Cool Britannia

Every Bentley is unique - but some are slightly more unique than others.

The reality of vehicle production depends on a series of compromises. They inform design and shape the finished project in some fairly predictable ways. The need for compromise is sometimes dictated by the physical sciences, but most often it is dictated by cost – yet problems don't magically melt away when that equation is changed.

Such is the case with the UK's new Bentley State Limousine. Designed and manufactured by Bentley, together with a consortium of suppliers, as a gift to The Queen for the Golden Jubilee year of 2002, the vehicle is based on the platform of an Arnage Red Label with a unique monocoque. Given its function the vehicle is something of a worst-case scenario for HVAC design. It features over 10m^2 of glazing (providing a very severe solar load) and, as the vehicle is intended for processional use, will spend long periods registering engine speeds barely above idle.

Diamond

MIRA carried out work on the project, codenamed Diamond, in a number of key areas. Encapsulating up-front 1D HVAC modelling, followed by rig-based system development in the Thermofluids Lab and finally, whole-vehicle validation in the Climatic Wind Tunnel, the project demonstrated the integrated and fully functional nature of the facilities and systems at the disposal of the Fluids Group.

Senior consultant Dr Martin Jones explains further: "About two years ago Bentley informed us they were pulling together a consortium, primarily within the British motor industry, to design, develop and manufacture a car as a gift for the Queen's Golden Jubilee. We were invited to perform, in the first instance, an analysis of the vehicle and specifically its HVAC system."

"The immediate problem was that the vehicle, in terms of thermal management, is a greenhouse on wheels. Even without a great knowledge of thermodynamics or solar transmission, it is obvious that being sat inside a predominantly glass structure on a sunny day is going to get pretty uncomfortable. In combination with the primarily processional duty of the vehicle this amounted to a considerable technical challenge."

MIRA's first task was to develop simple 1D thermal models of the cabin to predict the thermal loading that an air conditioning system would be required to deal with. "We ran the model with a range of different glazing options for the windscreen, roof, side windows and backlight," explains Jones. "Various tints and IR interlayers were simulated and in total we probably looked at about 50 different permutations. Aside from thermal issues we had to take aesthetics into account - visibility of the occupants is of prime importance." From the clear glass figure of 9kW the glass mix finally decided upon reduced that thermal load down to around 7.7kW (a 7.4kW model with a highly-tinted glass composition bonded around IR-reflective interlayers was also developed as the ultimate glass fit, in terms of solar transmissivity, but was not acceptable on the grounds of low light transmission through the side windows and front windscreen).

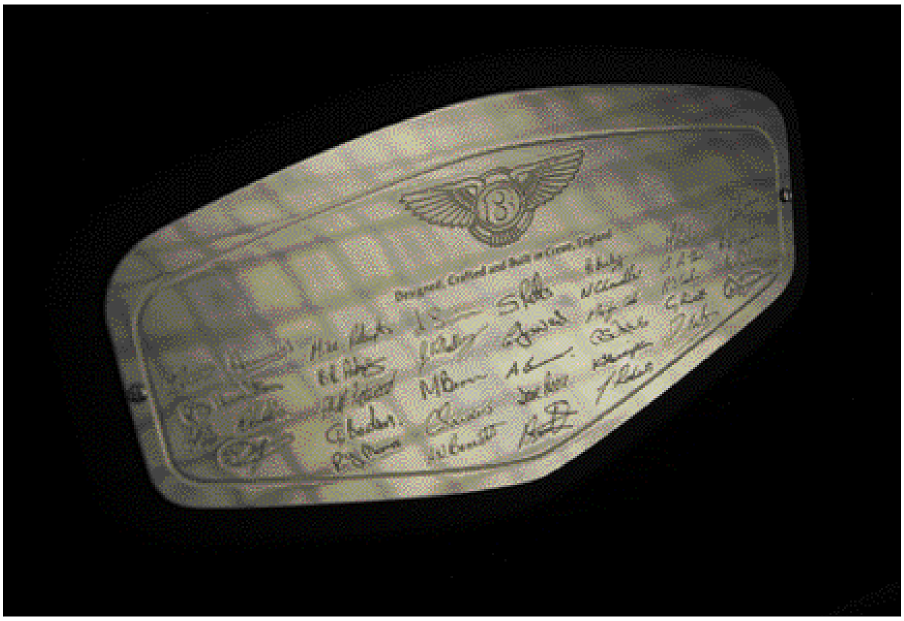
Validatory whole vehicle testing in the Climatic Wind Tunnel

From this figure MIRA was able to work back through the HVAC system and specify the various components required to keep the cabin conditioned to an acceptable temperature. As the vehicle was fitted with a carry-over front HVAC unit with a cooling capacity of around 3.5kW, it was decided that a second evaporator having a nominal capacity of 4.5kW should be packaged in a small HVAC unit in the front/rear glass division area of the car. The vehicle would be confined to duties in the UK, with worst-case ambient conditions for A/C operation set at 30°C, 40 per cent RH and 950 W/m^2. A target interior air temperature of 20°C completed the requirement.

