A Multi-Domain Thermo-Fluid Approach to Optimizing HVAC Systems

IMA Conference on Mathematical Modelling of Fluid Systems, Engineers' House, Bristol
10 –12 September 2014.

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Abstract **– Vehicle manufacturers are striving to improve overall vehicle efficiency. With increased complexity of today's vehicles, all systems need to be working in symbiosis in the most efficient way possible to achieve this target.**
In this paper we present the work undertaken to understand the impact of different cabin heating and cooling strategies on the cabin temperatures and potential effect on human comfort within the automotive cabin. At the same time, determine the effectiveness of each cabin technology of lowering cabin temperatures and its associated effect on human comfort and system power. The whole vehicle model and it's sub-systems are built using the Dymola (DYnamic MOdelling LAboratory) multi-domain physical systems engineering tool and simulation results are validated against physical test data.
The air conditioning system model has been created using 1d thermo-fluid physical models. The cabin has been modelled as a multi-zone 1d thermo-fluid model with layering effects. The boundaries take into account the thermal characteristics of the materials. The objective is to optimise the cabin cooling and heating strategies to lower the overall cabin temperature and achieve occupant comfort in the quickest and most efficient way possible. The reduction in physical testing time significantly cuts development costs.

1. INTRODUCTION

Typically during a pulldown test from a high ambient temperature an automotive cabin begins to feel comfortable at around 28°C and is considered fully comfortable around 23°C. This target can prove to be a significant challenge during a pulldown in high solar irradiance which is typically used to correctly size the AC components. Incorrect sizing of the system has a negative effect on thermal comfort and energy consumed when installed in the vehicle.
The final temperature at the end of a vehicle soak has a big impact on energy requirements and time to comfort in the cabin. The final soak temperature is primarily dominated by: surface area of the glazing, cabin volume, characteristics of the glazing, partition layers and the amount of solar radiation from the sun.

In the case of low emissivity (lowE) or Infra-red reflective (IRR) glazings they have a positive effect on reflecting long wave radiation and the final soak temperature will be lower and therefore pulldown energy requirement and time to comfort will be reduced. As a result the AC system may be downsized due to the cabin now requiring significantly less energy to get to the optimum temperature. D Turler et al have indicated that a reduction in cabin temperature between a baseline vehicle and a vehicle fitted with selective glazing and GFP insulation for a ambient solar soak of 41°C with 700W/m² of irradiance was 5°C at the end of a three hour soak. The addition of insulation in most cases adds an additional heating component to the interior cabin. [8]

This paper will discuss the relative improvements to be had by adding specific glazing technologies on cabin temperature and how this relates to cabin temperature and potential effects on comfort.. The paper will also cover the effect of insulation on cabin temperature, time to thermal comfort and which area of the vehicle the insulation has the most benefit. The test vehicle used was a luxury 4x4 vehicle which subsequently the Dymola model is based on. A vehicle with baseline glazing was used for the 1st round of testing and then for the 2nd round of testing the advanced glazing and insulation was fitted to the car.

2. TESTING CONDITIONS

The testing to assess the HVAC system was conducted at the Climatic Wind Tunnel at MIRA test facility in Nuneaton, where the chamber allowed the outside ambient temperature and irradiance to be set to the desired temperature.

There were two types of conditions that were being assessed in this study: steady state and transient conditions. Steady state refers to a condition where the cabin temperature starts and is maintained at a desired set temperature where the energy required to maintain that cabin temperature is recorded the MAC test and homologation cycles were considered as steady state. Pulldown and Warm-up tests can be considered as transient because the AC system works to bring a high cabin temperature down to a set point of 23°C. The peak load from the AC compressor during pulldown can be as high as 3-4 times greater than the steady state load.

The following drive cycles were run during testing:

	NEDC	MAC	Pulldown	Warmup
Time(s)	1185	4038	5400	5400
Max Speed (km/h)	120	100	100	100
Max Accel (m/s²)	1.1	1.95	1.168	1.168
Distance (km)	10.9	76.9	77.9	77.9
Cabin start temperature (°C)	22	22	43	-18
Condition	SState	SState	Transient	Transient

Table 1.0: Drive cycles applied on test vehicle

The pulldown test was run with 900W/m² irradiance from solar lamps directly above the test vehicle. No solar load was applied during the MAC and NEDC tests for comparison of steady state energy. The MAC test was run at a full sweep of ambient temperatures from 43degC-5degC. At the time of writing this report insufficient test data was obtained for the prototype car (LowE glazing). The Dymola model was therefore validated against the baseline data and no validation against test data was done for the prototype car.

3. INSTRUMENTATION

Prior to the testing at the wind tunnel the car had to be fitted with a solar/humidity sensor and thermocouples. Figure 1.0 shows example locations where the thermocouples were fitted on the test vehicle. The cabin temperature was calculated from an average of 10 thermocouples in all four zones of the cabin.

Figure 1.0: Thermocouple locations on glazing and defrost vents

The car was also fitted with an instrumented compressor so that the torque output could be measured directly. The transducer is a single channel strain gauge based transducer that is gauged and wired to measure torque only. Mounted to the transducer is a secondary inductive coil that supplies power to the electronics mounted to the transducer. Fig 2 also displays the internal mechanical function of the compressor.

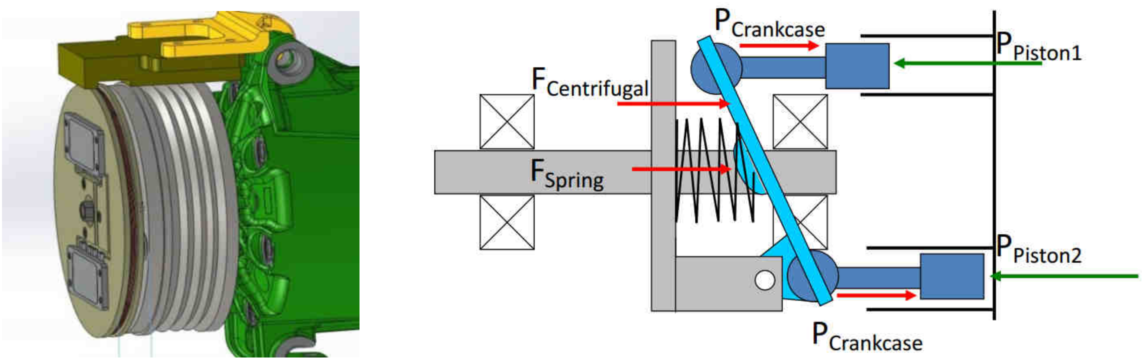


Figure 2.0: Instrumented AC compressor with torque measurement via single channel strain gauge [1]

4. GLAZING AND INSULATION PARAMETERS

For assessing the effect of glazing and insulation on occupant comfort and energy consumption relevant input parameters were required for the glazing and insulation in the test car in order to model the comparisons in Dymola. Data from the supplier for the all the glazing and insulation was required. Lwef, swaf and swtf parameters are calculated directly from the spectral curves for the glazing from the supplier.

Table 2.0: Glazing input parameters for Dymola model

Baseline Car	Type	lwef	lwtf	swaf	swtf
Front Windshield	Green Laminated	0.84	0.36	0.29	0.646
Panoramic Roof	Green Laminated	0.94	0.008	0.77	0.152
Front Side Window	Mon	0.84	0.26	0.34	0.596
Rear Side Window	Mon	0.84	0.26	0.34	0.596
Rear Windshield	Mon	0.83	0.26	0.34	0.596
Prototype Car		lwef	lwtf	swaf	swtf
Front Windshield	Lam/IRR	0.62	0.008	0.954	0.0257
Panoramic Roof	Lam/LowE	0.21	0.021	0.928	0.026
Front Side Window	Mon/LowE	0.21	0.164	0.376	0.57

lwef = Long wave emission factor (%)
swaf = Short wave absorption factor (%)
Mon = Monolithic glass

lwtf = Long wave transmission factor (%)
swtf = Short wave transmission factor (%)
Lam = Laminated Glass

As can be seen from the data in the table the lowE coated glazings have a much lower emissivity value compared to standard glazing which limits the infra-red heating into the cabin. The IRR windshield has a lower emissivity than with LowE coatings but the reflective capability of long wave radiation is much higher in IRR glazing, IRR glass also has a much lower transmittance of heat into the cabin. In both vehicle configurations the same windows were used for the rear side windows and rear windshield. The material used as insulation in the car was expandable polypropylene (EPP) as it has very low thermal conductivity and good insulating properties. The insulation in the prototype car was fitted within the front and rear door cards, the floor, ceiling and the boot space.

