Rocket science

An insider's perspective on the vehicle dynamics of Bloodhound SSC, which plans to raise the land speed record to 1,000mph

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The key issues in the dynamic behavior of Bloodhound SSC are the controllability and directional stability over its entire operating speed range, from zero to 1,000mph (1,600km/h), although its prime objective is extremely high-speed straight running rather than cornering, as is the case with high-speed racing vehicles.

It is important to define 'directional stability' from the outset: when the vehicle is perturbed from its equilibrium condition (straight running), it is directionally stable if the force and moment system causes it to return to the original equilibrium condition automatically.

The term 'controllability' refers to the fact that the driver has some degree of control over the external force system, so that he or she can provide input commands or corrections to the directional behavior of the vehicle. Good controllability – being responsive to driver demands, consistent and predictable over different conditions, and providing some feedback – give the driver confidence in the vehicle dynamic system, which is rather important when covering the length of four soccer fields every second!

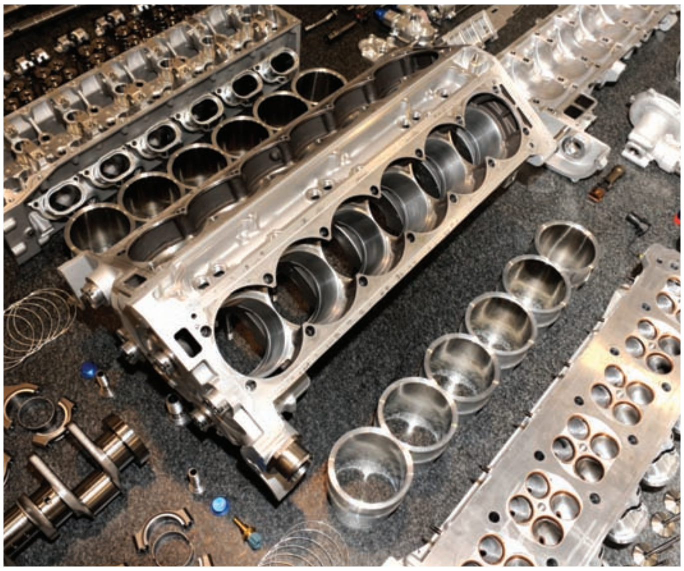
To some degree, there is a conflict between stability and controllability. Good stability requires the vehicle to be insensitive to unwanted external forces – for example, those caused by crosswinds or single wheel bump inputs. On the other hand, good controllability requires the vehicle to be sensitive to those external force inputs generated by the driver. It is interesting to observe that the driver does not actually have direct control over the external force systems, but has angular control over the steered wheels. This results ultimately in them being forced to operate at slip angles, and hence generate lateral forces at the wheel/ground contact patch that are transmitted to the vehicle body via the suspension links.

Despite the great design challenges with extremely high-speed vehicles, there are still only two fundamental sources of external forces and moments that contribute to its directional stability: wheel/ground interactions and aerodynamic properties.

The Bloodhound wheels are themselves a major design challenge – they have to withstand burst forces associated with centripetal accelerations of 25,000g, for example. It is impossible for anything resembling a tire to exist under these conditions, so the wheels will be made of titanium, possibly with some ribbed profile to achieve good ground/wheel interaction.

> "Bloodhound SSC's wheels are a design challenge – they have to withstand burst forces associated with centripetal accelerations of 25,000g"

The wheels are assumed to be able to generate lateral forces in response to slip angles in rather the same way that tires behave. The mechanics here are completely different, however – tires generate forces at the contact region due to friction between the rubber tread and the ground surface. For solid wheels operating on a deformable medium, some type of salt or silt desert surface, the force generation mechanism is controlled by the wheel/soil friction and the internal soil friction when it deforms.