Development

The up-front 1D simulation allowed MIRA to size the second evaporator to be packaged in the division area. This in turn led to the development of specifications for other components. "The next thing we looked at was sizing the compressor," continues Jones. "Here we encountered problems, because in the normal course of events the compressor would be driven very slowly by the low processional engine speed, which would typically be around 650rpm.

The high evaporator load required a lot of refrigerant to be pushed around the circuit – again the intended use of the vehicle made this a difficult function to realise. "In order to do this the compressor would generally need to be driven quite quickly," says Jones. "We were obviously constrained to have a



The Bentley State Limousine was developed and manufactured by a consortium of predominantly UK-based automotive industry companies

were then introduced to the condenser and the front and rear evaporators, and the compressor was driven at the required speeds by means of the rig's variable-speed electric drive. This enabled charge determination, component optimisation and thermal performance studies to be conducted well before the vehicle itself was built, leading to a high level of confidence in system design and functionality.

Schedule

"Remember that the entire project from beginning to end had to be done in about 12 months – which was a bit of a tight schedule," says Jones. "This was as near as we have come, to date, to a zero-prototype vehicle programme. Although a validation vehicle was built, we only had one shot at it. The amount of whole vehicle test time was absolutely minimal."

Following some fine-tuning and charge determination trials, the rig work confirmed that the system was capable of achieving the required heat rejection duty, and the set of components was thus built into the validation car. When that validation vehicle was finally made available for testing, MIRA carried out its final tasks for the project only a few weeks before the finished vehicle was due to be presented.

compressor doing of the order of 1,000rpm." It immediately became apparent that a standard passenger car unit would not be adequate, and options such as a highly geared-up scroll compressor, and a dual compressor set were evaluated. Unfortunately, both of these options were demonstrated as being infeasible by the project's underbonnet packaging team. After some searching, a suitable 10-cylinder fixed-displacement piston compressor having a swept volume of over 300 cm^3/rev was deemed to be suitable.

Finally, having identified a suitable rear evaporator and compressor, it was then necessary to size the condenser. Obviously, an important aspect of condenser performance relates to the cooling airflow across the heat exchanger, and a sample of five different cooling fans was evaluated in the laboratory in order to develop an understanding of the airflow that would be available for condenser cooling. Data from the fan tests fed into the packaging team's front-end airflow model, enabled the selection of a suitable fan, and hence the condenser. (In the event, a condenser based on an existing Bentley production part, but increased in size by around 30 per cent, was used.)

After this stage of preliminary R&D, MIRA took the project into a physical testing stage. Given that whole-vehicle availability would obviously be very limited on this project, it was important that any major physical system performance issues were identified and resolved prior to vehicle integration. Therefore all of the components were sourced and built into the air conditioning test bench in the Thermofluids Lab. The complete air conditioning refrigerant circuit, including front and rear HVAC modules, was mounted on the bench, with all hoses, heat exchangers, compressor and receiver-drier mounted as per the proposed vehicle installation. Representative conditioned airflows

Diamond cutting

The engine idle pulldown test, conducted in MIRA's Climatic Wind Tunnel at ambient conditions of 30°C, 40 per cent RH and 950 W/m2 solar loading involved a hot solar soak until a head temperature of 58°C was achieved, followed by an idle pulldown in full air recirculation mode. With a 7.7kW evaporator duty, the transient simulation work predicted that an average interior temperature of around 24°C should be achieved after 30 minutes of pulldown, while the test work indicated a fairly stable average interior air temperature of around 30°C after the same time. This was clearly unacceptable, being some 6°C higher than the predicted level, and prompted further investigations. As the installed rear compartment interior airflow was subjectively considered poor, it was decided that measurements of rear evaporator airflow should be conducted. This was achieved by means of a rear vent-outlet airflow test, and immediately highlighted a very probable cause of the poor pulldown performance.

The airflow measurements indicated an installed rear-evaporator airflow of just 76l/s compared with a target of 150l/s; examination of the evaporator component performance curves showed that this would result in a de-rating in cooling capacity of around 2.4kW. In view of this, the transient simulation model was re-run with a total evaporator capacity of 5.3kW rather than 7.7kW, and a very good correlation was obtained with the CWT results. Obviously, this tended to confirm the suspicion that low rear-unit airflow was considerably degrading A/C pulldown performance. Steps were taken to improve rear compartment airflow, and a level of 143l/s was achieved with alternative blower motors and improved packaging, which brought total evaporator performance in line with target.

Unfortunately, vehicle-scheduling constraints precluded the possibility of a pulldown performance validation with the improved rear-unit airflow, but the simulation results provided sufficient evidence to suggest that the required levels of cabin cooling performance would now be achieved. Running the simulations out to a stable thermal condition with the 7.7kW evaporator predicts an average interior air temperature of just under 20°C, which agrees well with the early steady-state predictions; simulations under dynamic exterior airflow conditions of just 10 km/h give average interior air temperature predictions as low as around 16°C. These results, coupled with the test work, confirmed that the target levels of thermal comfort would be achieved when the rear-unit airflow enhancement was fully implemented on the Bentley State Limousine.