Multi-Domain Thermo-Fluid Approach to Optimizing HVAC Systems

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JLR Research – Project STRIVE
Claytex Ltd

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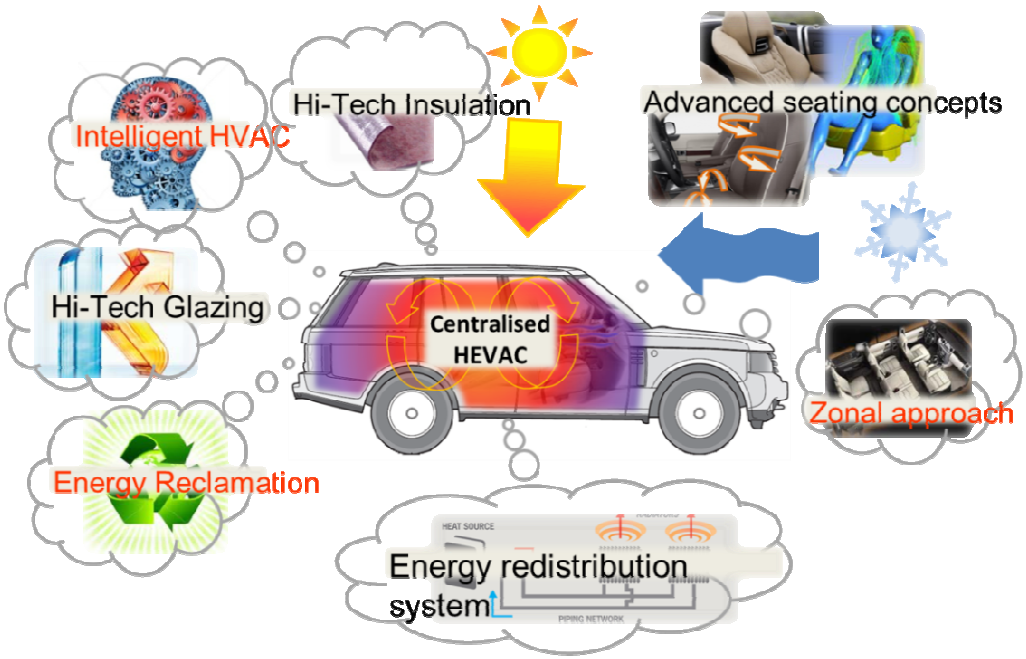
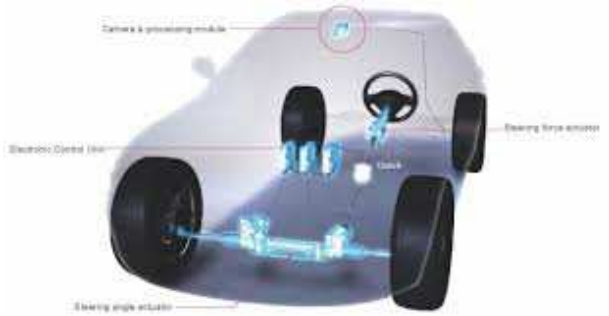
STRIVE Research Aims

- Systems,
- Technologies,
- Research and
- Innovation for
- Vehicle
- Efficiency





HVAC Energy Consumption
Size of the Issue

1. **HVAC systems have a significant impact on fuel economy for a conventional vehicle and a greater impact on electric range for hybrid and electric vehicles.**

2. **Fuel Economy and range impact greatest at extremes of ambient temperatures.**
   - *Impact on Conventional Vehicle:* *20-30% Reduction in Fuel Economy*
   - *Impact on Electric Vehicle:* *40-60% Reduction in Electric Range*

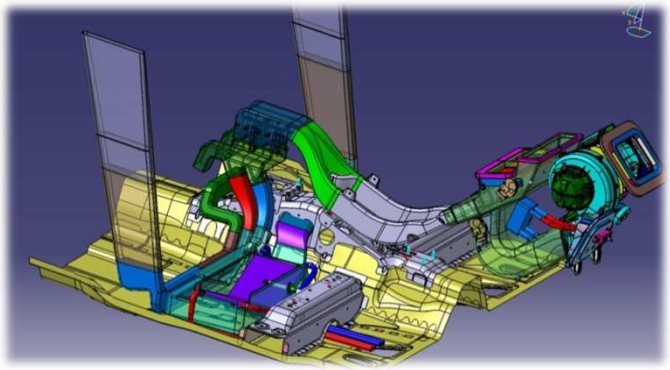
3. **Poor cooling performance will result if the AC compressor or condenser is insufficiently sized to meet the cabin setpoint temperature.**