Table 3.0: Insulation input parameters for Dymola model

Prototype Vehicle	ρ	k	Cp
Expandable Polypropylene	2230	0.04	1700

EFFECTS OF GLAZING PROPERTIES ON CABIN HEATING

The testing of both vehicle configurations (baseline & advanced glazing) an overall constant solar load of 900W/m² was used to mimic the typical values for maximum direct solar radiation (excluding the scattering effect). In reality the solar load is not constant but varies on factors such as: time of day, location, time of year and humidity. To be more representative of real world conditions the standard AM 1.5 was generated as below, which allows different types of glazing to be compared under the same conditions.

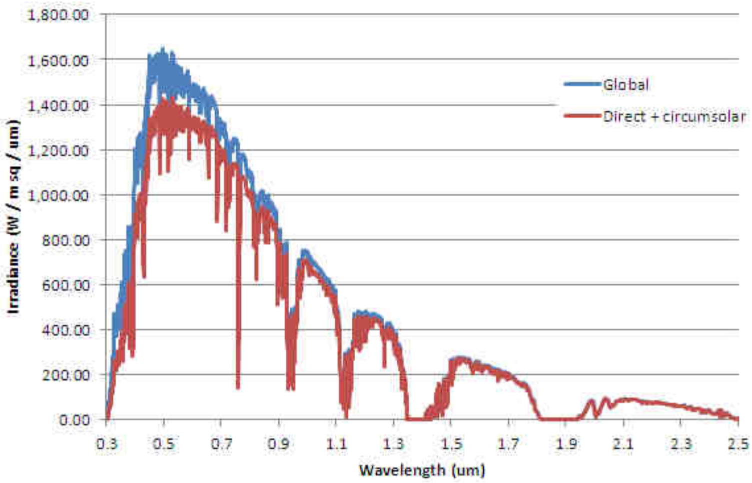


Figure 3.0: Solar radiation from the sun according to AM 1.5 for entire solar spectrum [3]

The direct solar radiation from 0.300 to 2.5µm is shown in Figure 3 (AM 1.5).Under these conditions, the direct solar radiation peaks at 525 nm at an irradiance of 1434 W/m2-µm and the integrated power density over this wavelength range is approximately 1000 W/m². The ultraviolet (300-400nm), visible (400-800 nm), and the infrared (800-2500nm) regions of the global circum solar solar spectrum (ASTME-891) contain approximately 3%, 38%, and 57% of the irradiance respectively.

This shows that the largest contributor to heat flux into the cabin is in the infrared section of the spectral curve. Therefore glazing that targets the infrared portion of the spectrum are most beneficial to lowering cabin soak temperatures. Figure 4 shows the spectral curves for the LowE glazing and baseline glazing for the front side lights used in the prototype vehicle.

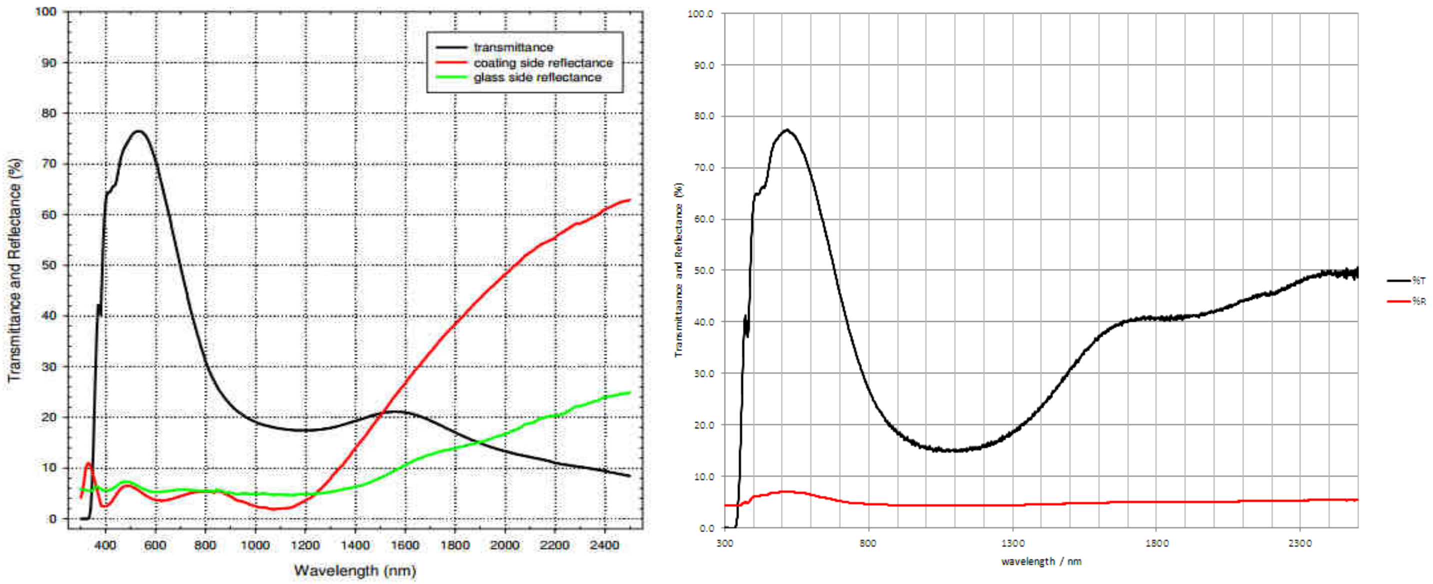


Figure 4.0: Spectral curves for LowE side windows & Baseline side windows in test vehicle

The spectral curves show that the transmittance of the infra-red portion of the spectrum above 800nm is significantly lower in the LowE glazing (left) compared with the baseline glazing (right) which contributes to a significant proportion of cabin heating. The coating side reflectance is significantly higher in the LowE glazing meaning less solar load is emitted into the cabin.

Spectral data for the IRR windshield used in the prototype vehicle shows the percentage of transmitted light at the infra-red section of the spectrum is negligible. The main outcome of the simulations is to compare the effectiveness of LowE and IRR glazings to test data. Typically LowE glazing is able to absorb more thermal energy and reflect it away however IRR glazings may have lower absorption capability but are able to reflect a significantly higher proportion of thermal energy which needs to be compared.

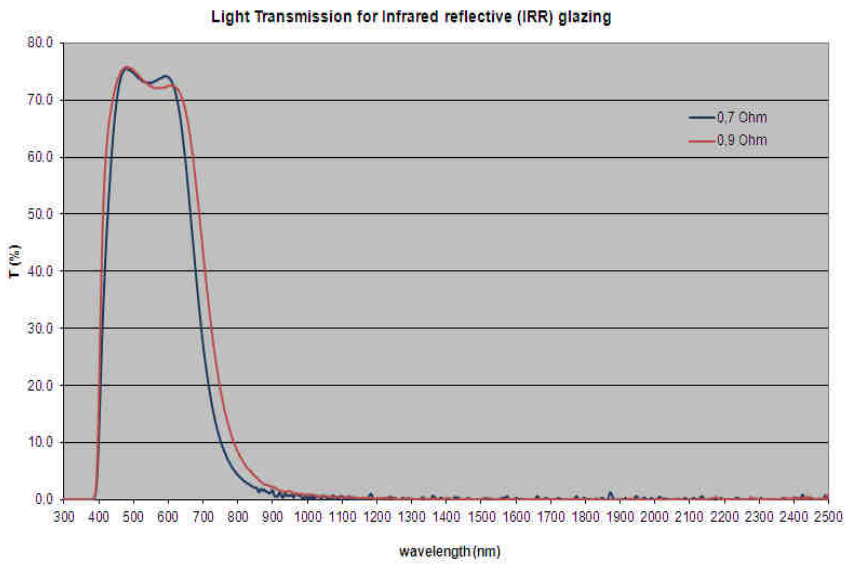


Figure 5.0: Spectral curves Infra-red reflective (IRR) front windshield

5. DYMOLA MODEL - DESCRIPTION

CABIN MODEL

The first step was to develop a physical model of the cabin and the AC loop for the test vehicle and parameterise the each model with values that are representative to the test vehicle. The cabin model was developed around a standard 8 zone (4 upper and 4 lower occupant zones) from the Dymola Human Comfort library with some modifications to accommodate some of the parameters required for the vehicle. A great deal of the cabin and air conditioning modelling discussed here was supported by Claytex Limited.