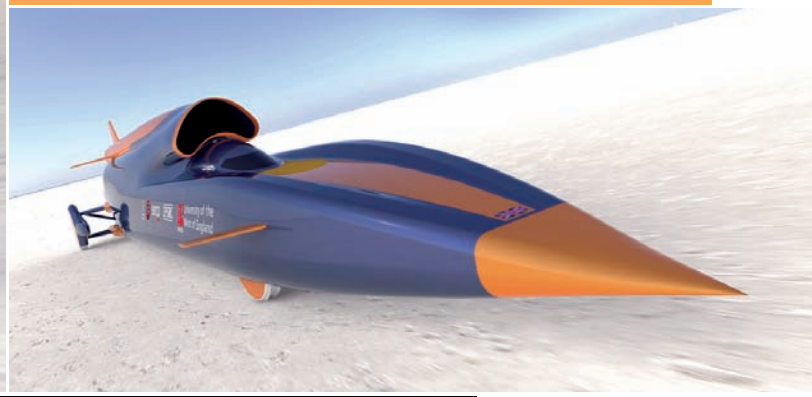


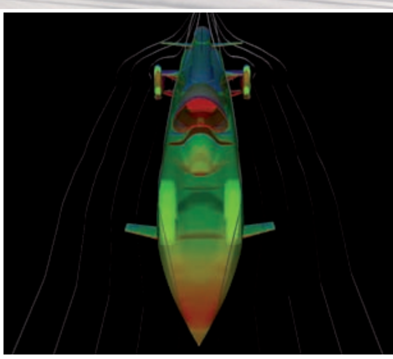
Push to pass

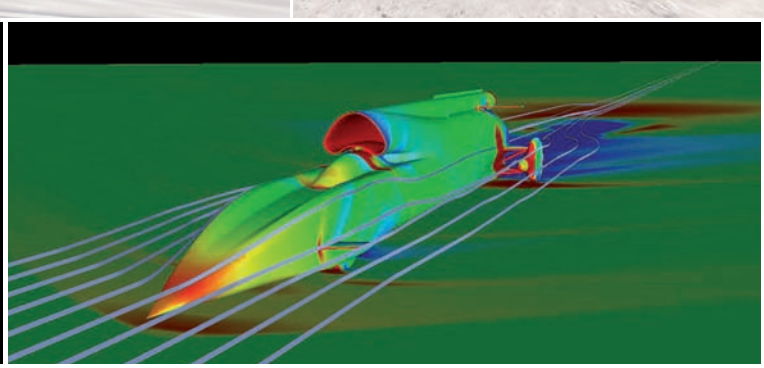
Alongside its EJ200 jet and Falcon rocket engines, Bloodhound has a third powerplant, a fly-by-wire, race-derived ICE that powers the hydraulic systems and drives a pump for the high test peroxide (HTP) rocket fuel. Built by Menard Competition Technologies (MCT), the V12 started life as the first prototype engine for Superleague Formula (see PMW, June-August 2007). "It's like the ultimate push-to-pass button," laughs Charlie Bamber, commercial director of MCT. "With the throttle closed it's making about 160-170bhp as an auxiliary power unit, allowing the EJ200 to start up and power the vehicle up to around 700mph. Mounted on the back of the engine is a clutched pump for the HTP; at the appropriate time it's engaged and we go to wide-open throttle. We move a ton of fluid in around 17 seconds over the catalyst in the Falcon rocket, and that will take Bloodhound the rest of the way to 1,000mph." Following dyno testing, the V12 – already mounted in its frame for installation in Bloodhound, complete with the pump assembly – has been shipped to the rocket testing site at Mojave.

State of play

Raising the funds for a land speed record car is tough at the best of times, so the Bloodhound team certainly has its work cut out at the moment. Nonetheless, the project is moving forward. Richard Noble reports that a decision on where to build the team's permanent base will be made in July; further aerodynamic analysis is being done on the rear of the car; rocket test-firings are underway in Mojave, USA; and a show car has been built. Soon will come the biggest challenge of all: getting £6 million together to build Bloodhound proper.







