

## MEASUREMENT OF JET ENGINE THRUST IN A SUPERSONIC CAR

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*Abstract: On 15 October 1997 on the Black Rock desert, Nevada, Squadron Leader Andy Green drove ThrustSSC through a measured mile at an average speed of Mach 1.02 (763.035 mph or 1 227.986 kmph) to achieve the first supersonic land speed record.*

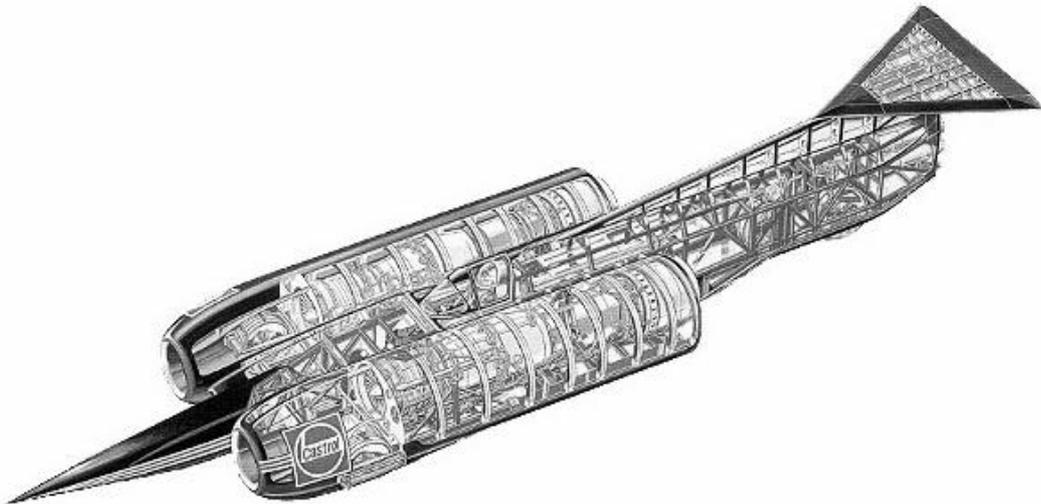
*This paper presents the work carried out at NPL to develop a method of directly measuring the thrust of each of ThrustSSC's jet engines. This was a safety-critical application, the thrust imbalance being monitored by the car's computers and presented on a gauge in the cockpit.*

*Without this thrust-measuring system, it is likely that the risks involved in driving the car would have been too great for the project to proceed. Its success has demonstrated the possibility of real-time direct engine thrust measurement.*

*Keywords: Jet engine, thrust, measurement.*

### 1 INTRODUCTION

In 1983, Britain's Richard Noble took the land speed record from the USA's Gary Gabelich when he drove his Rolls-Royce Avon turbofan powered car, Thrust 2, at a speed of 633 mph / 1 019 kmph. In 1990, American Craig Breedlove announced his intention to build a car, 'Spirit of America', capable of over 700 mph / 1 127 kmph, prompting Richard Noble to initiate a project to build a British rival to be first through the sound barrier. Further impetus was given by news that the McLaren Grand Prix organisation and an Australian team were pursuing the same goal. The new car was christened 'ThrustSSC' (SuperSonic Car).



**Figure 1.** Cutaway view of ThrustSSC.

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After several years of fundraising, research, development, and testing, the ThrustSSC team arrived at the Black Rock desert, Nevada, in Autumn 1997 to compete head-to-head with Spirit of America. After Spirit of America lost control at high speed and later damaged its engine, ThrustSSC was left to continue to attempt the record unchallenged. Finally, on 15 October 1997, RAF Squadron Leader Andy Green drove ThrustSSC through a measured mile at an average speed of Mach 1.02 (763.035 mph or 1 227.986 kmph) to set the first, and so far the only, supersonic land speed record.

### 1.1 The design of ThrustSSC

The main design challenge was not the provision of sufficient power but the maintenance of lateral and longitudinal stability and control. ThrustSSC aerodynamicist Ron Ayers therefore designed a highly stable configuration using two jet engines (Figure 1) whereas all previous, and the competing, cars had used a single engine only.

