motorsport

Sonic boom

CRANFIELD UNIVERSITY'S **DAVID CROLLA** GIVES AN INSIDER'S PERSPECTIVE ON THE DYNAMICS OF THE PLANNED BLOODHOUND SSC LAND SPEED RECORD CHALLENGER

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). At low speeds, the vehicle must also be able to steer and turn like a conventional wheeled vehicle, but its prime objective is extremely high-speed straight running rather than cornering, as is the case with high-speed racing vehicles, for example.

The term 'stability' is used in many vehicle design contexts, but 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. It has, therefore, a strict mathematical definition although it is often used in an imprecise, qualitative way to judge vehicle behavior. A classic example of instability is an oversteering vehicle above its critical speed – in this case, the force and moment system acts so as to cause the vehicle to spin rather than return to an equilibrium condition.

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. In conventional wheeled vehicles, controllability is exercised via the driver's steering wheel, which is directly connected to the steered wheels. Most commonly this involves only the front wheels, but rear-wheel steering has been tried (see panel overleaf about the current land speed record holder, Thrust SSC).

The connection between the driver's steering wheel and the vehicle's steered wheels is conventionally a mechanical device with a fixed gear ratio, although active steering or steer-by-wire in

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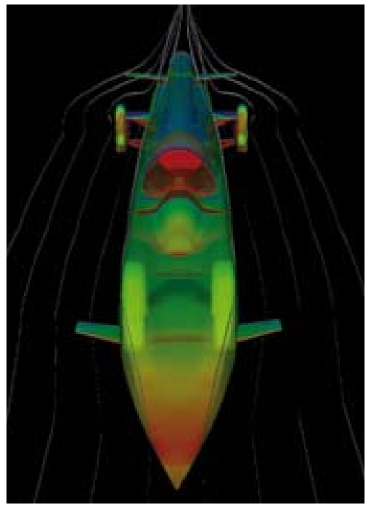
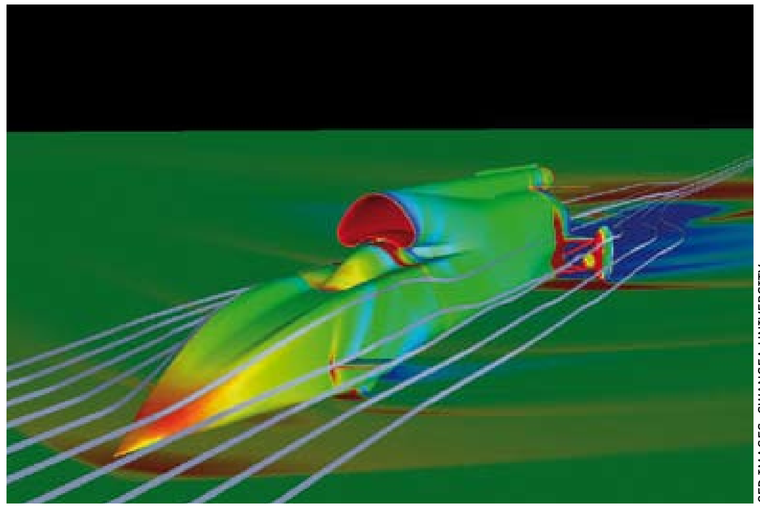
"The Bloodhound SSC's wheels are themselves a major design challenge – they have to withstand burst forces associated with centripetal accelerations of 25,000g"





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which the mechanical connection is removed has been experimented with on prototype vehicles. Of course, in contrast to automotive applications, by-wire systems are common in aircraft engineering where the aerodynamic control surfaces rather than wheels or tires are used to generate the external forces. A vehicle with good controllability characteristics would be described as being responsive to driver demands, consistent and predictable over different conditions, providing some feedback information to the driver, usually through the steering feel – and all these combine to provide the driver with confidence in the vehicle dynamic system – rather important when covering the length of four soccer pitches 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.