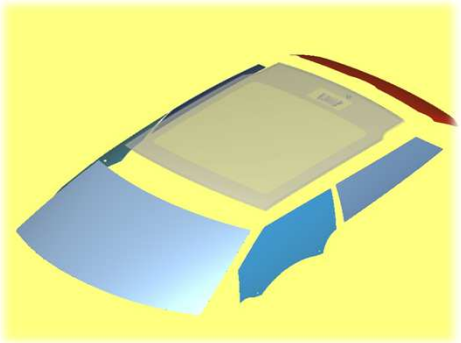
4. **“Pull-down” energy requirement circa 7kW for condition – High ambient temperatures.**
5. **“Warm-up” energy requirement circa 14kW for condition – Low ambient temperatures.**

6. **Warm-up energy requirement not an FE issue for conventional vehicles, engine waste heat can be used to warm the cabin and occupants.**

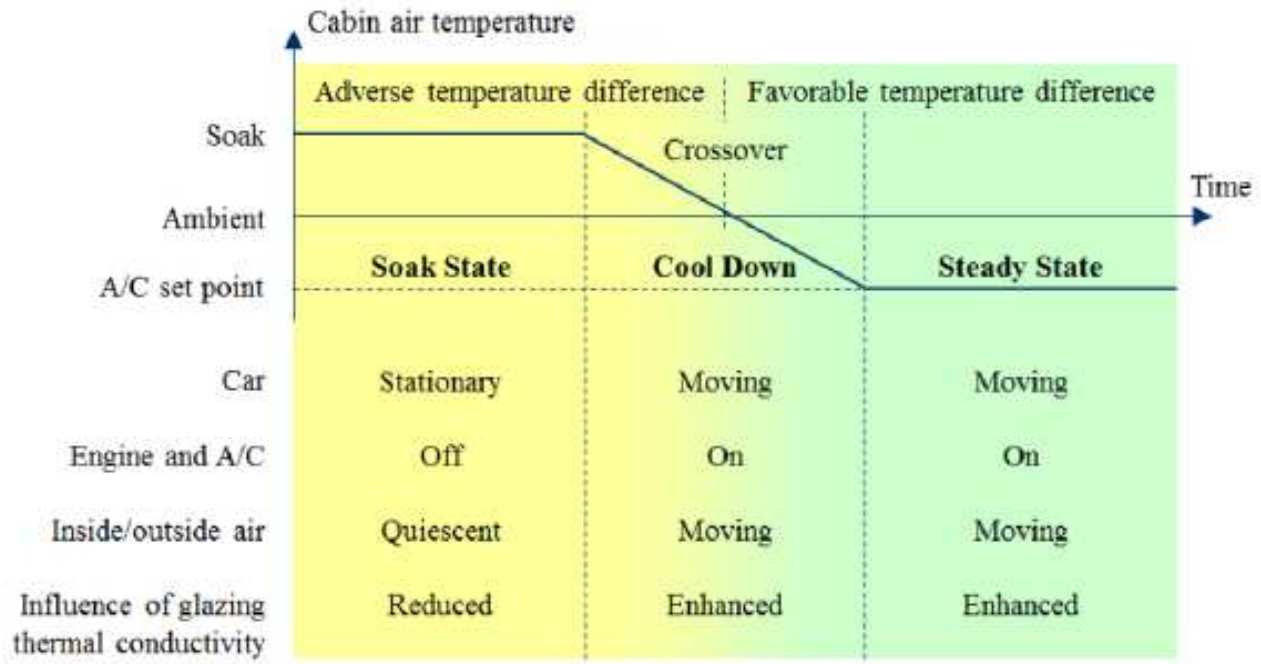
Key Modelling Objectives

1. *Model an automotive cabin that represents the vehicle with Dymola Human Comfort Library*
2. *Replicate the vehicles air conditioning loop in Dymola*
3. *Generate a cabin model that can have inter-changeable zones for higher levels of fidelity.*
4. *Integrate the AC loop & cabin model for system modelling and correlate to test data.*
5. *Model the effect of a centrally mounted HVAC system on temperature and comfort.*
6. *The Effect of glazing & insulation technologies on cabin temperature during soak conditions.*
7. *The Effect of glazing & insulation technologies on cabin temperature on pull-down & warm-up.*
8. *Generate a vehicle model so that the entire HVAC system can be integrated into the vehicle.*
9. *Determine energy and fuel economy benefits of glazing and insulation for the vehicle.*





Typical Cabin Conditions



Typical test phases for hot climate conditions [1]

Baseline Vehicle: Standard Glazing, Panoramic Roof, no thermal Insulation

Prototype Variants: LowE glazing in the roof, windshield & side windows, thermal insulation in the doors, floor, boot and ceiling.