The two Rolls-Royce Spey 202 turbofan engines were mounted forward and to either side of the driver with a vertical tail fin mounted aft. This placed the car's centre of gravity well ahead of its aerodynamic centre of lateral resistance, providing good yaw stability. The twin engine configuration also allowed the front wheels to be placed wide apart, providing good roll stability. Longitudinal stability was derived from a horizontal fin, mounted clear of the jet efflux on top of the vertical tail fin. The longitudinal stability of the car was further enhanced by an active control system, to keep the car on 'the fine line between flying and mining'. Glynne Bowsher, the car's mechanical designer, developed a stiff steel space frame chassis, and a steering geometry which allowed the car to be steered via its asymmetrically positioned rear wheels rather than the much larger and more heavily loaded front wheels. Leading figures from the car's final specification are presented in Table 1.

**Table 1.** ThrustSSC specification.

Length	15.5 m
Width	3.66 m
Mass (with fuel)	10.7 tonnes
Fuel mass	1 tonne
Engines	Two Rolls-Royce Spey 202s
Chassis	Welded T45 steel space frame
Body shell	Aluminium, carbon fibre, and titanium
Steering	Worm drive acting on the rear wheels
Wheels	Forged aluminium alloy
Brake parachute	2.28 m diameter ribbon parachute
Peak speed achieved	771 mph / 1 241 kmph
Thrust of each engine	~90 kN
Max output power	~80 000 hp / 60 MW

## 2 THRUST MEASUREMENT SYSTEM DEVELOPMENT

### 2.1 Background

While the twin engine configuration had many advantages for stability, the lateral offset of the engines introduced an additional potential failure mode. Calculations showed that relatively small asymmetry of thrust between the engines would directionally destabilise the car, leading to a catastrophic accident. Such an asymmetry could possibly arise from:

- differences in engine spool-up rates;
- failure of an afterburner to ignite; or
- failure of an engine component.

The safety of the car was therefore critically dependent on accurate real-time measurement of the thrust of the car's two jet engines. For this reason, Andy Green, the car's driver, specified that an instrument indicating thrust balance should be provided as one of his primary instruments (Figure 2).



**Figure 2.** Cockpit layout showing thrust balance gauge.

In addition, it was required that the car's redundant computer system would continually monitor the two engine thrust values and trigger an abort sequence if any significant asymmetry was detected. Accurate thrust measurement was also required for performance monitoring during the development of the car. The ThrustSSC team therefore asked the National Physical Laboratory (NPL) whether it could provide a system for measuring the engine thrusts.

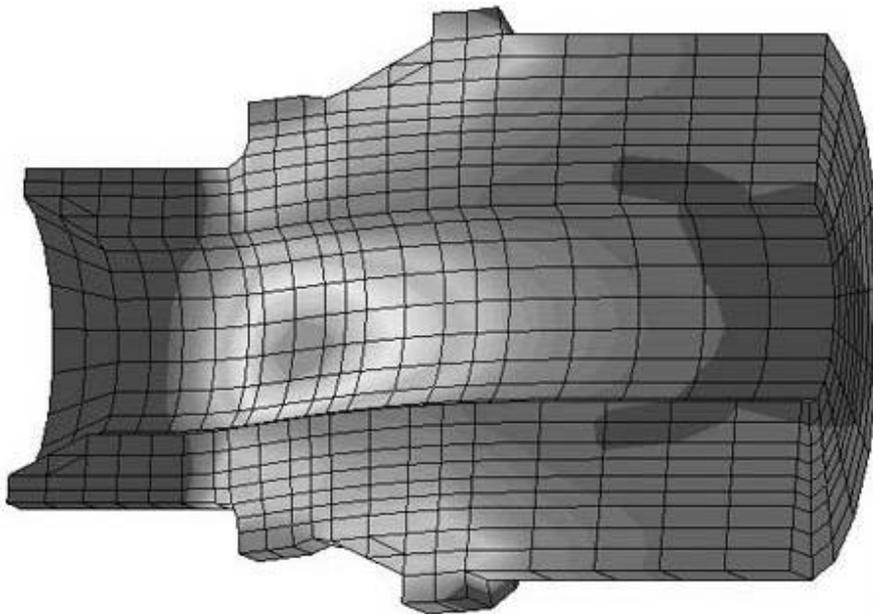
## 2.2 Methods of jet engine thrust measurement