Left, far left: CFD for Bloodhound has been performed on the Supercomputing Cluster at Swansea University's School of Engineering

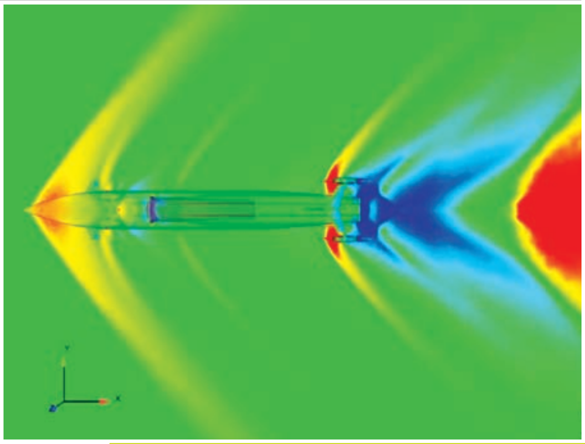
One of the most serious shortcomings in attempting to predict the dynamic behavior of Bloodhound SSC is the lack of data or understanding of this wheel/soil interaction.

There are three mechanisms by which the aerodynamic forces and moments have major influences on stability. The first is in directly influencing the directional stability through the substantial aerodynamic side forces and yaw moments on the vehicle body. These forces and moments arise when the vehicle body acts at a small angle of attack relative to the straight-ahead position. The net resulting aerodynamic side force and yaw moment are sometimes combined and referred to as a single force acting at the aerodynamic center of pressure in side view. Directional stability is associated with this center of pressure being aft of the vehicle mass center – often referred to as the aerodynamic static margin.

The second mechanism is associated with the wheels. For the non-steered wheels, which may be directly in the airstream or faired in, the aerodynamics simply add on to the body terms and are therefore included directly. However, for the steered wheels, the aerodynamics are capable of generating additional lateral forces by operating at an angle to the vehicle body, and hence, a different angle of attack relative to the airstream. They behave in a similar way to the wheel/ground system in generating a lateral force in response to a slip angle. The effectiveness of this mechanism depends on how much the steered wheels are in the airstream rather than hidden in the body.

The third mechanism is via an indirect route. As the speed varies, the aerodynamic downforce and pitch moment vary. These control the wheel loads, which in turn influence the wheels' ability to generate lateral forces at the wheel ground contact region. On Bloodhound SSC it is proposed to manage these wheel loads throughout an entire run using programmable winglets over the front and rear axles.

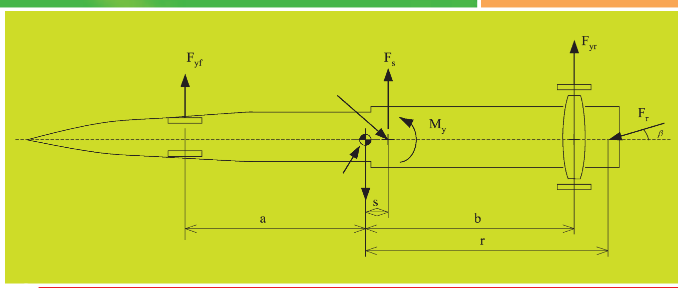
It is important to remember that the vehicle must retain stable behavior right throughout its speed range, rather than focusing attention on extremely high speeds. Broadly speaking, it is fair to assume that its low-speed behavior (up to 200mph (320km/h)) will be dominated by the wheel forces. Assuming that the wheels behave something like tires in generating lateral forces, then conventional vehicle design wisdom should apply. A vehicle mass center slightly forward of the mid-wheelbase position will promote a mild understeering characteristic. This of course is not easy to achieve with the turbine and rocket systems mounted toward the rear of the vehicle.



Every little helps

One feature of the Bloodhound project is how motorsport suppliers from all fields are getting behind it by offering product sponsorship and technical support. The electrical systems specialist DC Electronics, for example, will wire the Bloodhound car: "Being an ex-Royal Air Force Apprentice, this is the perfect project for me," says David Cunliffe, director and co-founder of DC Electronics. "I know my way around the airframe and engine wiring systems that will be used to control the jet engine, and then we will wire the rest of the vehicle in the same way we would a Formula 1 car." DC will be using the new ASDD System 30 wiring system from Deutsch on the relevant data harnesses within the vehicle, a product so new that it's yet to appear on a car.

