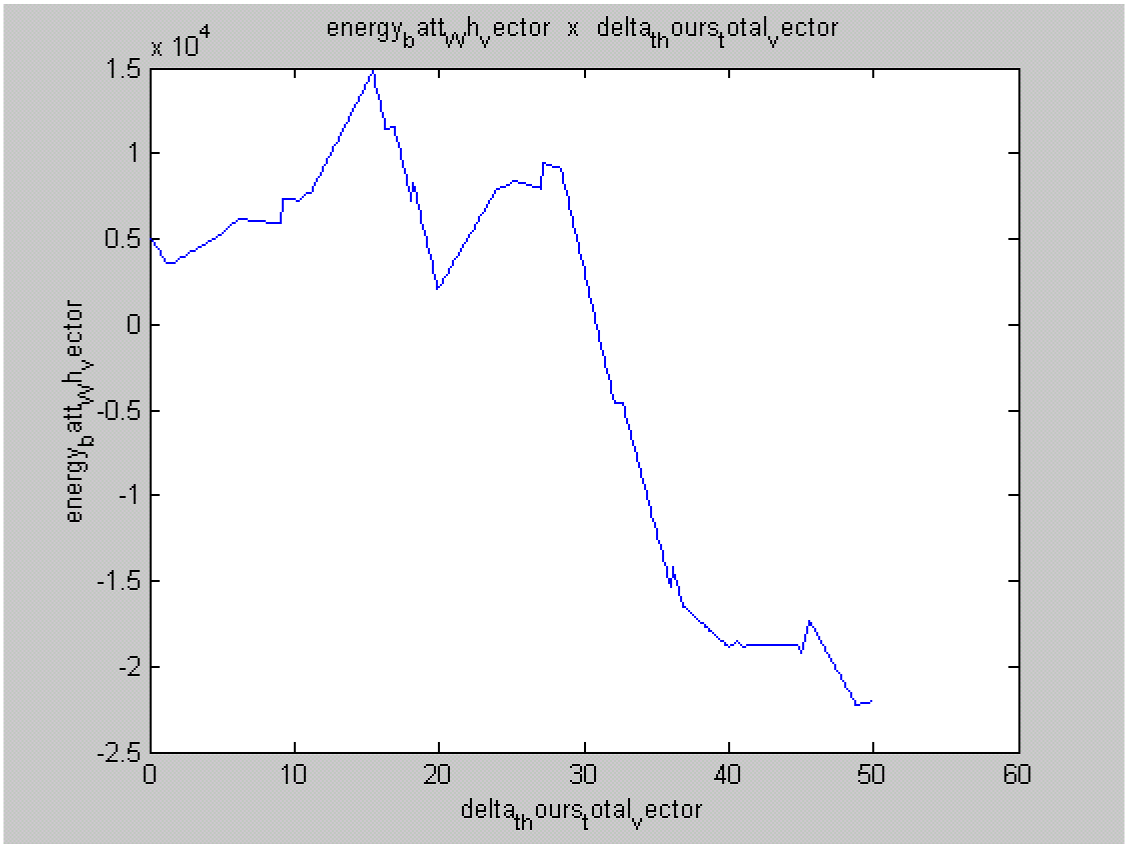

Figure 3: Battery pack charge *versus* time when pure constant speed strategy is used.

The main pro of this strategy is that, given the cubic relation between required power and velocity, changing velocity – instead of keeping it constant – is a significant waste of energy, which is avoided by this strategy. This phenomenon has been described earlier.

The drawbacks of keeping speed changing as little as possible is that there is too much batteries charge and discharge, what can lead to some problems:

1. as shown in Fig. 3, the battery can be charged to a level that is too close to its maximum, what can cause two problems:
    1.1. if there is enough insolation power to further charge the batteries, they will reach maximum charge and thus will not be charged any more (at least until a little discharge is done), what is obviously a waste of power;
    1.2. when the full-charged batteries condition described right above is reached, the exceeding power (power that is converted by the panel but is not used) must be discarded in form of heat via Joule Effect. This, besides being inefficient, increases even more the already high temperature inside the car, what is bad for the pilot, decreases cells efficiency and jeopardises motor and electronics good functioning;
2. as shown in Fig. 3, the battery can be discharged to a level that is too close to its minimum, what can cause a very serious problem: not enough energy for the car to proceed at desired speed, what is a failure on the strategy *per se*, for the velocity will not be constant. Even worse, if insolation and/or wind and/or topography are against the car, it might even be totally stopped. This has, in fact, happened in the *WSC* with some cars, during overcast days and even cloudy days on very tilted slopes;
3. some of the batteries that have a high energy density (energy capacity per mass unity), such as Ni/Zn and Ag/Zn, easily lose their charging capability, much like a cell phone battery does. The lead/acid batteries take much longer to suffer this ill process, but they have a very low energy density when compared to the other two. With the many charge-discharge cycles, the batteries would too soon lose, progressively, their charging ability, i.e. would hold each time less energy;
4. the processes of charging batteries, discharging batteries and regenerative breaking have each an efficiency lower than 100%, i.e. energy is wasted each time one realises there is exceeding available external power and chooses to keep speed at a value lower than possible – thus charging the batteries with the exceeding solar power and/or breaking using energy regeneration. It is important to note that even if one chooses not to use energy regeneration, there is still a batteries charge/discharge cycle if a constant speed strategy is to be maintained.