Figure 6.0 shows the experiment level (top layer) of the model with integrated cabin and AC loop and also the simulation inputs to the cabin and AC models. There were two versions of this model developed, one that allowed the test data to be played back (excluding the AC loop) for correlation to test data and the second included the integrated AC loop as displayed in Fig 8.0. The AC system was used so that optimisations could be run looking at the effect of different parameters on the cabin temperature in different zones.

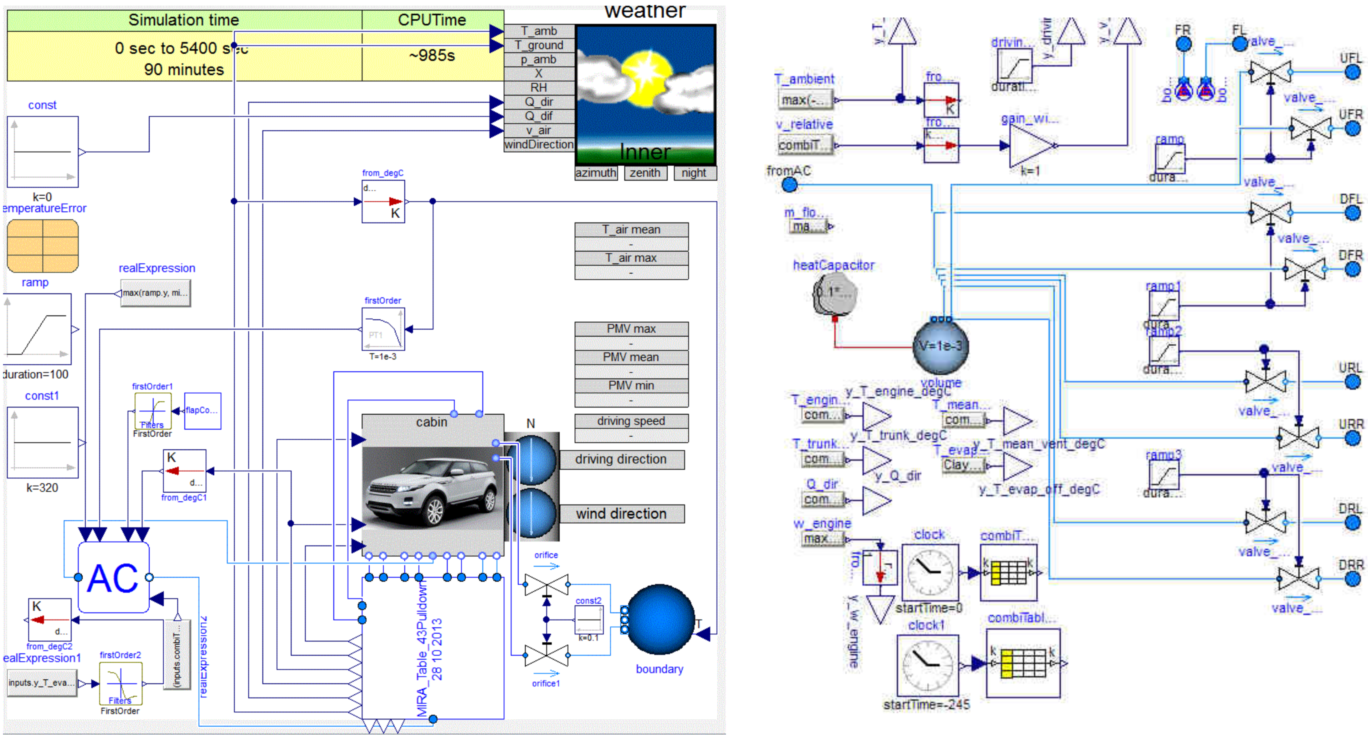


Figure 6.0: Experiment level of integrated AC & cabin model [4]

The model image in Fig 5 also displays the inputs block which feeds the test data into the cabin model:

- Engine temperature
- Trunk temperature
- Solar Load
- Zonal Temperatures
- Weather Conditions

The weather model feeds outputs of ambient conditions into the cabin model which is then connected to the heat ports that correspond to each glazing partition. The experiment also shows two orifices connected to a fluid boundary seen at the bottom right of the screenshot which acts as the expected body air leakage of the car. Body air leakage tends to have a greater effect at high vehicle speed and when running with high levels of recirculated cabin air.

The cabin model itself is displayed in Fig 6 where in the centre of the model is the submodel for the zonal regions of the cabin. Each zone has two port volumes, two heat ports (upper & lower) and a flow split so that air cabin be circulated between the volumes of the cabin with convective heat transfer.

Figure 7.0 shows the 8 zone cabin model for tested cabin. The example shown is for an 8 zone (4 lower, 4 upper) cabin model where for each ‘zone column’ there is a predicted mean vote model for calculation of human comfort in that region.

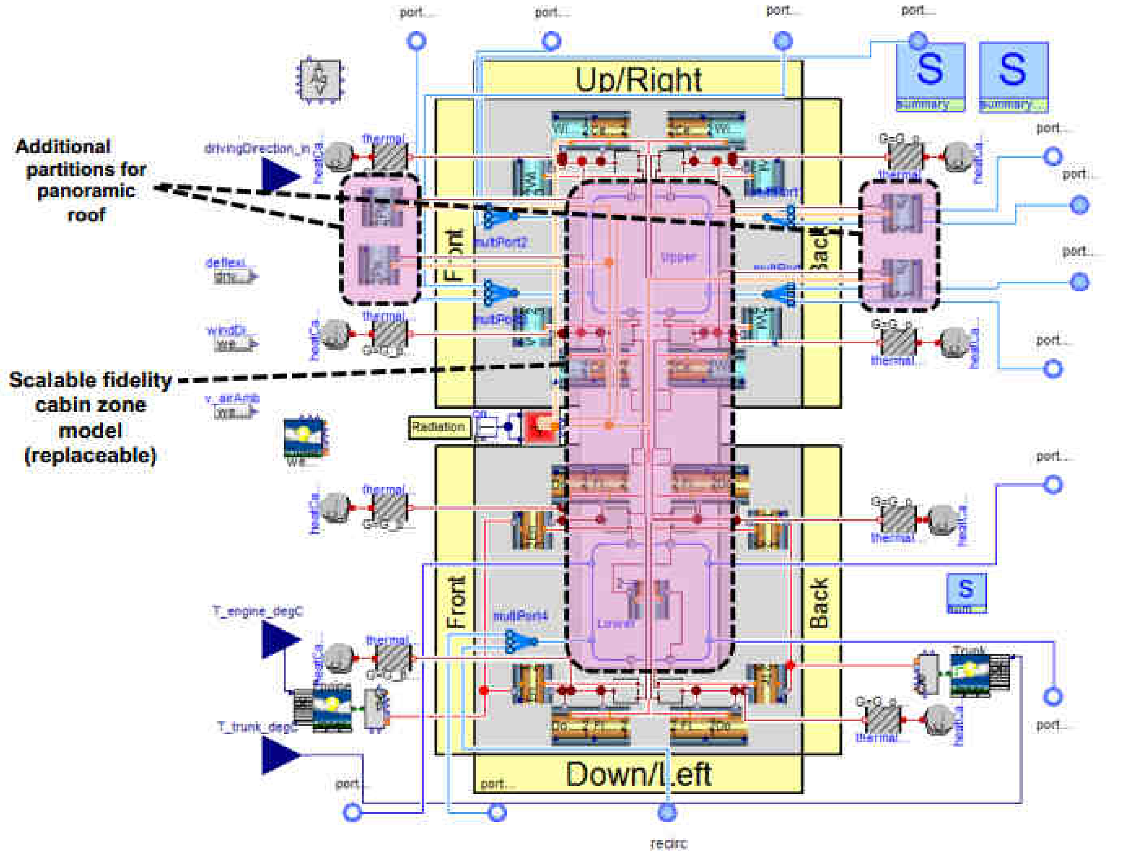
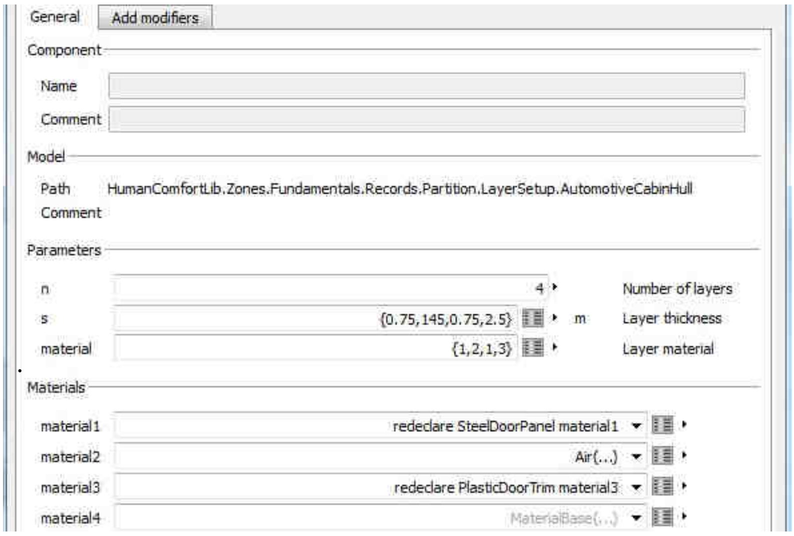
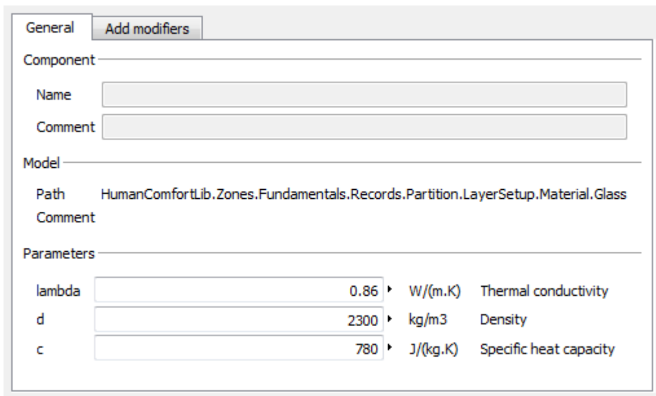