Homologation & NEDC Cycles

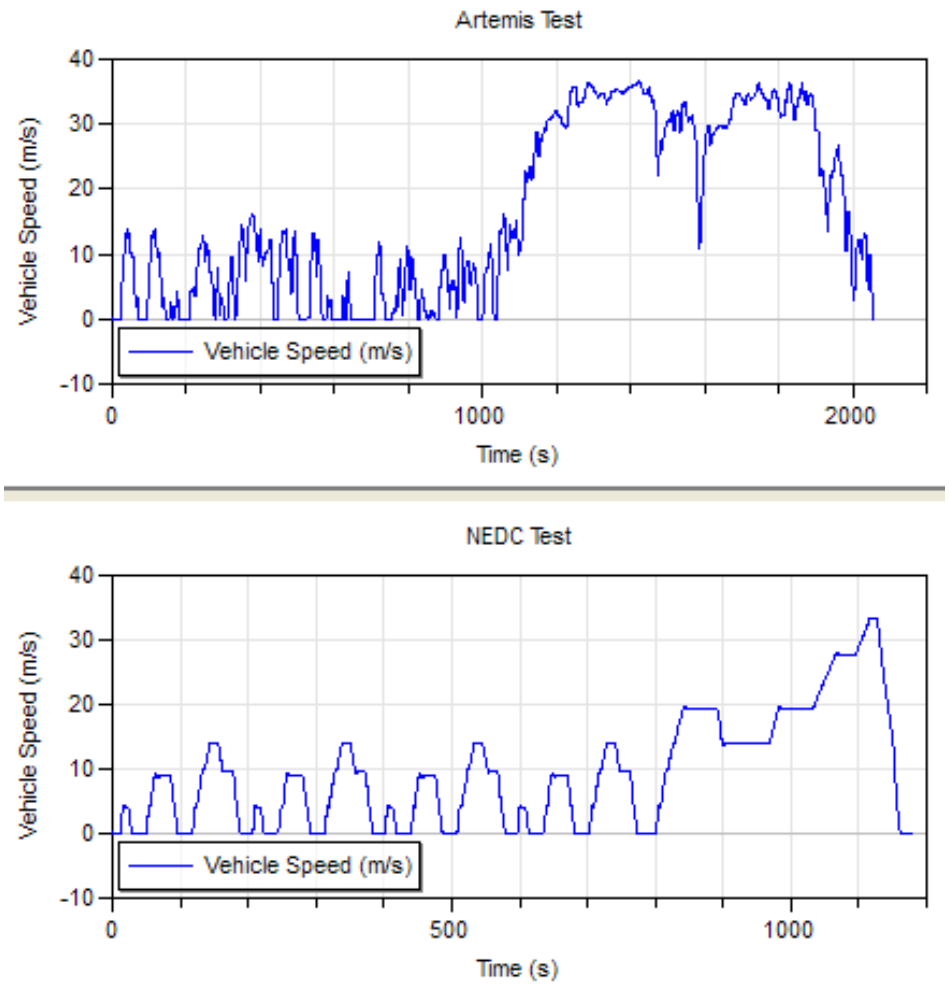
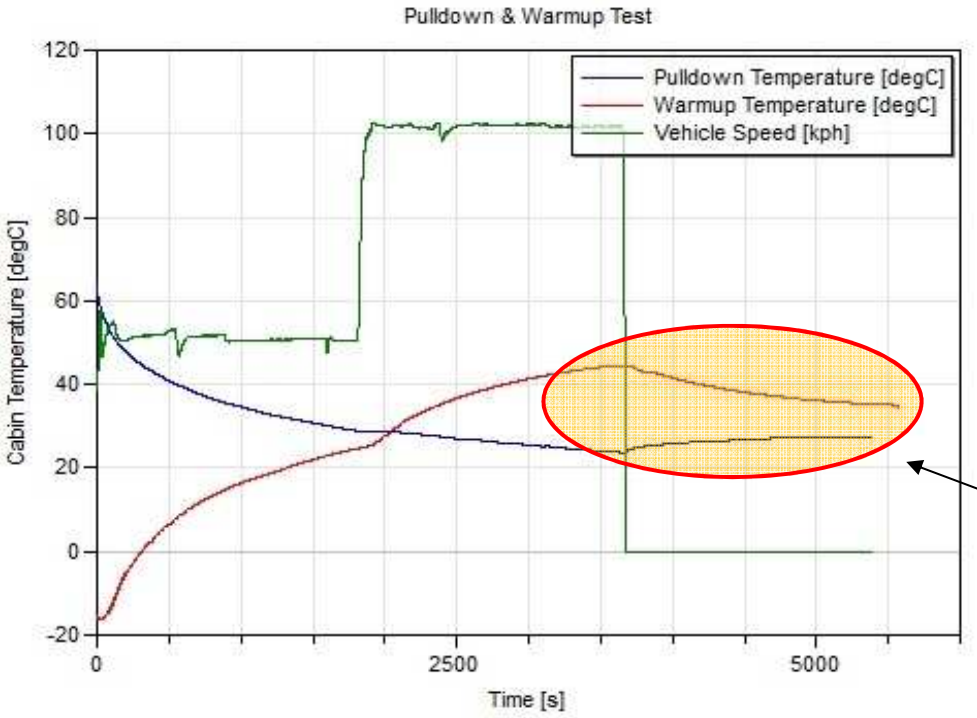