In Fig. 3, note that the charge is allowed to go both below zero and over the maximum capacity (varying from a maximum of 15kW*h to a minimum of –22kW*h) in order to show how “wild” is its behaviour. As the scale of the Y-axis is large, the stationary charging periods are not easy to spot (but they can easily be seen in Figs. 6 and 9).

6.2 The Constant Batteries Discharge Strategy

The constant batteries discharge strategy is based on the idea of keeping batteries discharge rate constant as much as possible as shown in Fig. 6. To accomplish this, the vehicle velocity must vary a lot (as shown in Figs. 4 and 5), what is a waste of energy due to air drag resistance.

It is now necessary to introduce something about the competition rules. First, *WSC* competitors can ride only from 8:00 to 17:00. At 17:00 they must stop wherever they are and park their solar vehicle, only being allowed to resume racing at 8:00 next day. Second, the so-called "stationary charging periods" are moments when the car is obligated to remain stopped, though it can still remain exposed to the sun and thus receive solar energy. There are two types of stationary charging periods: the overnight stops (between 17:00 and 8:00) and the media stops (which occur at seven control points along the race). The little instant increases in time without any distance progress – shown in Figs. 2, 5 and 8 - are the media stops, half-an-hour long each.

In Fig. 6, note that the batteries charge is very well behaved now: it appears exactly as expected: a constant negative slope and some steep, positive ones. These represent the stationary charging periods, being the smaller ones the media stops and the bigger ones, the overnight stops. Note that in this simulation the seventh media stop occurred right after the fifth overnight stop.

The calculations of how much the batteries should be discharged each moment will be explained by first introducing an easier case. Actually, it is a sub-case of the desired one: pretending the discharge to be zero (e.g. in a constant batteries charge strategy), that would be accomplished easily by using all the instantaneous solar energy input to the car – that is, the instantaneous power converted by the solar panel –, and only that power.

The stated just above makes a lot of sense for a car that is exposed to the sun only when it is racing, because the car uses – to move itself - at all times the power it is converting at that moment, no more, no less. However, there are the stationary charging periods, thus there is additional energy available, what makes a constant batteries discharge possible (instead of discharge zero, present in a constant batteries charge strategy).

The additional energy stored - in the set of batteries - during the stationary charging periods is not one to be neglected. It usually ranges from 1.0kW*h to 2.0kW*h. The total batteries recharge expected during all the – estimated six – days of race is around 8kW*h (almost two times the total batteries energy capacity, to give an idea). Adding the energy that is stored every day during the daily, obligatory half-hour "media stop" – which we estimated to be 2.5kW*h -, there is a total energy of 10.5kW*h that is stored in the set of batteries while the car is not moving.

With the total race distance being 3007km and the estimated average velocity being 57kph, the total race time would be 52.75 hours (52.75 is a decimal number), what means 5 full days and about six sevenths of the sixth day.

Considering the 10.5kW*h stated above, the initial 5kW*h energy stored at the beginning of the race and the time of 52.75 hours, the average power that must be drawn from the set of batteries, while the car is moving, is:

$$Pow_{CONST\_DISCHARGE} = (10.5 + 5)kW*h / 52.75h = 293.8W$$

Thus, the power to be transmitted to the motor wheel is:

$$Pow_{CONST\_DISCHARGE\_MOTOR} = (Power_{SUN} * eta_{SUN\_TO\_WHEELS}) + \\ + (Pow_{CONST\_DISCHARGE\_RATE} * eta_{BATT\_TO\_WHEELS}) \qquad (16)$$

with the value of $eta_{BATT\_TO\_WHEELS}$ being given by equation 15.

The instantaneous used power is thus the instantaneous solar power plus a positive offset of 293.8W. This total value varies with time of day, weather and latitude - whose change along the route is not negligible -, therefore velocity changes as well. During the initial and final moments of each race day (8:00 and 17:00), the solar power density ranges approximately from 200W/m^2 to 400W/m^2. At noon, it may be as high as 1200W/m^2 in a sunny, clear day and even 1350W/m2 if there are sparse clouds (the additional 150 W/m2 being giving by the reflection provided by the clouds).

The main pro of this strategy is that there is almost no batteries charging, thus there are no losses due to batteries charge/recharge cycle. Actually, of all drawbacks of the constant speed strategy listed above, only the number 2 (excessive little charge left in batteries) is not minimised with the use of the constant batteries discharge strategy.