Figure 7.0: Internal cabin model with partitions and submodel for cabin zonal regions [4]

Also within the cabin model are data records that are used in the partitions that represent the glazing and trim material & thermal properties and also the spectral properties of the glazing. The values detailed in Table 2.0 are applied here and also the positioning of each material and it's relative thickness within the partition stack.





For the lowE and IRR glazing the outside surface was modelled as standard glass transmittance, absorption and emissivity values. Whereas the inside surface the relevant properties possessed by the coating.

AIR CONDITIONING SYSTEM MODEL

The AC loop was being fed in the ambient temperature, condenser airflow and initialization values for the AC compressor such as suction and discharge pressure, system charge. For iterations using the AC loop the zonal temperatures are derived from the evaporator air off temperature modelled in the AC loop and valves are used to represent the relevant paths into the cabin, excluding the AC loop measured data from thermocouples was used for the zonal temperatures. The mean cabin temperature was the average of all 8 zonal temperatures which applies to both test data and simulations.

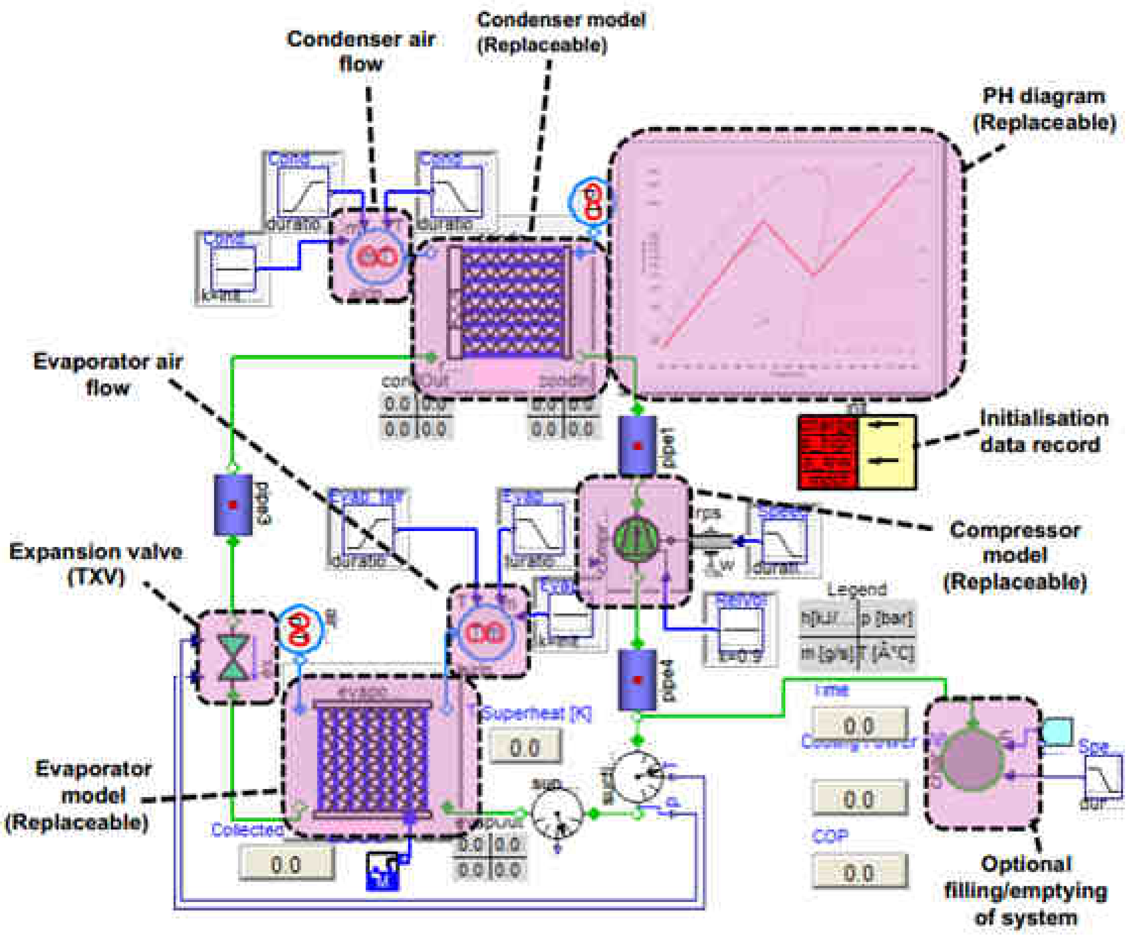


Figure 8.0: Air Conditioning system model [4]

The air conditioning model conventionally uses a condenser and compressor model that has been re-parameterised to match the conditions in the vehicle. The AC compressor is of variable displacement with tabular efficiencies for:

- Volumetric – Volumetric efficiency of the compressor
- Isentropic – Relating to enthalpy changes
- Effective – Mechanical Efficiency of the compressor

The TXV was modelled as a 4 quadrant valve and based around a TXV within the Dymola AC library. Data from the supplier was used to parameterise the TXV.

One of the biggest limitations found was the ability to parameterize the compressor effectively. The compressor is of variable displacement type such that the displacement and suction pressure can vary greatly at different compressor speeds. At the time of writing this paper only full displacement data at two suction pressures of 207kPa and 301kPa was available. If the displacement of the compressor or variation in suction pressure is unchanged assessment of the effect of cabin technologies on compressor torque is negligible.

In order to get around this issue, on iterations that were comparing energy benefits of glazing and insulation compared to the base vehicle a PID controller was used to vary the displacement of the compressor which forced the cabin temperature to match the cabin temperature in the baseline vehicle.

This method generally works well if the cabin temperature is steady state and at the required setpoint, however there are limitations to this method. For example during a pulldown in a cabin with LowE glazing a cabin setpoint temperature of 23°C would be achieved more quickly than a cabin with the base windows fitted as a result there would be more steady state cooling and less overall energy consumption for the compressor and the vehicle.

To account for this, if the cabin temperature was above 24°C full displacement of the compressor was applied and then PID control was targeted at 23°C with limits.

VEHICLE MODEL

In order to assess the effect of energy consumption from compressor torque relating to vehicle traction power a vehicle model which integrates the entire AC loop and cabin was generated. Originally a detailed engine warm-up model was included and also a more complex driveline arrangement, however they significantly increased simulation time so a table based warm-up model and a more simple powertrain arrangement produced a similar result.