Figure 2.0: Simulation Drive Cycles

	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

- **NEDC & Artemis Cycles can be started from a steady state or transient cabin temperature.**
- **Vehicle Speed is transient in nature.**
- **Highest NEDC energy consumption when cabin temperature is at ambient soak temperature.**
- **At steady state cabin temperature HVAC energy is significantly reduced.**

Pull-down & Warm-up Test



Pull-down Drive Cycle Profile

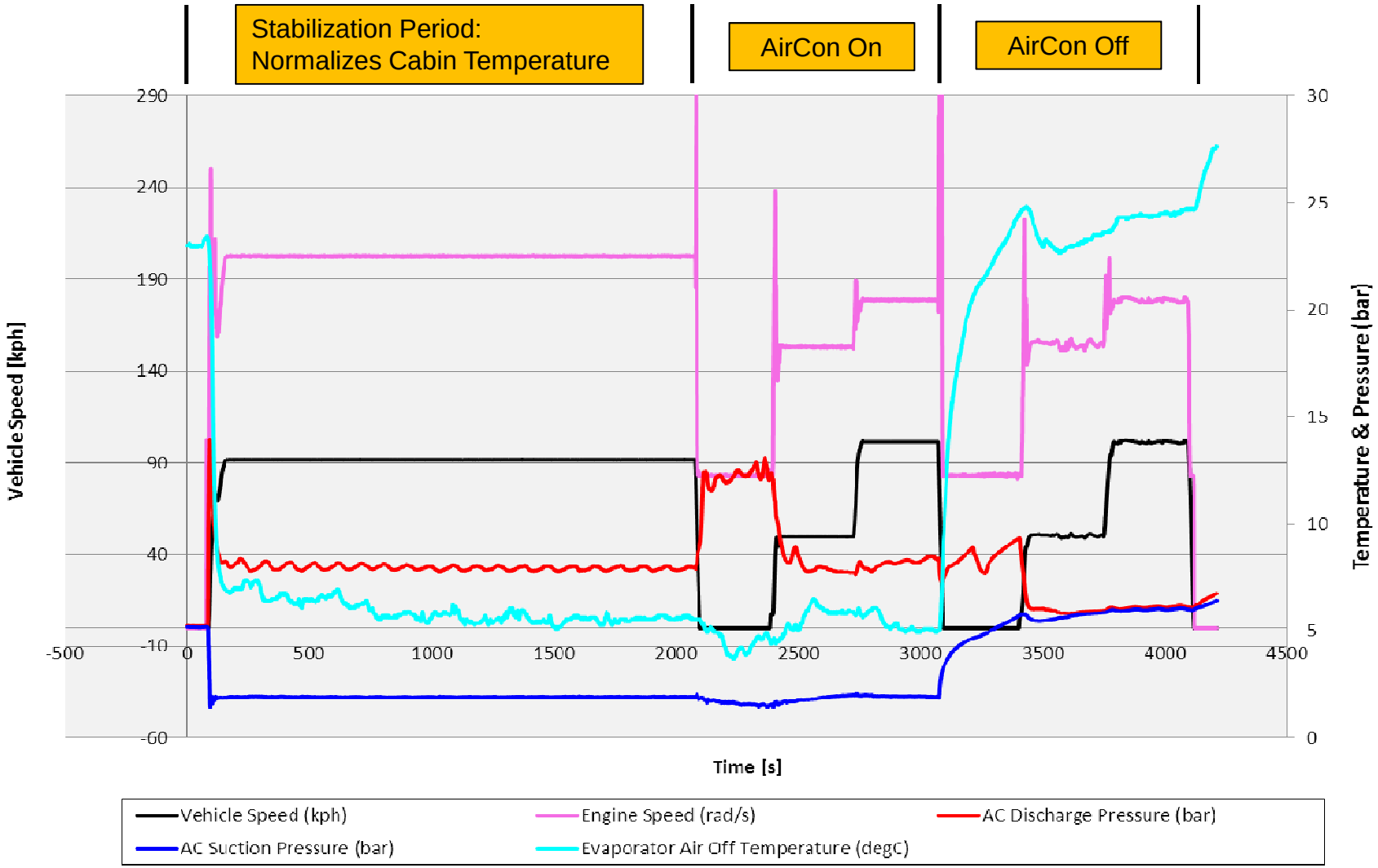
	NEDC	MAC	Pulldown	Warmup
Time(s)	1185	4038	5400	5400
Max Speed (km/h)	120	100	100	100
Max Accel (m/s^2)	1.1	1.95	1.168	1.168
Distance (km)	10.9	76.9	77.9	77.9
Cabin start temperature (°C)	22	22	43	-18
Condition	SState	SState	Transient	Transient