The drawbacks are again those of the losses imposed by excessive variation on velocity.

We shall now explain it in detail, using an example: when there is little sun power available (e.g. at the end of an overcast day), the vehicle will proceed at very low speed, specially if it encounters a steep slope upwards, case in which the car could even stop, not being able to climb it up, as already explained.

Similarly, when there is a lot of sun power available (e.g. at noon, in a clear, sunny day), the car can ride really fast. If it encounters a 3% downwards slope, per example, the Simulator, already implemented, shows it can go as fast as about 110kph, what seems desirable at first, but the power lost - overcoming aerodynamic drag - to keep the car at that amazing speed is too high, i.e., energy is lost and, in race terms, performance decreases.

With the just stated above, one can easily realise, once more, that it is an interesting strategy to avoid - as much as possible - speed changes along the race.

We sometimes speak of maximising performance (saving time in order to maximise speed), which are important for racing. However, it is important to remember that the main goal of this work is promote intelligent management of energy - be it electric or not.

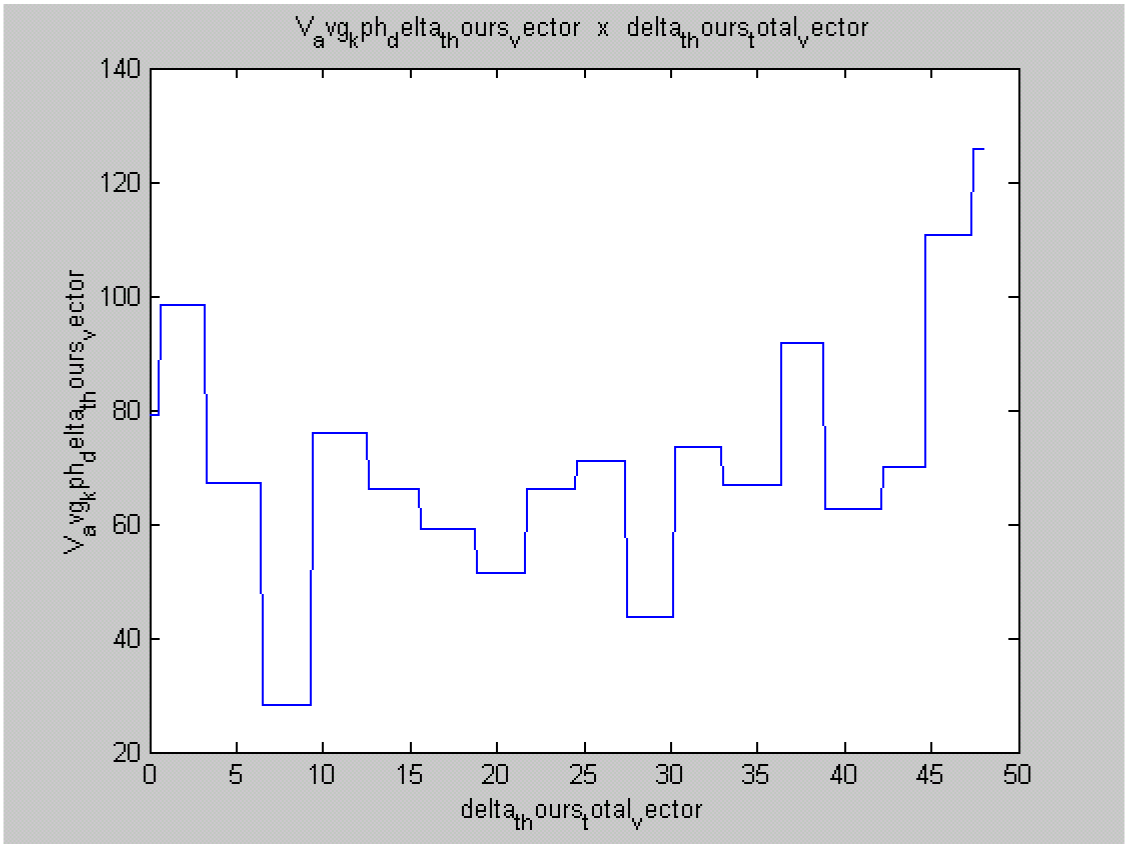

Figure 4: Speed (kph) *versus* time (h) when pure constant discharge strategy is used. Note that the speed changes a lot during the race.