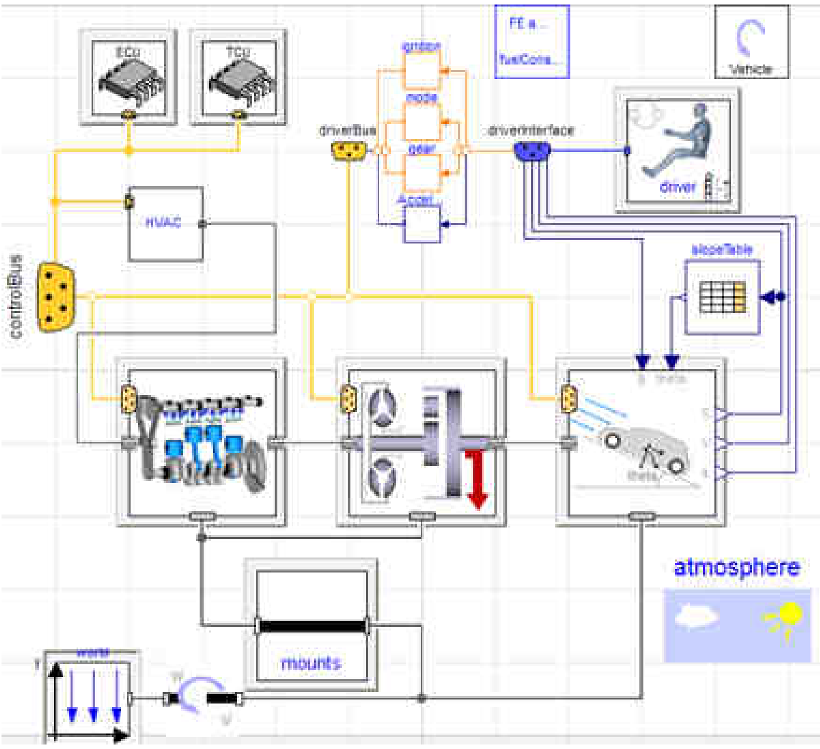


Figure 9.0: Experiment level of Vehicle Model for a Luxury 4x4

Driver Model: The driver model feeds in the test cycle profile, required accelerator pedal position and required brake pedal position to the control bus. Any particular drive cycle can be used, i.e. NEDC, Artemis Urban, WLTP.

Engine Model: Is table based and uses MEP and BSFC table data to calculate the fuel flow which is dependent on throttle angle and is controlled by the engine controller (ECU)

Transmission Model: Six speed automatic gearbox with torque convertor and lockup clutch. The transmission controller defines the gear shift points and when to open or lock the clutch.

Chassis Model: A simplified model which includes the final drive ratio, friction brakes, wheels, vehicle mass, car resistance (including aero and rolling resistance) Brake signals are fed into the model from the brake demand requested from the driver and vehicle position, speed and acceleration are fed back to the driver model for PID control of accelerator and brake demand signals.

HVAC model: The HVAC model consists of the cabin and AC loop where the AC compressor is connected to the accessory flange of the engine. A simple gear has been used to represent the AC pulley ratio in relation the engine crankshaft.

To validate the model, the vehicle was ran through an NEDC test cycle where the FE for the urban, extra urban and combined cycle was compared to FE figures quoted for the vehicle. The model was found to have very similar values to the FE figures quoted online.

	Urban Cyc.	Extra Urban	Combined Cyc.
Vehicle Model	40	53.7	48
Quoted Figures	40.9	54.3	48.7

Table 4.0: Base Fuel Economy figures Model vs. Real Data

6. ANALYSIS OF TEST DATA

After completing the first round of testing at the wind tunnel with the baseline car it can be seen how much the steady state energy requirement changes with different ambient temperatures.

The plot below shows the steady state energy consumption data during a MAC test for a range of ambient temperatures for the vehicle tested. It can be seen that the energy required by the AC system is much higher at the high end of ambient temperatures. There is still an AC compressor torque value at MAC tests below 25°C ambient as it can be used to aid with de-mist and de-icing capabilities.

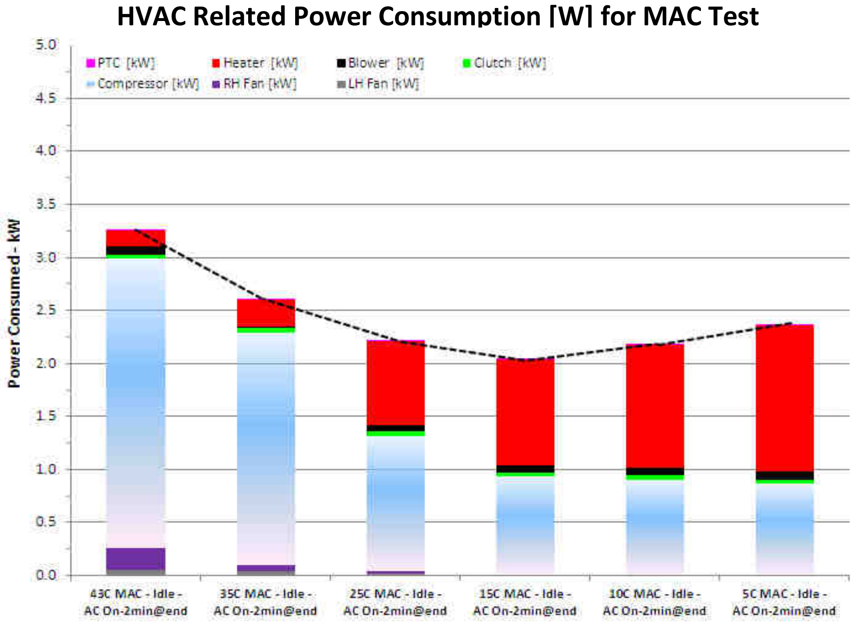


Figure 10: Energy consumption of HVAC system at different ambient temperatures

The MAC test is a steady state test so the peak energy requirement for a given ambient will be fairly low. In a conventional gasoline or diesel powered car the energy for heating effectively comes for free (excluding any PTC heaters) due to utilisation of the rejected heat from the engine. In an electric vehicle this can be a major issue as the heating energy has to be provided from the car batteries through a PTC heater and during a warmup the energy demand to warm the cabin to a suitable ambient can reduce the range of an electric vehicle anywhere between 25-50%.

For the conventional vehicle the highest peak load on the AC system is during a pulldown where the AC compressor is at full displacement to achieve a cabin temperature of 22-23°C. Figure 11 shows that during a pulldown in a 43°C ambient the system was unable to achieve the required 23°C ambient with the automatic blind open. With the blind closed there is a 4°C improvement in cabin temperature and reaches a minimum of 24.3°C.

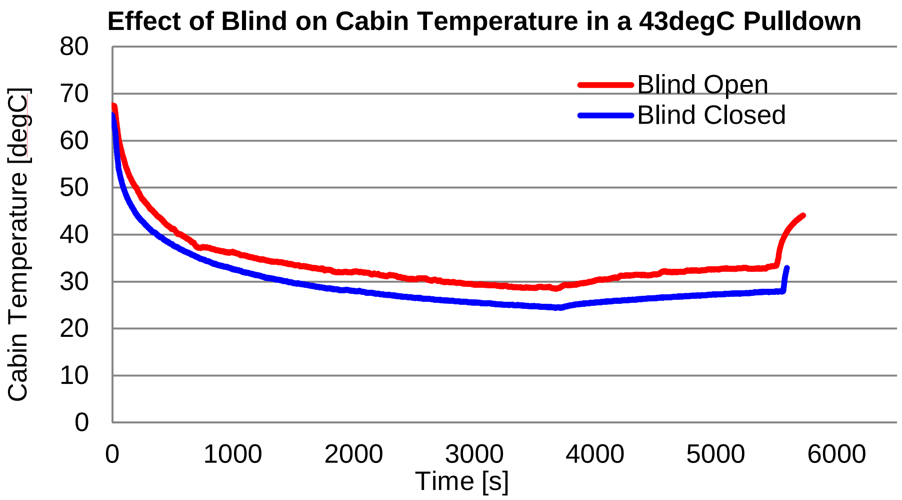


Figure 11: Pulldown test in a 43°C ambient temperature

Figure 11 shows that the average cabin temperature at the start of the baseline pulldown reaches temperatures as high as 68ºC where during testing some vent temperatures reached as high as 83°C. Although the cabin temperature is reduced from the blind being closed it adds a significant mass to the vehicle therefore advanced glazing is the preferred alternative if similar solar benefits can be achieved.

At the time of testing the prototype car multiple new technologies were deployed into the vehicle, therefore analysis of each individual technology on FE benefits is difficult to determine only overall improvement can be known. Figure 12 shows data for another soak on another vehicle platform tested within the company shows that advanced glazings have a positive effect on reducing cabin temperatures during a soak with a 3°C reduction in cabin temperature.