Worse performance at idle:

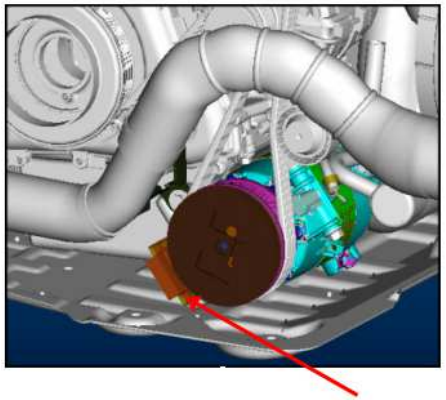
- Airflow over condenser is reduced at idle during cooling.
- Engine heat rejection lower at idle during heating

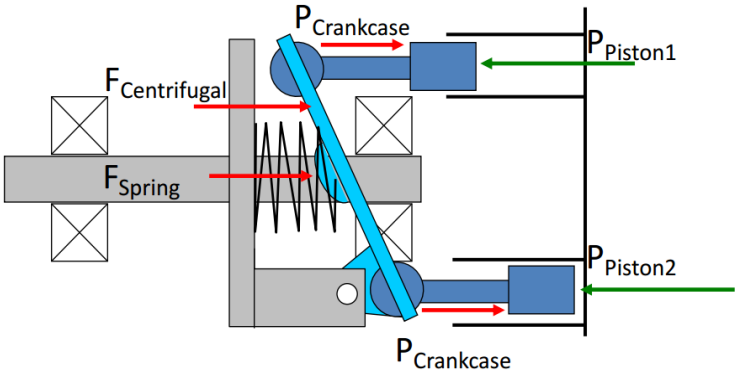
- **For Pull-down and Warm-up tests cabin temperatures are always transient.**
- **Test is started with cabin temperature at the end of the vehicle soak.**
- **The vehicle is soaked for 3hours with 1000W/m^2 of solar irradiance.**
- **The same solar load is applied throughout the pull-down test.**