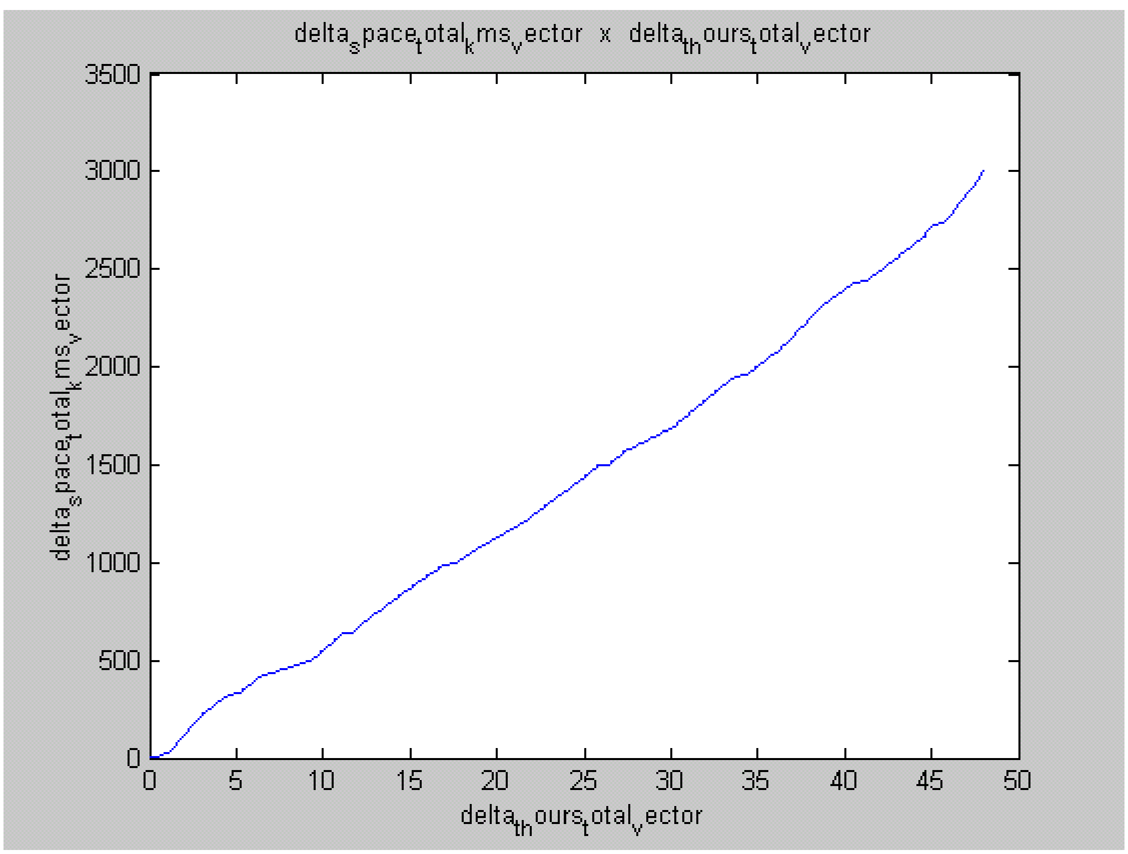

Figure 5: Total distance raced (km) *versus* time (h) when pure constant discharge strategy is used. Note that the total distance raced grows with many different slopes during the race, showing that speed is being changed all the time.