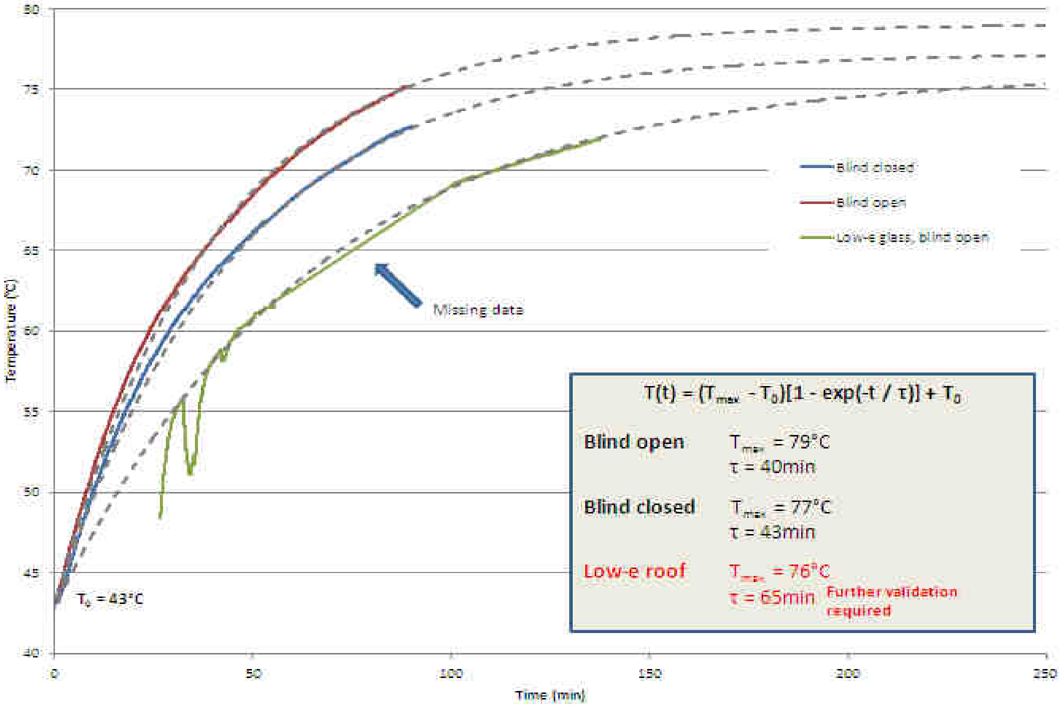


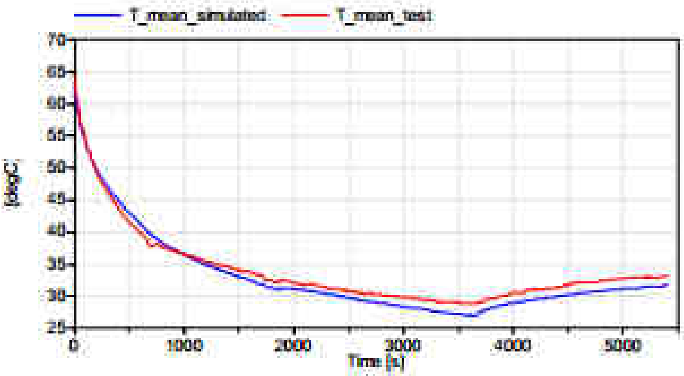
Figure 12: 43°C Soak cabin temperature comparison between baseline and prototype glazings

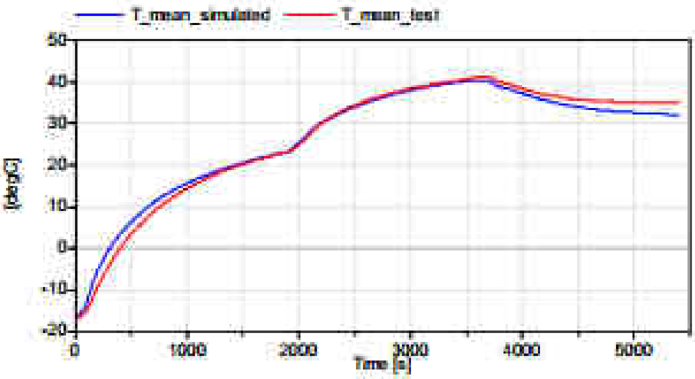
7. SIMULATION DATA

CORRELATION OF MODEL TO TEST DATA

Once the entire model was developed to the required standard comparisons between the test data was conducted. A comparison of the final temperatures between test data and simulations is as follows:

Pulldown: 1.5°C
Warmup: 2.9°C
43°C Soak: 0.5°C





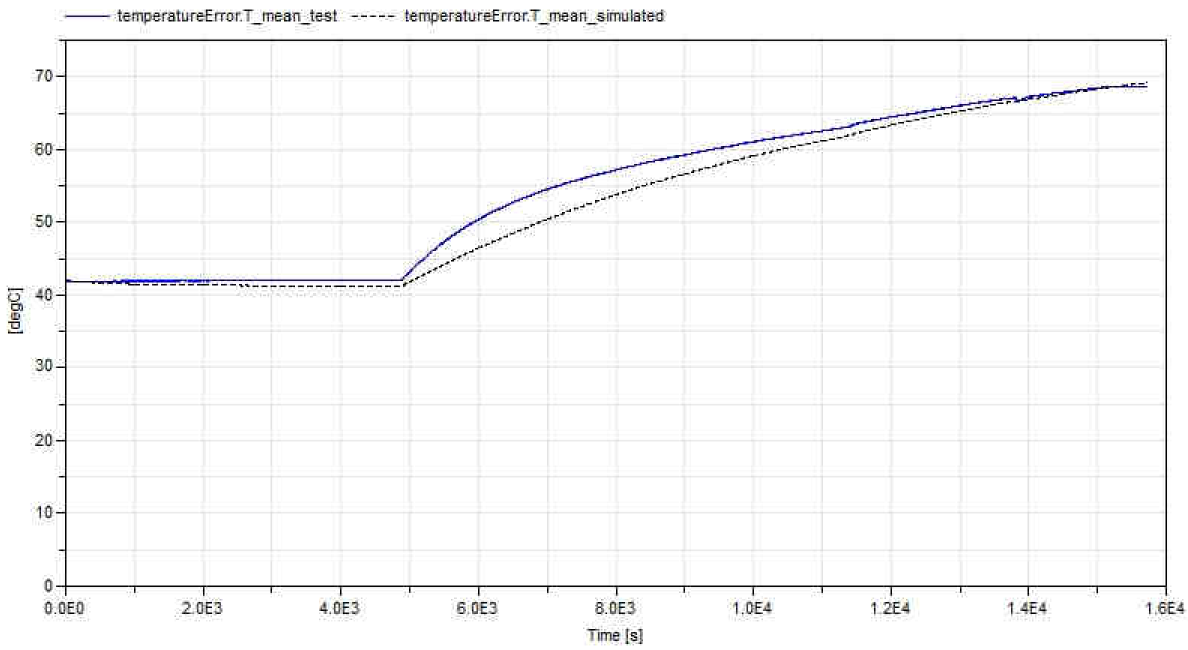


Figure 13: Comparison of Test Data vs. Simulation data for Pulldown, Warmup and Soak tests

Towards the end of the pulldown and warmup the cabin temperature increases and decreases respectively, this is because this is the idle section of the test and there is significantly less airflow over the condenser and thereby reduced cooling power. For the warmup test the heat rejection from the engine is much lower at idle so the coolant temperature passing over the heater core is much lower. Differences in cabin soak temperatures during the initial warmup phase need to be investigated.

MODEL ASSUMPTIONS

As previously discussed, at the time of writing this paper insufficient test data for the prototype car was available therefore correlation of the model was done only against the baseline test data. The model vs. data comparisons were mainly completed for an 8 zone cabin model with 2 layers (upper and lower). However a simple 2 zone cabin model (one upper, one lower volume) was compared to the test data and was found to be an additional 1.5°C lower temperature at the end of the pulldown.

The data available for the airflow over the condenser was also very limited due to ambient temperature not being fixed at different vehicle speeds. The best approximation was made, to allow the airflow to be more representative over a range of vehicle speeds. Another assumption is that the average temperature is calculated in the model by summing all of the temperatures in each volume, however the test data calculates the average of 8 thermocouple readings at the face vents, footwells, breath sensor and belt level bar. The differences between both this averaging method was deemed to be minimal. For simulations where the insulation was fitted it was assumed that the insulation was of even thickness throughout the entire partition and that the air gap between the insulation and the layer either side could be varied to any desired value.