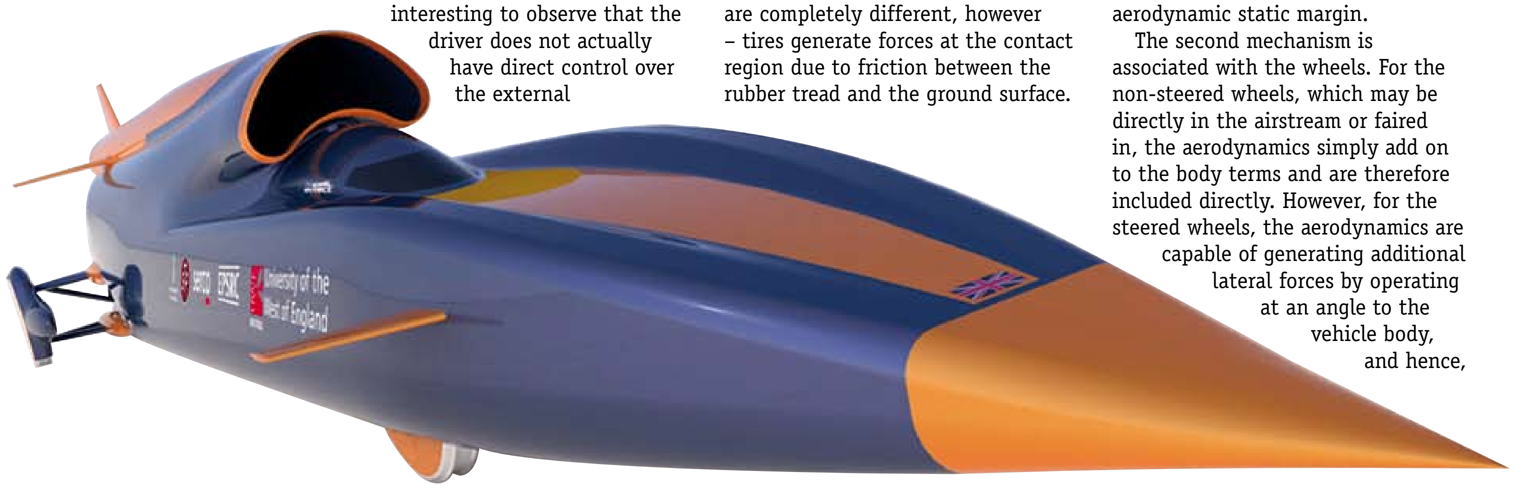
Despite the great design challenges with extremely high-speed vehicles, there are still only two fundamental sources of external forces and moments that contribute to its directional stability: wheel/ground interactions, and aerodynamic properties.

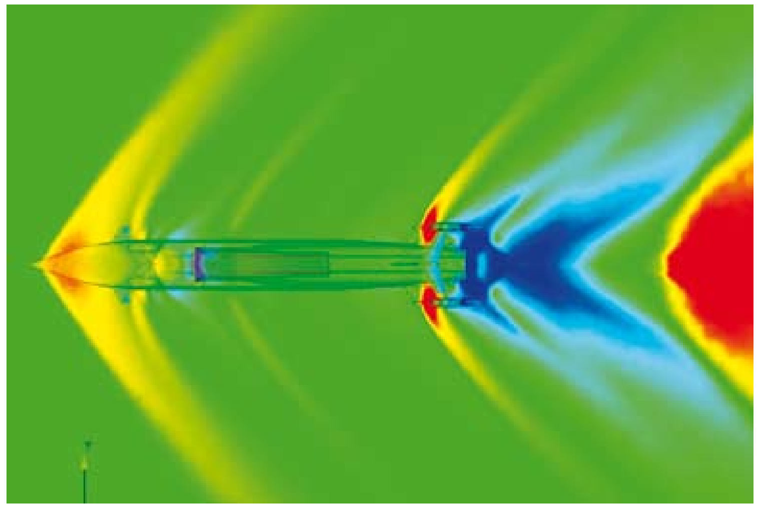
The Bloodhound wheels are themselves a major design challenge – they have to withstand burst forces associated with centripetal accelerations of 25,000*g*, for example. It is impossible for anything resembling a tire to exist under these conditions, so the wheels will be made of titanium, possibly with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