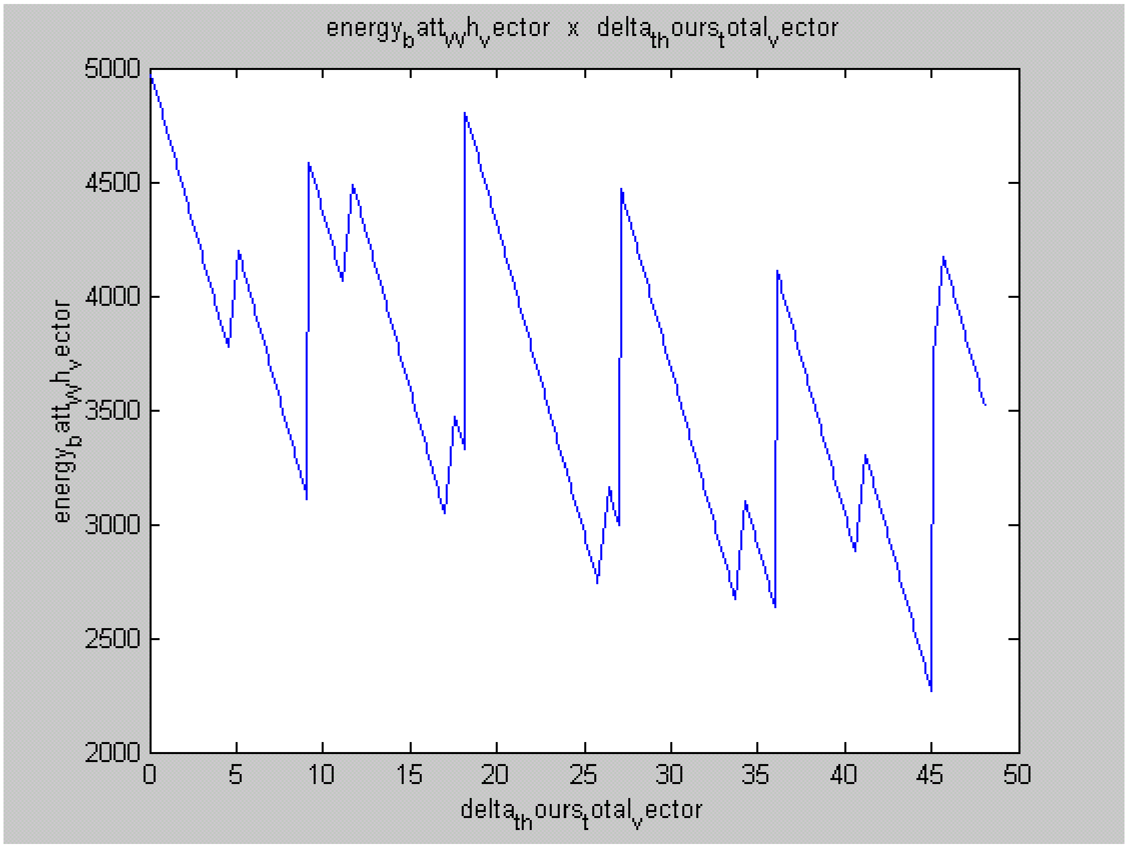

Figure 6: Battery pack charge *versus* time when pure constant discharge strategy is used.

7 Merging Both Strategies to Get Better Results

The ideal strategy is one that has the pros of both strategies and, at the same time, minimise the cons of each of them. If that is accomplished, one can expect less energy loss, which yields both better average speed and lower speed variance. Such a strategy would, thus, make the vehicle more efficient and also more reliable.

To accomplish this, a mixed strategy shall be used: a strategy that manages energy usage based on both strategies.

We shall now compare the mixed strategy with each of the called "pure strategies", in order to understand what the expected enhancements are. From the constant batteries discharge strategy point of view: the total power used along the day – which varies too much when such a strategy is used – will vary less, so will velocity. From the constant speed strategy point of view: constant speed is abandoned (however, little variation on velocity is introduced), but it is not a problem: the undesired effects of constant speed strategy (the high variations on batteries energy and the many of charges and discharges of batteries) are diminished.

When using a mixed strategy, an intermediate point must be found. A variable called **α** is introduced to represent how close to the constant speed strategy that intermediate point will be – and thus how far from the constant batteries discharge strategy. Hence, we calculate a weighted arithmetic average value of the two power values (the powers yielded by the two pure strategies), following the equation:

$$Pow_{MIXED} = (Pow_{V\_CONST} * \alpha) + (Pow_{DISCHARGE\_BATT\_CONST} * \beta) \quad (17)$$

where:

$$0 \leq \alpha \leq 1$$

$$\beta = 1- \alpha \quad (18)$$

Note that if α=1 is used, the mixed strategy is reduced to the constant speed strategy, while that if α=0 is used, it is reduced to the constant batteries discharge strategy.

But what is the optimal value of **α**? It will be determined by the long-term optimising process based on Simulated Annealing. The mixed power, calculated as shown in Eq. 17, is the one to be used in that process: the "car" will "race" many times in the Simulator until the process converges.

8 Implementation of the Optimisation Algorithm

Understanding the output of the algorithm: it yields as result a configuration that tells two things: how the batteries should be discharged along each race day and the goal velocity.

The goal velocity is the velocity that is used to calculate the power used on constant speed strategy (and, thus, the mixed strategy).

The initial values used are average values. Their function is only to begin the algorithm with consistent data, in order to enhance the algorithm performance. They are listed below:

1) $V_{GOAL} = 18.06$m/s

The goal velocity of 18.06m/s – which is equivalent to 65kph - is the estimated velocity based on many simulations taken. The car parameters used in the simulator were $\mathbf{C_{DA}}$=0.13, **m**=283kg and $\mathbf{C_{RR}}$=0.0056. A "virtual track" has been built, with the slopes all along the almost 3000km across Australia. The wind velocity, of course, was "partially random", that is, wind behaviour has been reproduced: frequent changes on direction and speed (more often on speed). This virtual track has been created entirely based on real track data provided by *WSC* observers, competitors and designers (Kyle, 1990 and 1993).

2) $\boldsymbol{\alpha}$ is a random value in interval [0,1] and β is found using Eq. 18.

3) expected energy at the end of each race day (discharge of 293.8W):
- batteries energy end of day 1: 3.20kW*h;
- batteries energy end of day 2: 2.56kW*h;
- batteries energy end of day 3: 1.92kW*h;
- batteries energy end of day 4: 1.28kW*h and
- batteries energy end of day 5: 0.64kW*h.