SIMULATION RESULTS – CABIN TEMPERATURE

Simulations were then run comparing the model with the baseline glazing with no insulation, baseline with insulation, advanced glazing w/no insulation & advanced glazing with insulation. Figure 14 highlights the differences in cabin temperature between different glazings for different soak conditions. Note that figure 16 displays pulldown comparisons for a fixed soak of 3 hours where each results start temperature is the also the end temperature of its corresponding soak test.

Figure 14: Comparison of Soak Temperature for baseline vs. LowE glazing vs. LowE glazing & Insulation

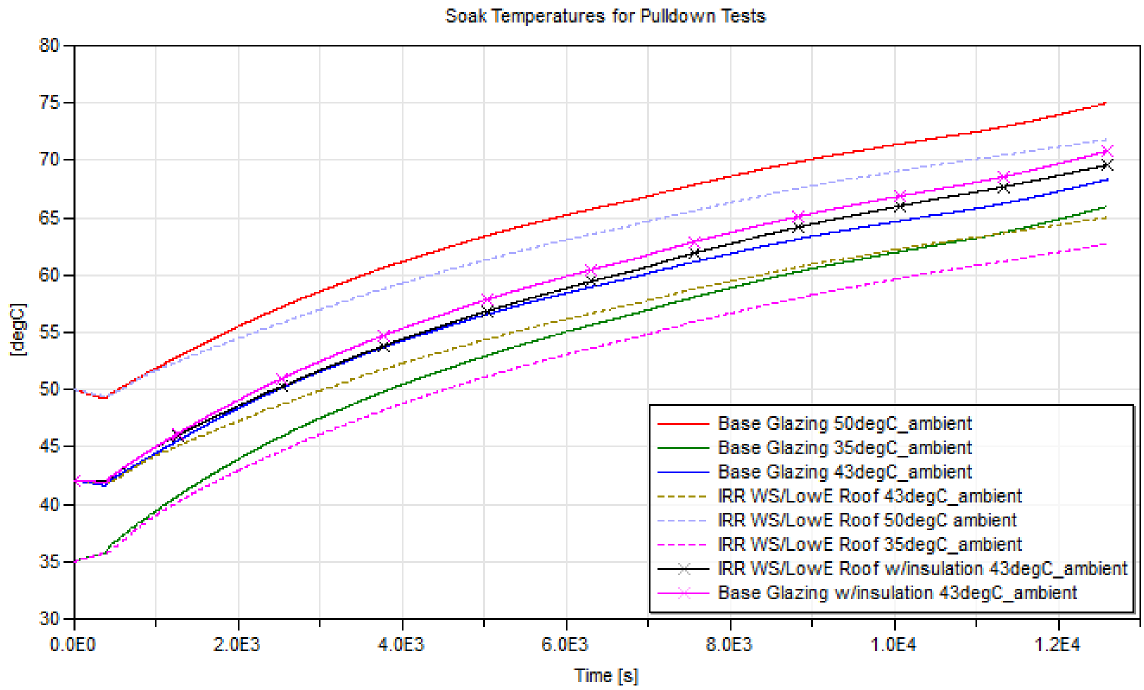
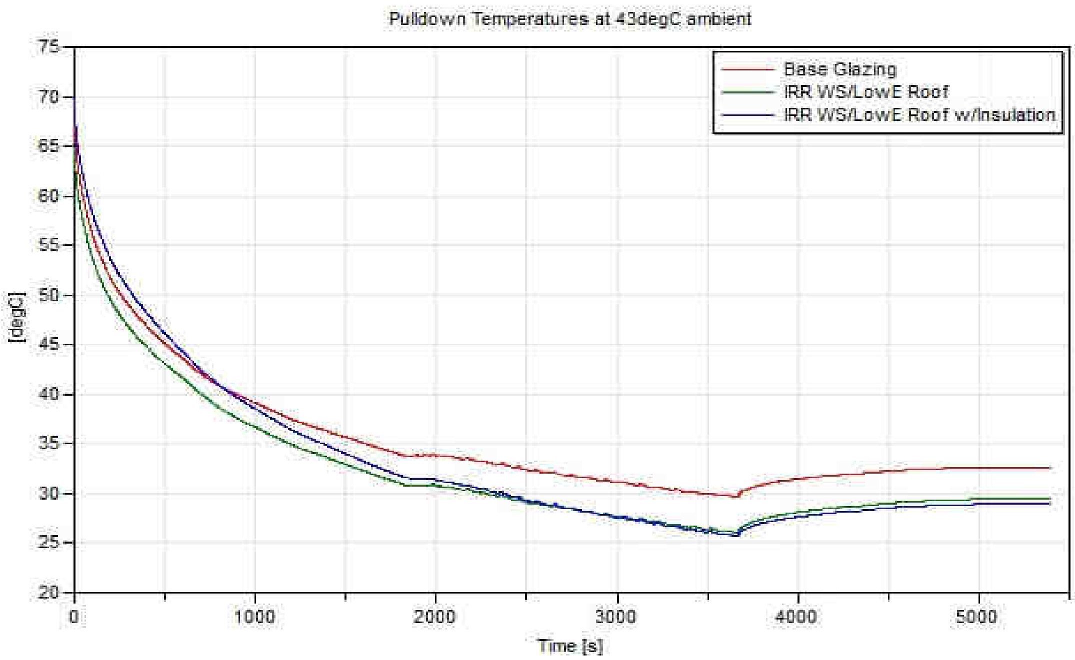


Figure 15: Comparison of Pulldown Temperature s for 43ºC ambient after hot soak



The results show that starting the pulldown from the soak end temperature has a significant effect on the temperatures seen during pulldown for each different type of glazing. The most thermally efficient setup was with the IRR Windscreen and LowE Panoramic roof fitted with a 3ºC improvement from baseline. Adding insulation during pulldown lowers the cabin temperature by a further 0.5°C. Figure 17 shows how starting the pulldown test for each type of glazing at the same temperature has less noticeable differences in cabin temperature, however the advanced glazing setup still has an improvement over baseline glazing at 1.5ºC.

