Notes on stability considerations for solar cars

Version 1.1, 23 May 2020

John Storey

Background

The goal for BWSC solar car designers is to design a highly efficient vehicle. An efficient vehicle will be lightweight, have low rolling resistance and low aerodynamic drag. However, the most important consideration, overriding everything else, is that the car be stable and controllable in all foreseeable weather conditions.

High wind speeds are common on particular parts of the course, with gusts regularly exceeding 70 km/h. Many solar cars are capable of sustained travel at speeds approaching or even exceeding the open-road speed limits of 130 km/h in the Northern Territory and 110 km/h in South Australia. Solar car designers must always keep their team's drivers fully informed about the vehicle's handling limits, so drivers can drive at a speed appropriate for the conditions and with safety as a priority.

This document is intended to be a non-exhaustive list of design decisions that, in my opinion, teams should think carefully about. It is most emphatically not a "How-to-do-it" prescription; that would require at least one text book, and probably several. It is my view that the Science Faculty are not here to teach people how to build the most efficient solar car. Rather, they aim to draft a set of regulations for the event organisers that will create a broad framework within which teams can exercise a maximum of design freedom, building vehicles for the future that no-one has imagined before and—most importantly—without any need to compromise safety.

Static stability

The most basic stability requirement is that the solar car should not tip over. On a reasonably smooth road, this means that the tyres should slide before the car rolls. The Static Stability Factor for a four-wheeled vehicle with the same track front and rear is defined as

$$SSF = t/2h,$$

where t is the track width and h the height of the centre of gravity above the road.

An SSF of at least 1 is usually considered desirable.

For a vehicle with differing front and rear tracks, asymmetric wheel placement or three wheels, it can be assumed that the maximum horizontal forces on the tyres could occur in any direction relative to the vehicle's longitudinal axis. In other words, the vehicle could be sliding, temporarily out of control, in any direction. The appropriate ratio for roll-over stability is then the horizontal distance from the centre of gravity to a line joining any pair of wheels, divided by the height of the centre of gravity.

It is particularly important to note that:

1. any suspension movement will alter the car's static stability,
2. aerodynamic forces from side winds will invariably act to produce an overturning moment,

3. dynamic effects, e.g. angular momentum along the longitudinal axis, can further contribute to a tendency to roll over, and
4. an uneven road surface can flip even a well designed car that is sliding sideways.

Thus, having a good SSF is no guarantee that the car will not roll over. However, having a low SSF makes it very likely that it will.

In what follows we assume that the car has been designed with a good static stability factor and is therefore unlikely to roll. What is important next is that:

1. the car can cope with powerful wind gusts from any direction without sliding, and
2. the controllability, or "handling", of the car—even when it has been subject to a sudden and unexpected disturbance—is sufficiently precise and benign to be well within the capability of every one of the team's drivers.

Dynamic stability

Suspension

Suspension design has a profound effect on both the stability of a car and its controllability, or "handling". It is also important to keep all wheels pointing in the same direction when travelling in a straight line, ie minimizing toe-in/toe out changes, in order to minimize rolling resistance, but that is a separate matter. Some important parameters to consider are:

- Bump steer and roll steer, where the steering angle of a wheel changes with suspension travel,
- Caster angle,
- Camber angle,
- Scrub radius, and kingpin offset,
- Trail, or caster offset,
- Roll-centre heights,
- Spring rates (i.e., stiffness),
- Damper rates, both on bump and rebound,
- Any coupling between suspension movement of one wheel to that of another (e.g., anti-roll bars, hydraulic or hydro-pneumatic systems).

Steering

In order to be controllable, a solar car must have a direct, smoothly operating steering system, with minimum stiction and minimum backlash or "free-play".

The steering must also be able to move the wheels through a sufficiently large angle that understeer or oversteer can be corrected and that the car can be recovered from an unexpected rear-wheel slide before a full spin develops.

Stiffness, or rigidity

The best suspension and steering designs are worthless if they are not constructed with a high degree of control over the rigidity. The same consideration applies to the vehicle chassis as well. If the vehicle body can flex, for example because the carbon fibre shell lacks sufficient torsional stiffness, the effect is the same as if the suspension itself lacked rigidity.

It is particularly important that the steering angles and the toe-in/toe-out angles are always well controlled. Free play, stiction or lack of rigidity in the steering mechanism can result in a car that is difficult to control in normal circumstances and impossible to control under gusty wind conditions.

Tyre behaviour

When a tyre is called upon to resist lateral forces the vehicle no longer travels in exactly the same direction that the tyre is rolling, the difference being described as the slip angle. The slip angle increases with lateral force in a non-linear manner until the tyre loses traction, sliding as much as rolling. Once this occurs the car is skidding and potentially out of control. Control can only be restored by reducing the lateral force or orienting the wheels in a direction close enough to the direction of travel to allow the tyres to once again roll with an acceptable slip angle.

In the absence of a suspension, the slip angle of the front tyres relative to that of the rear tyres determines whether the car initially understeers or oversteers. Suspension design can compensate for this initial behaviour to make the car easier to drive. However, as cornering speeds increase, either the front or the rear (or both ends) of the car will eventually reach the point where the tyres can no longer generate enough lateral force to keep the vehicle on course. The vehicle will then either spin (ultimate oversteer) or continue ploughing onwards (ultimate understeer). The load on each of the wheels at the point where the tyres are about to lose traction depends on many factors, including wheel placement, mass distribution and suspension design.