Being 10.5kW*h the total energy store in the set of batteries while the car is stopped and being 5 the number of nights existent in 6 race days, the average daily charge obtained during periods in which the vehicle is stopped is 2.1kW*h. That is done pretending that there are one media stop per day in days one to five and two in day 6. Using that number and the constant discharge strategy approach (only to calculate the expected energy at the end of each race day) with a discharge of 293.8W ($Pow_{CONST\_DISCHARGE}$), the numbers above are found.

It is important to note that the energy batteries at the end of day 6 – supposedly the last one – is to be zero (to optimise energy usage), therefore it is subject nor to changes nor to optimisation.

The core of the general Simulated Annealing algorithm follows in structured language:

```
begin (1)
  S ← initial solution // vector with random values for the parameters to be optimised
  T ← initial temperature T0
  while (stopping criterion is not satisfied)
  begin (2)
    while (not yet in equilibrium)
    begin (3)
      S’ ← some random neighbour of S // one of the elements of the vector is changed
      δ ← Cost(S’)-Cost(S) // δ is the cost difference of the two solutions
      Probability ← min(1, exp(-δ/T)) // applied Boltzmann Probability: p = exp (-δ/T)
      if (random(0,1) <= Probability) then
        S ← S’ // candidate solution is accepted
    end (3)
    update T according to annealing schedule
  end (2)
  output best solution
end (1)
```

The temperature parameter is inherent to the SA algorithm: it controls the pace, the progression of the algorithm.

In this work's case, cost (S) is the total race time of the last accepted solution (a solution is a set containing the parameters to be optimised). Cost (S') is the total race time of the candidate solution (another set of parameters: it has got all parameters but one unchanged when compared to the actual solution). The chosen annealing schedule is Adaptive Simulated Annealing, an evolution of the Geometric Cooling. The stopping criterion is the "freezing state": the algorithm stops after three consecutive temperatures are processed without enhancement to the solution.

9 The Results

An optimal value has been found for each one of the parameters previously stated. Those parameters working together kept achieved:

- velocity: the velocity most of the time between the maximum and minimum desired velocities;
- charge of the set of batteries: the batteries have never been totally discharged (except for Adelaide, what was desirable) or charged (except for Darwin, where the race starts and the battery pack is, by team choice, totally full);

- regenerative breaking was not used, even though it will during the real race, what makes this paper's result quite conservative: its achieved average speed is around 1kph slower of the potential race speed;
- maximum batteries output current seldom exceeded the upper bound value, what makes the motor operate at low temperatures, what is both reliable (motor can fail at high temperatures) and efficient (motor efficiency drops with temperature).

Undesirable consequences of the pure strategies – batteries pack full when not at the start of the race, batteries entirely drained when not at the finish of the race, excessive speed variance* and excessive batteries charging and discharging, as previously discussed – have thus been avoided. This can be seen in Figs. 7 to 9, which show results of a simulation made with α=0.75 i.e. a mixed strategy which remains a bit closer to constant speed strategy than to constant discharge strategy.

* In Fig. 7, note that although the use of α=0.75 keeps the strategy closer to the constant speed strategy, velocity does change a lot during the race. Using values closer to 1 for α would avoid it.

Fig. 9 shows that the charge is very well behaved now: it appears exactly as expected: a constant negative slope and some positive ones (the smaller ones are the media stops and the bigger ones, the overnight stops). Also note the five "rounded" positive slopes representing the pack of batteries being charged through the use of regenerative breaking.