Figure 16: Comparison of Pulldown Temperature s for 43ºC same start Temperature

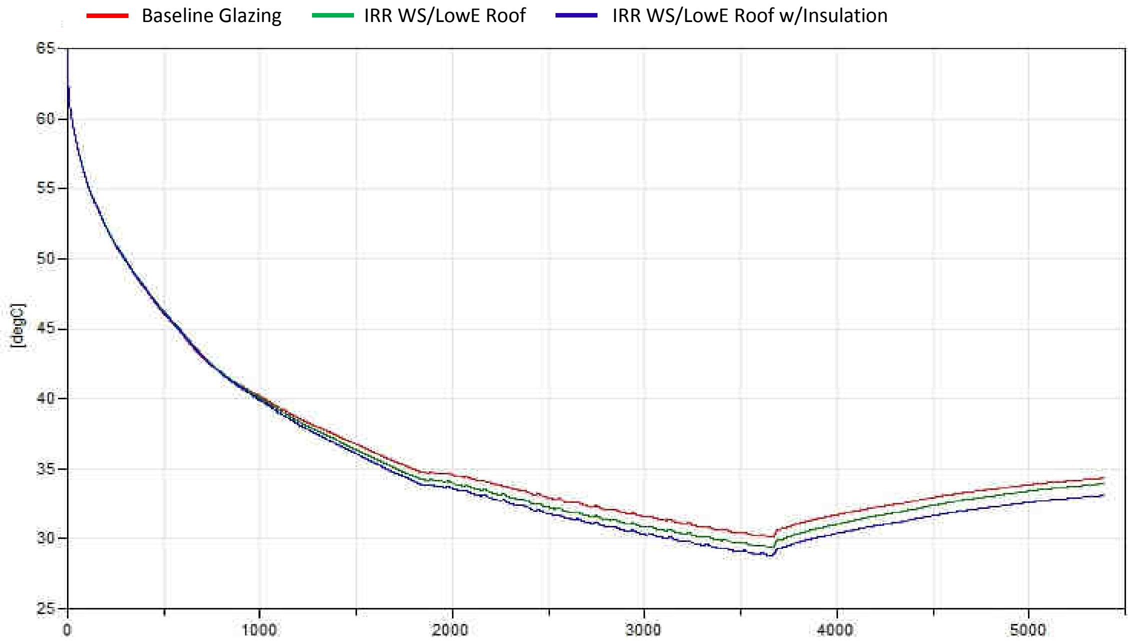
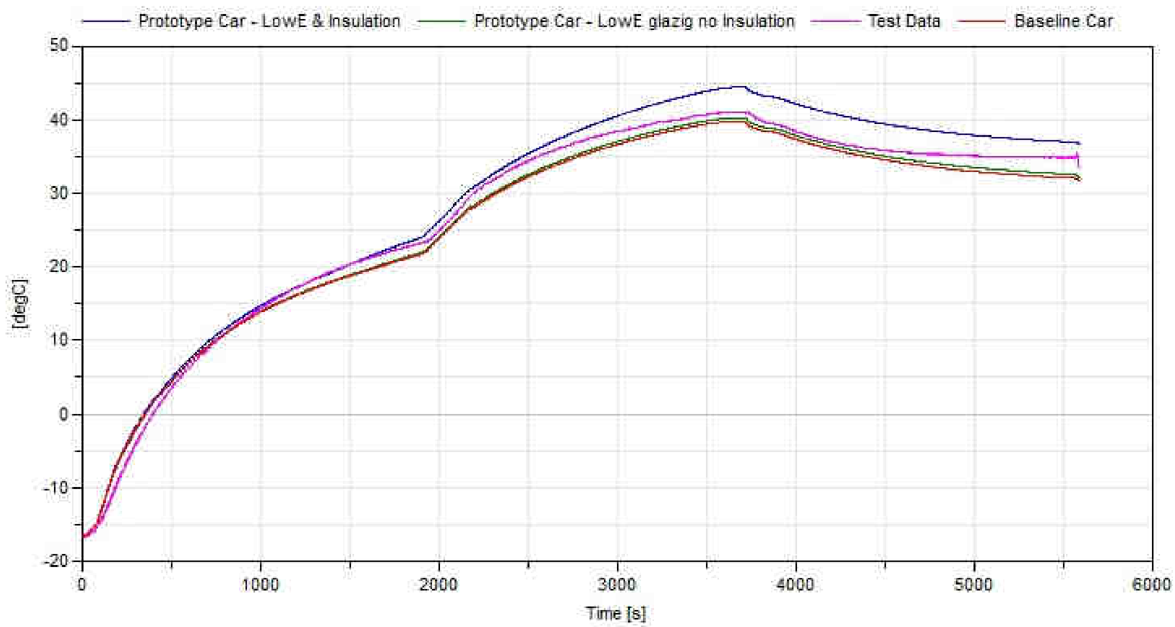


Figure 17: Comparison of Warmup Temperature for baseline vs. LowE glazing vs. LowE glazing & Insulation



During warmup from -18ºC simulation shows little difference between baseline and with special glazing fitted. When the insulation is fitted along with the lowE glazing this is shown to increase the cabin temperature much more quickly. The theory behind this is that the insulation acts as a thermal barrier and therefore far less heat is able to exit the cabin the effect is a 5°C warmer temperature at the end of the warm-up compared to baseline (no insulation fitted).

Further work is required to understand the interaction of the insulation within the cabin, based on how different thickness levels and varying the material properties of the insulation has an effect on cabin warmup and pulldown temperatures.

Figure 18 compares the total net heat flow into the cabin from all of the glazing derived from the U-values obtained through the simulation due to solar radiation during the soak and pulldown tests between baseline glazing (blue) and vehicle with IRR windscreen and LowE panoramic roof and front side windows(red). There was a steep decline in heat energy into the cabin at the start of the pulldown due to a transient cabin temperature and levels off when cabin temperature is more stable. Figure 19 shows how much the solar power into the cabin can be reduced considerably by installing advanced glazing.

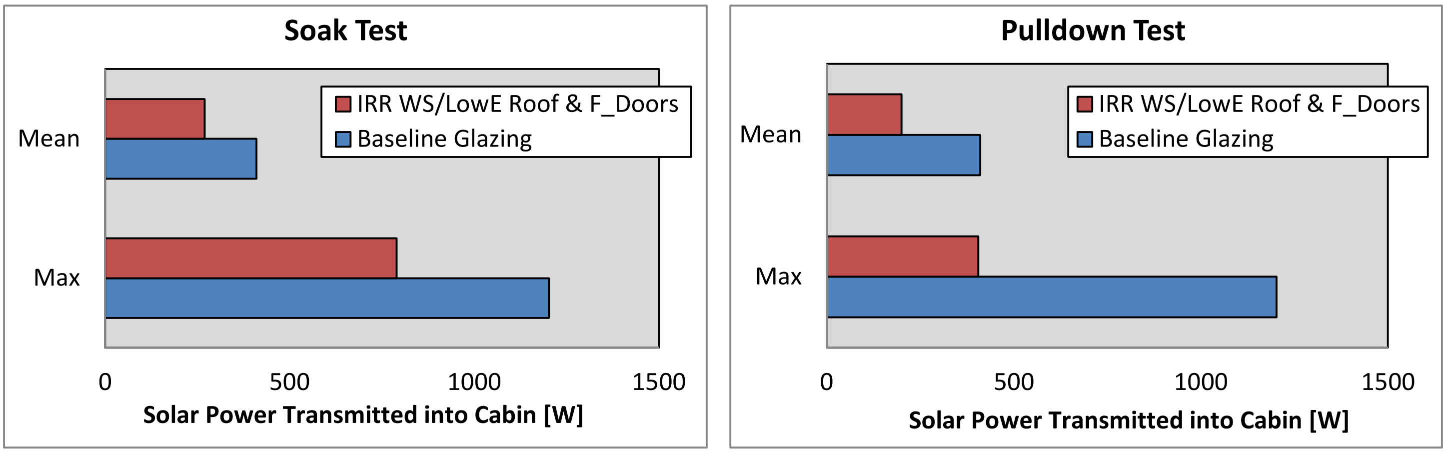


Figure 18: Heating Power into the cabin for Baseline glazing and LowE glazing during Soak & Pulldown Test

EFFECT OF ADVANCED GLAZING AND INSULATION ON ENERGY CONSUMPTION

Ultimately these changes to the vehicle cabin will result in an energy saving due a lower demand on the AC compressor. To determine these benefits two methods in the model can be used which is the reduction in fuel volume used by the vehicle during the drive cycle or the reduction in energy usage for the cycle derived from compressor torque. The main goal was to determine the energy differences between each glazing technology relating back to traction power.

At the time of writing this paper the energy contributions of the each of the cabin technologies discussed in this paper were not available due on going work to characterise the displacement control strategy of the compressor. The next steps for this work are to generate fuel savings for each of the cabin technologies.

8. CONCLUSIONS

With reference to the results seen during pulldown this is the most important assessment to determine if the HVAC system: can achieve the required setpoint cabin temperature, the occupant/s are comfortable within the cabin and what the peak cooling load is from the AC compressor and ideally how this effects parasitic loss for the engine. From the literature investigated and comparison with other data results show that advanced glazings and insulation have a reasonable benefit and that it is promising that a clear fuel economy improvement is available. The following key points were concluded from this study:

1. As was seen from the test data and in Simulation the base car was unable to achieve the desired cabin temperature of 23° during the 43°C pulldown, the most cost effective solution is to continue to optimise cabin technologies to achieve the required setpoint temperature, modification of AC components should be prevented due to cost issues.

2. The model correlates well with the baseline test data which was used for validation purposes, therefore further changes to cabin material properties should correlate closely with expected results from prototype vehicles.

3. Simulations show that changing the glass transmission/absorption factors for the windshield and panoramic roof had the biggest effect on changing the cabin temperature for all cases.

4. The difference in the soak temperature for baseline glazing vs. advanced glazing was in the order of 3-4°C.

5. Fitting IRR and lowE glazing technologies can potentially allow a 3°C reduction in cabin temperature during a pulldown.

6. Test data shows that closing the blind has a 4°C reduction in cabin temperature over a pulldown. This will therefore be included in any future modelling work to determine the time to reach the required setpoint temperature.

7. Closing the blind during pulldown also has a significant effect on reducing cabin temperature, a combination of advanced glazings and an automatic blind closure will achieve better cooling performance and reduced load on the AC compressor.

8. The insulation fitted within the cabin had virtually no effect on improving pulldown temperatures when fitted to cars with baseline and advanced glazing. However the insulation had a positive effect on heating the cabin much faster during a -18°C warm-up.

9. REFERENCES

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