The springiness of the tyres in bump and their ability to operate at significant slip angles introduce an unavoidable compliance, or lack of stiffness, into the suspension behaviour.

Because the slip angle can be quite large before the tyres actually lose traction, it is important that the driver has sufficient steering authority (i.e., range of steering angle) to control the car even when a strong wind gust is encountered while cornering.

Aerodynamic considerations

Solar cars are normally designed to have the lowest possible aerodynamic drag. The need to package the wheels, the driver and other large components is all part of the challenge. Minimum drag will be achieved when the body has zero lift, reducing the induced drag to zero. (This is because the coefficient of rolling resistance of the tyres is invariably lower than the lift/drag ratio of the airfoil.) Even in the absence of a crosswind, there are two further considerations:

1. At highway speeds, many solar cars are capable of generating enough lift to fly if they pitch upwards enough to create a large angle of attack. The centre of lift of an airfoil is typically about 1/3 of the way back from the front. If the centre of gravity of the car is rearward of the centre of lift a car may become unstable in pitch.
2. Unless the lateral centre of pressure is rearward of the centre of gravity, the car will initially be aerodynamically unstable—ie, any initial yaw will be amplified. (It is for this reason that an arrow has feathers at the back, not the front.) The position of the lateral centre of

pressure relative to the tyres will determine how the car eventually reacts to this yaw. Having a larger lateral cross section towards the rear of the car will invariably make it more “stable” in the aerodynamic sense. However, too much of this stability will make the car behave like a weather vane and try to point into the wind, perhaps uncontrollably.

In the presence of a small crosswind, the airflow over the body is not greatly different to the zero wind case. Many solar teams extend their computational fluid dynamics (CFD) modelling and wind tunnel testing to include a range of crosswind angles. In some cases, the drag can become lower than in the zero-wind case, in extreme cases (such as a land yacht) becoming negative. This effect can be used to advantage, although the increased lateral aerodynamic forces must be resisted by the tyres. Most solar car designers therefore attempt to minimise the side area.

The position of the lateral centres of lift and pressure become increasingly important as the crosswind increases relative to the speed of the car, i.e., as the apparent wind direction rotates to the side. Initially, in a well-designed car, the airflow will be mostly attached. As the apparent wind angle increases, sections of the body will eventually stall and as they do the centre of pressure will abruptly jump rearward. The vehicle’s response to this will once again depend on the position of the centre of mass and the tyre contact points with the road relative to the aerodynamic centres of pressure.

Weight distribution

From the above discussion it can be concluded that both the fore-aft position of the centre of mass and the height of the centre of gravity have a profound effect on the stability of the car.

However, not only is the location of the fore-aft centre of gravity important, but so too is the distribution of the mass as this determines the polar moment of inertia. A low polar moment will result in a vehicle with a fast response to a lateral perturbation (e.g., wind gusts) and to a pitching perturbation (e.g., bumps in the road).

This dynamic response of the vehicle will, of course, depend not only on the mass distribution, but also on the suspension design and wheel placement.

Wheel placement

It is important to take into account not only the static stability but also the weight transfer during cornering. Design of three-wheeled cars, or cars with asymmetric wheel placement, is particularly challenging. The initial response of the vehicle as it enters a corner (or is hit by a sideways wind gust) depends on all of the factors described above. The point at which the car begins to slide or spin depends on all of the above plus the extent of the weight transfer following both this initial response and driver’s actions that follow.

Locating the wheels close to the corners of the car can help reduce its sensitivity to any lack of stiffness in the suspension and steering, and also to the cornering stiffness (or slip compliance) of the tyres.

Interactions

None of the design considerations discussed above can be considered in isolation. There are a vast number of decisions that have to be made during the design process and it is vital that specialists on the design team have a good understanding of the challenges facing those specialists working on other areas. The importance of good communication within the design team becomes no less important once the vehicle goes into the testing phase. Changes made to, for example, the aerodynamics of the vehicle might have an unexpected effect on the roll behaviour of the car, leading to a change in the way the suspension reacts. Last-minute changes to any part of the design should be carefully reviewed by engineers involved in all other areas of the design—even if there is no immediately obvious connection.

Testing

There is no substitute for pre-event testing. The Bridgestone World Solar Challenge is first and foremost a design competition, with the proof of design being the on-road component from Darwin to Adelaide. The most successful teams are invariably those who have not only put immense effort into the design, but who have also exhaustively tested their vehicle under every possible foreseeable condition.

It is impossible to reproduce all of the conditions that are likely to be encountered en route from Darwin to Adelaide at the Hidden Valley Racetrack. The purpose of the dynamic scrutineering is not to “prove” that vehicles are stable under all conditions. Similarly, a good lap-time around the Hidden Valley circuit does not guarantee that the car will not become difficult to control under severe conditions.

Responsibility

The onus remains on the teams to ensure that they have designed a vehicle whose limitations are well characterised and understood, and that the vehicle is driven safely within these limitations at all times. This is exactly the same obligation that all drivers carry when they take a normal, mass-produced production car onto the road. Solar car drivers enjoy a privilege that members of the public who purchase a car from the showroom do not, in that they can and must discuss, one-on-one, the handling characteristics of the vehicle with the engineers who designed it. All privileges carry with them a corresponding responsibility—in this case the responsibility is to fully understand the road-holding limitations of their vehicle and to drive within them.