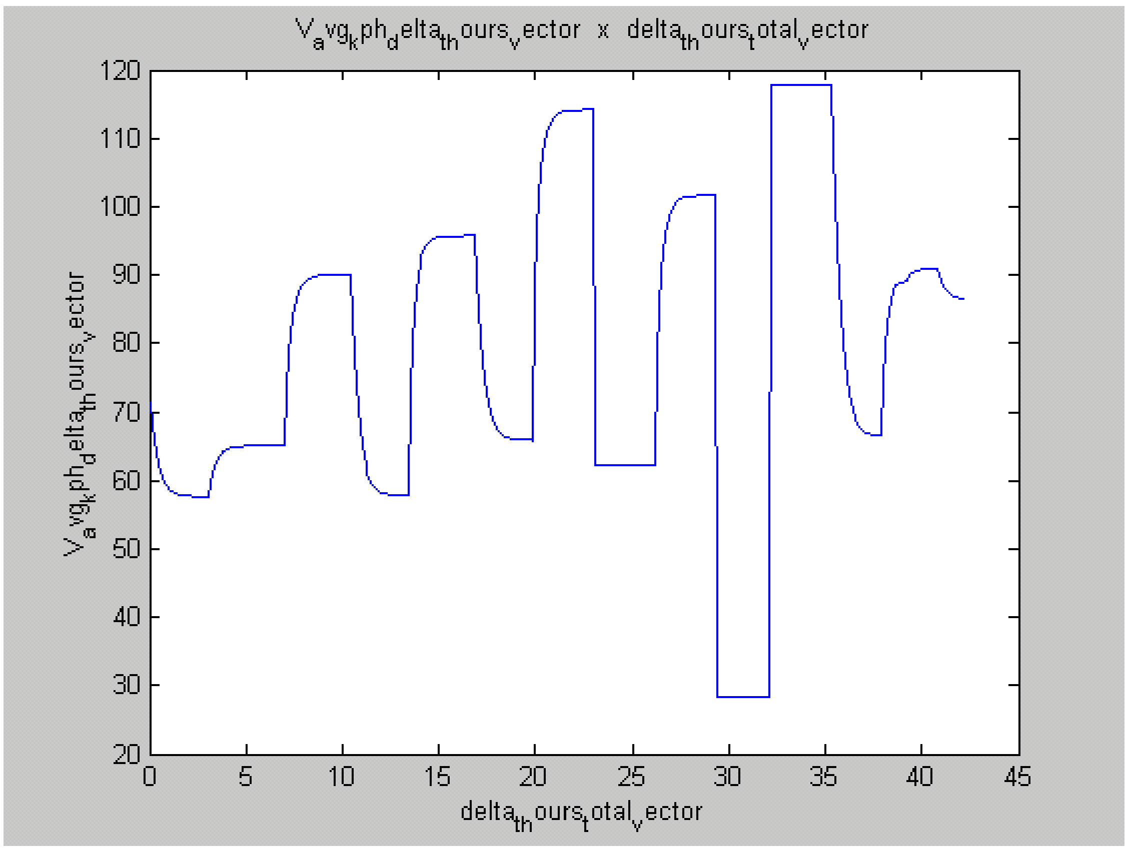

Figure 7: Speed (kph) *versus* time (h) when α=0.75 is used (i.e. mixed strategy).

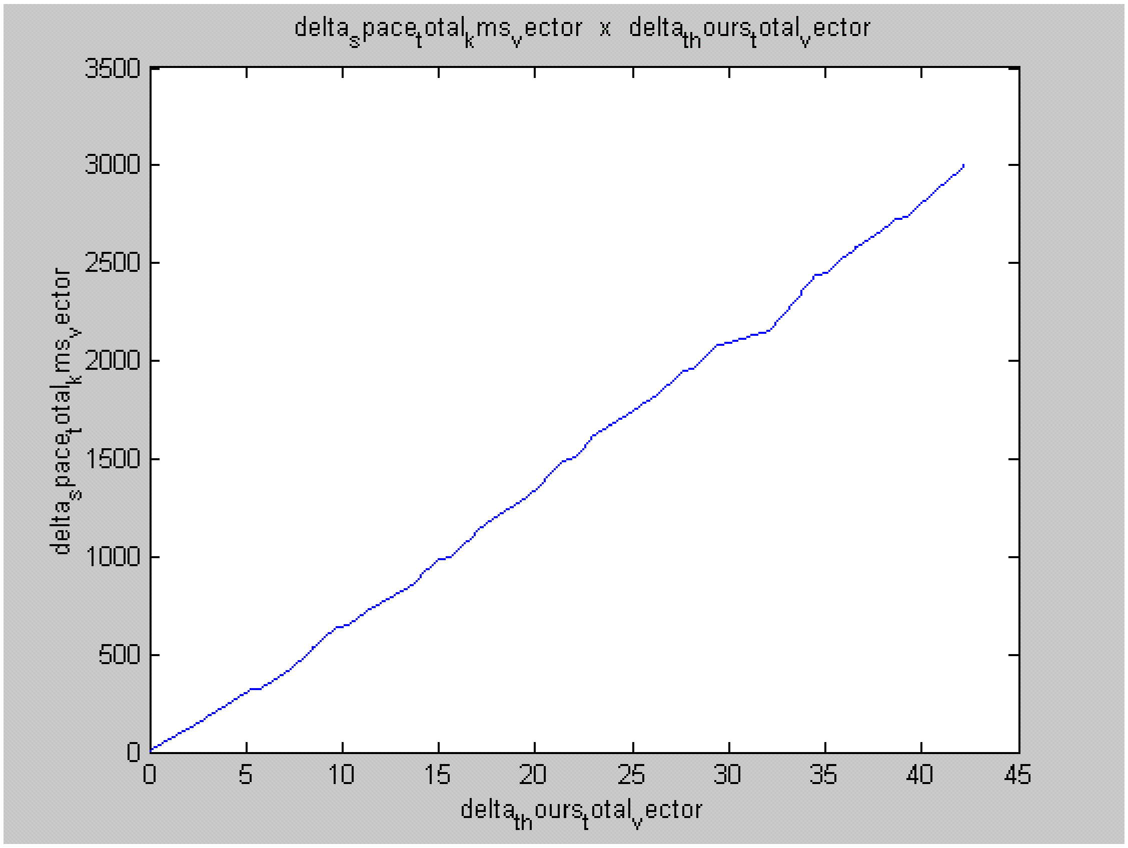

Figure 8: Total distance raced (km) *versus* time (h) when α=0.75 is used (i.e. mixed strategy). Note that the total distance raced grows with many different slopes during the race, showing that speed is being changed all the time.