Meanwhile, in its 40th year of business, Goodridge has followed up its involvement in Richard Noble's earlier land speed record projects – Thrust 2 and Thrust SSC – by confirming its participation in Bloodhound. Keen to be involved with the project's goal of inspiring the next generation of engineers, Goodridge has supplied the fuel delivery assembly taking the HTP into the Falcon rocket, and as such its products have already been delivered to Mojave with the MCT V12 and fuel pump assembly.



Above left: Shockwaves visible in this CFD image
Left: The wheel/ground and aerodynamic restoring forces and moments for Bloodhound SSC are shown on this plan view of the MATLAB/Simulink vehicle model

ON THE WEB Follow the Bloodhound SSC land speed record team's progress on the project website: www.bloodhoundssc.com

At higher speeds, the aerodynamic forces grow dramatically in proportion to the square of the speed – and this results in a compromise between stability and controllability. The aerodynamic lateral force system must effectively act aft of the mass center so that it has a stabilizing effect as the vehicle goes from the subsonic through the transonic into the supersonic region. However, the driver can still only exert control through the wheel/ground contact forces – so too large an aerodynamic stabilizing force system will swamp the wheel force effects and compromise controllability.

From the foregoing analysis, it is clear that retaining good wheel/ground contact is crucial for maintaining vehicle controllability. Hence, the suspension design is absolutely critical. It has to maintain highly accurate wheel geometry, withstand huge loads due to vehicle accelerations and decelerations of up to 3g, isolate the vehicle body from ground roughness input excitation, and finally, the suspension movement must be controlled through the spring and damper so that the vertical wheel force fluctuations are minimized.

The suspension is based on rather conventional-looking double wishbone arrangements. A relatively generous amount of bump and rebound travel, ±100mm, will try to control the vehicle and wheel vertical excitations at extreme speeds.

One of the biggest challenges of the suspension design is to control any toe-in or toe-out deflections. For example, at the rear suspension any toe-out movement results in a destabilizing effect. And the longitudinal forces at these wheels, which are out in the main airstream, are enormous due to the combined effects of rolling resistance and aerodynamic drag forces.

At the front suspension, the tight control of toe stiffness is further compromised by the addition of the steering system. The controllability properties will depend on a compromise between the steering gear ratio, the steering system stiffness, and the provision of steering feedback feel to the driver. A quick calculation, for those interested, reveals just how extreme the vehicle design numerics become at high speeds. For example, how much steer angle is needed at 500mph (800km/h) to generate a turn of 0.1g with a vehicle wheelbase of 8.9m? Answer at the end of the article!

Throughout the speed range, therefore, it is necessary to have data or estimates of how the following parameters change both with speed and acceleration/deceleration in order to estimate a complete stability profile for the vehicle: vehicle mass, mass center position, aerodynamic forces and moments, wheel loads, and wheel/soil interaction.

The directional stability of Bloodhound SSC has been analyzed via a linear dynamics model using the MATLAB/Simulink package. The data requirements for this model pose some problems; the vehicle layout, mass and inertia properties are relatively straightforward outputs from the overall CAD model. The aerodynamic force and moment data are estimated from some highly sophisticated CFD prediction work, as described previously. However, the estimated data for the properties of the wheel/ground forces are one of the least certain areas. There is very little data in the off-road literature on the force properties of rigid wheels on deformable surfaces, and none at all above low speeds of several mph, so we have been forced to estimate these properties based on collecting together off-road experiences from a range of sources, including the Thrust SSC and JCB Dieselmax land speed record cars.

Some of the design guidelines emerging from this study are: maintain the vehicle mass center ahead of the mid-wheelbase position, maintain the aerodynamic center of pressure aft of the mass center by around 3-5% of the body length, and maintain the axle loadings close to their static values with a bias toward slightly more at the rear.

Bloodhound is a great UK engineering adventure, pushing our understanding of vehicle design to its absolute limits – but it is a particularly fascinating challenge for the vehicle dynamics community.

And the answer to the question? 0.01°...