The standard method of on-line monitoring of jet engine thrust in aircraft is indirect, the crew being required to infer thrust from a number of displays of shaft speeds, temperatures, fuel flows, and pressure ratios. With each run of ThrustSSC lasting for less than two minutes, such a system would have imposed an unacceptable workload on the driver and would not have provided sufficient accuracy. A few systems have been developed which computationally combine these inputs to generate a single indication of thrust, e.g. [1]. However, the slow response and difficulty of calibrating such a system ruled out its use on the car.

It is occasionally suggested that 'direct' measurement of the loads in the engine mounts would provide the most suitable thrust measurement system for jet engines, e.g. [2, 3]. However, it has been the accepted wisdom that the practical problems of doing so are insurmountable. For example, the standard guide to in-flight thrust measurement [4] opens with the sentence 'Direct measurement of thrust and drag in flight is not feasible'. Similarly Woodfield [5] states '... it is not practical to install load measuring links between the engine and airframe ...'. Perhaps because of these views, in-flight direct thrust measurement systems have not found favour.

## 2.3 NPL's approach

Despite the supposed difficulty of measuring thrust via the engine mounts, NPL analysed the forward engine thrust trunnions (which transmit the force from the engine to the vehicle frame), to see if it would be possible to transform them into force measuring devices, or load cells. Finite element models of these standard Rolls-Royce trunnions were constructed and analysed under various loading conditions. Figure 3 shows the shear strain distribution obtained on the internal bore of the trunnion, under one particular loading condition. Apparent in the figure is a highly stressed 'sweet spot' in the centre of the bore. Analysis of the finite element results for all the load cases suggested that it might be possible to design a modified trunnion incorporating shear strain gauges in the bore.



**Figure 3.** Plot showing the shear strain distribution on the trunnion's internal bore.

A number of mechanical modifications needed to be made to the original trunnion, so an analysis of the effects of these on the strength requirements of the assembly was carried out. This demonstrated that the modifications had, as expected, slightly weakened the central component, but that it retained a sufficiently high safety factor. The modified trunnion incorporating NPL-designed force instrumentation is shown in Figures 4 and 5.



**Figure 4.** NPL-modified thrust trunnion prior to assembly.



**Figure 5.** NPL-modified thrust trunnion and associated instrumentation.

## 2.4 Temperature effects

Analysis of the trunnion's temperature environment revealed that standard temperature compensation techniques would be insufficient to eliminate the temperature-induced errors. The inboard end of the trunnions attach to the engine's combustor casing, which operates at 160 °C, while

the outboard ends are clamped to the car's space frame structure, which would typically be at  $-5\text{ }^{\circ}\text{C}$  in the early desert morning. Immediately after engine start-up, the trunnions would therefore be subject to a very large temperature differential. In order to limit the errors induced by this, NPL developed a novel technique which significantly reduced the temperature gradient sensitivity of the instrumented trunnions.

## 2.5 Instrumentation

Each instrumented thrust trunnion was provided with an NPL-designed signal conditioning system. This provided the excitation voltage and amplified the output signal to within the 0 V to 5 V range required by the car's computer system. The computer system calculated the difference in thrusts and provided the output driving the driver's thrust balance display. The signal conditioning system was designed to be vibration resistant and to have excellent long term stability, there being no opportunity for periodic recalibration once installed in the car. Being safety-critical, the system was designed to be fail-safe, breaks or shorts in the circuit or failure of the excitation supply being detected and triggering an 'invalid' output.