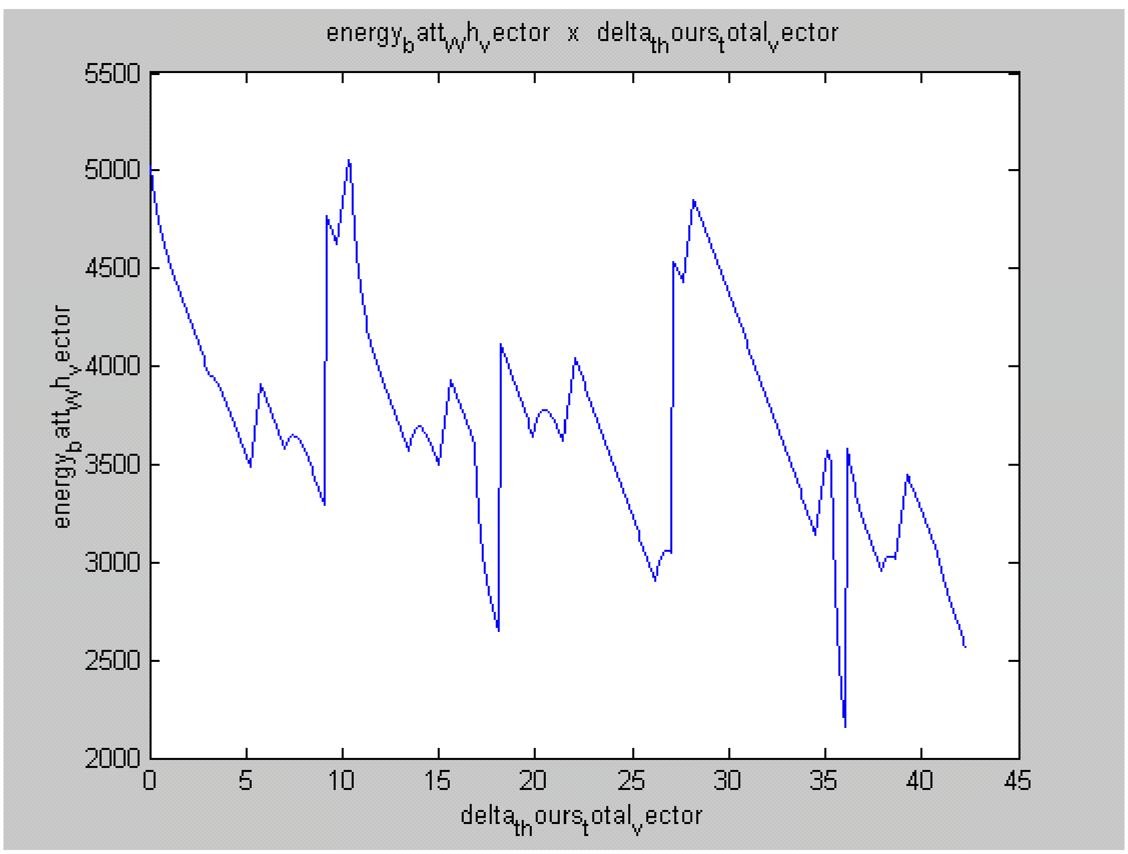

Figure 9: Battery pack charge *versus* time when α=0.75 is used (i.e. mixed strategy).

For the above case – alfa=0.75 – the result was the best of the three cases studied i.e. the mixed strategy had the best average speed during the race. This testifies the exposed.

The output data of the MATLAB Simulator are:

delta_t_hours_total = 42.3000;
delta_space_total_kms = 3.0095e+003 (the distance is slightly larger than the actual race distance because of the 0.1 hours discretisation of the simulator);
V_avg_kph_total = 71.1462.

One can easily see in Figs. 1 to 6 that the total time taken to complete the race using the pure strategies were:

- constant speed strategy (alfa=1): 50h;
- constant discharge strategy (alfa=0): 48h.

These numbers illustrate the enhancement in the race final result achieved by the use of a mixed strategy. As it is desirable to take a time as little as possible to finish the race, the numbers show that constant speed and constant discharge strategies are similar in quality, for 50 hours and 48 hours are similar results. In its turn, the mixed strategy is far better than both, taking the vehicle to the finish line in one entire day less than the constant speed strategy.

10 Conclusions

Simulated Annealing has proven suitable to optimise the parameters of an expert system, in order to determine the optimal racing strategy of a racing vehicle powered exclusively by solar power.

Optimising internal and external critical steps of energy conversion has proven to make a great difference: all precautions cited along the paper, working together, yielded a solar power usage that is twice or even three times more economic than that which would be obtained with a careless energy management.

11 References

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