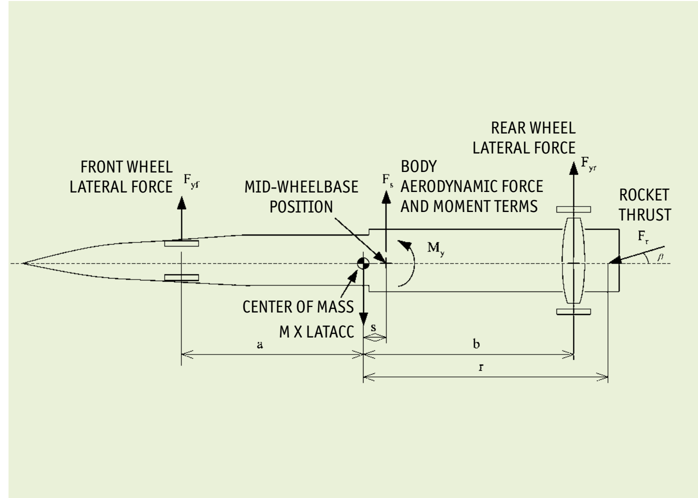
The wheels are assumed to be able to generate lateral forces in response to slip angles in rather the same way that tires behave. The mechanics here are completely different, however – tires generate forces at the contact region due to friction between the rubber tread and the ground surface. For solid 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. 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 very much 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.

The vehicle has an enormous speed range and it is important to remember that it must retain stable behavior right throughout this range, rather than focusing attention on its extremely high-speed range. 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 all the turbine and rocket systems mounted toward the rear of the vehicle.

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 if the aerodynamic stabilizing force system is too large, it will compromise controllability by swamping the wheel force effects.

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 3*g*, 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 front and rear suspension designs are both based on rather conventional-looking double

ABOVE LEFT AND OPPOSITE: **A SELECTION OF CFD IMAGES OF THE AIRFLOW AROUND THE CAR; NOTE SHOCKWAVES. CFD FOR BLOODHOUND HAS BEEN PERFORMED ON THE SUPERCOMPUTING CLUSTER AT SWANSEA UNIVERSITY'S SCHOOL OF ENGINEERING IN WALES.**
ABOVE: **THE WHEEL/GROUND AND AERODYNAMIC RESTORING FORCES AND MOMENTS FOR BLOODHOUND SSC ARE HIGHLIGHTED ON THIS PLAN VIEW OF THE MATLAB/SIMULINK VEHICLE MODEL**

The record holder

JEREMY DAVEY/SSC PROGRAMME LTD

Thrust SSC achieved a speed of 763.035mph (1,227.952km/h) in 1997 at Black Rock Desert, USA. It remains the first and only vehicle to exceed the speed of sound on land. One of its controversial design features was the use of rear wheel steering – which according to many experts could never work at normal speeds, never mind extreme record speeds! This design choice was first considered because it solved some fundamental vehicle layout problems (see *VDI*, March/April 2005). Thrust SSC was powered by two Rolls Royce Spey engines; these were mounted forward in the vehicle and so although they ensured a desirable forward center of mass position, they left little space for the steered-wheel mechanisms. A range of stability and dynamics calculations suggested that the steered rear wheels would be acceptable for controlling the vehicle at high speeds – by acting effectively as a trimming mechanism during straight-ahead running. Although there were problems associated with the length of linkage required to the driver's cockpit, this rather radical design solution obviously worked in the end – so a rear-wheel steer vehicle is the current record holder, at least until it is eclipsed by Bloodhound SSC.

IN THE MIDDLE OF THE BLOODHOUND SSC, AN MCT-BUILT V12 800BHP RACE ENGINE DOUBLES AS AN APU TO DELIVER HYDRAULIC POWER AS NEEDED, STARTING THE EJ200 TYPHOON JET ENGINE AND PUMPING HIGH TEST PEROXIDE (HTP) TO THE FALCON ROCKET MOTOR (ABOVE)

"The Bloodhound project is a great UK engineering adventure, and a particularly fascinating challenge for the vehicle dynamics community"

wishbone arrangements. A relatively generous amount of bump and rebound travel, ±100mm, has been selected to 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 0.1*g* 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.

The Bloodhound project is now universally referred to as a great UK engineering adventure. It is pushing our understanding of vehicle design to its absolute limits – but it is a particularly fascinating challenge for the vehicle dynamics community.

Oh, and the answer to the question? 0.01°…