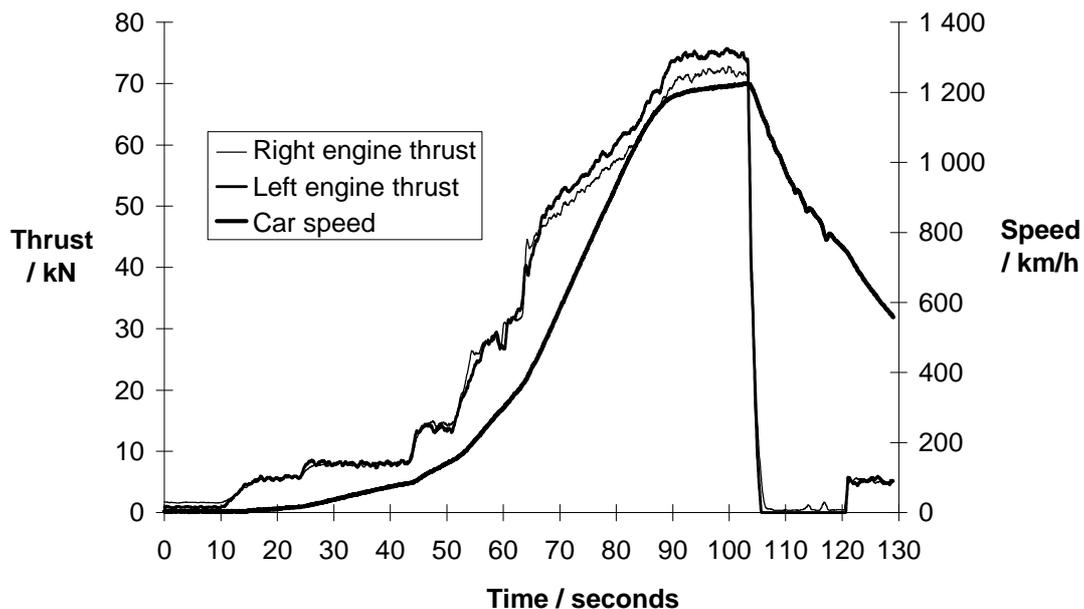
## 3 SYSTEM CALIBRATION

The assembled instrumented thrust trunnions were calibrated in the NPL 1.2 MN deadweight force standard machine and temperature compensated in an environmental chamber. The output signals from the two trunnions were matched such that identical output voltages corresponded to identical thrusts and thus no thrust imbalance. After installation in the car, the outputs of the trunnions were compared both with the engines' thrust performances as measured in an engine test bed, and also with total thrust values measured during tie-down testing of the car. The results of these tests gave further confidence that the trunnions would provide correct information to the control system.

## 4 RESULTS

During the runs of the car in both Jordan and Nevada, the instrumented thrust trunnions allowed the spool-up rates of the engines to be monitored and adjusted between runs so as to maintain thrust symmetry. As a result, no abort sequences were initiated due to thrust asymmetry. The recorded outputs of the thrust sensors were also used extensively during post-mortem analysis. In particular, when the car was found to exhibit some directional instability at approximately 600 mph, the ability to exclude any contribution due to thrust asymmetry allowed the team to concentrate on analysis of the steering and suspension.

The trunnion outputs recorded during the final record-breaking run are presented in Figure 6. The close matching of the engine thrusts during the initial engine spool-up is apparent, as is some asymmetry of thrust at high speed with the afterburners lit. The rapid response of the transducers is



**Figure 6.** Engine thrusts and car speed recorded during record-breaking run on 15 October 1997. apparent when the throttles are closed at the end of the measured mile. This rapid response was

essential to the car's safety and could not have been achieved by the use of other methods.

## 5 CONCLUSIONS

The NPL-instrumented strain gauge thrust trunnions made a vital contribution to the success of the ThrustSSC supersonic land speed record attempt (Figure 7).



**Figure 7.** ThrustSSC at full speed, with shock waves visible.

Furthermore, the system has demonstrated the practicality of direct monitoring of jet engine thrust. The system's full details have yet to be disclosed to the public, but it is possible that similar systems will find safety-related applications in future aircraft jet engine installations.

## ACKNOWLEDGEMENTS

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