The MAC Test

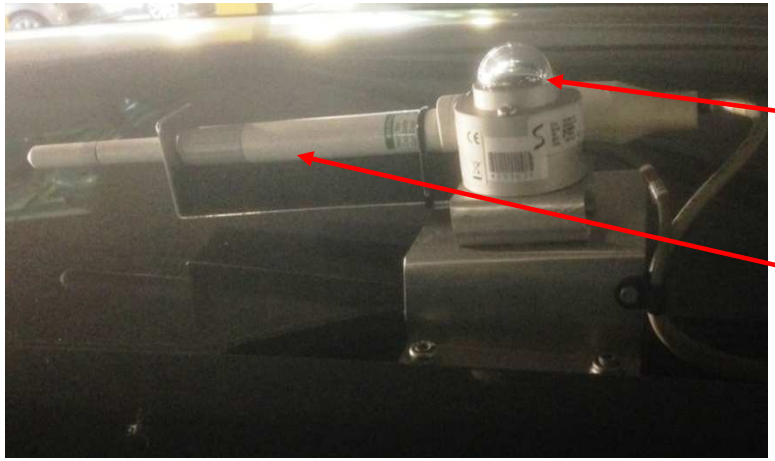

Stabilization Period:
Normalizes Cabin Temperature
AirCon On
AirCon Off
Vehicle Speed [kph]
Temperature & Pressure (bar)
Time [s]
290
240
190
140
90
40
-10
-60
30
25
20
15
10
5
0
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Vehicle Speed (kph)
Engine Speed (rad/s)
AC Discharge Pressure (bar)
AC Suction Pressure (bar)
Evaporator Air Off Temperature (degC)

Test Vehicle Instrumentation





$$F_{Centrifugal} + F_{Spring} + \Sigma(P_{i,Crankcase} \times A_i) = \Sigma(P_{i,Piston} \times A_i)$$

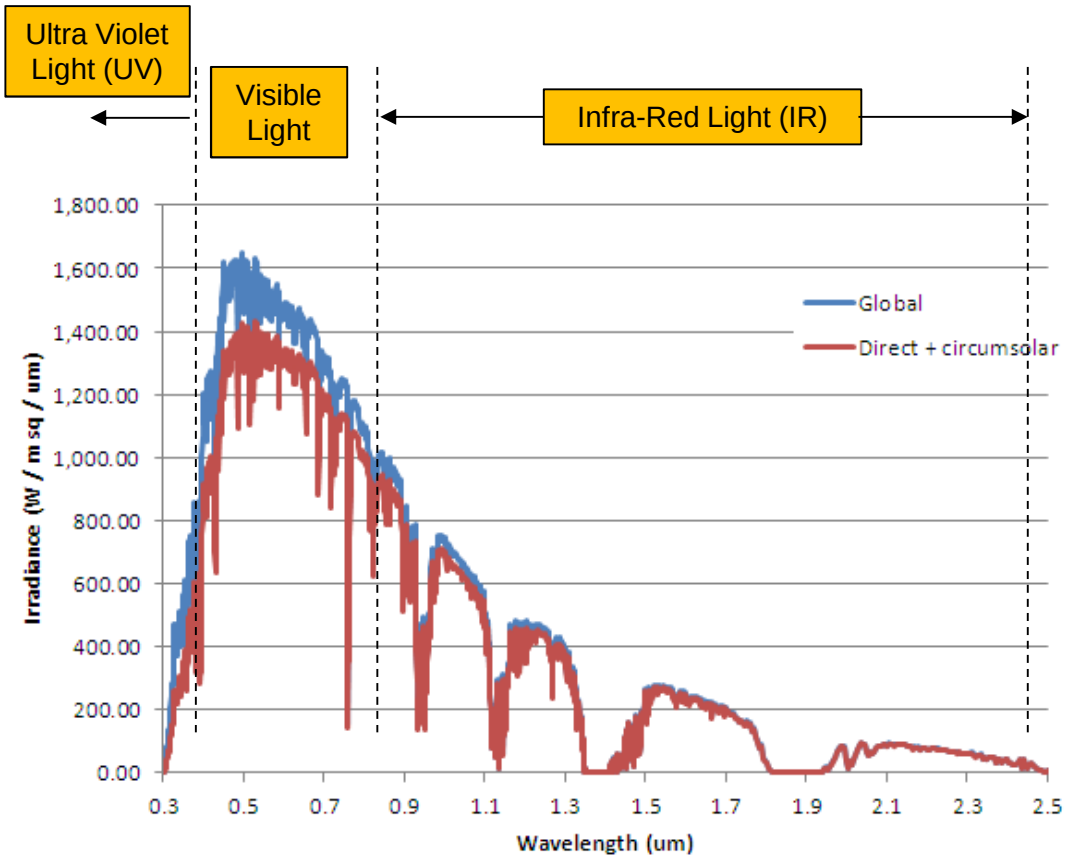


Solar Pyranometer

Humidity Sensor

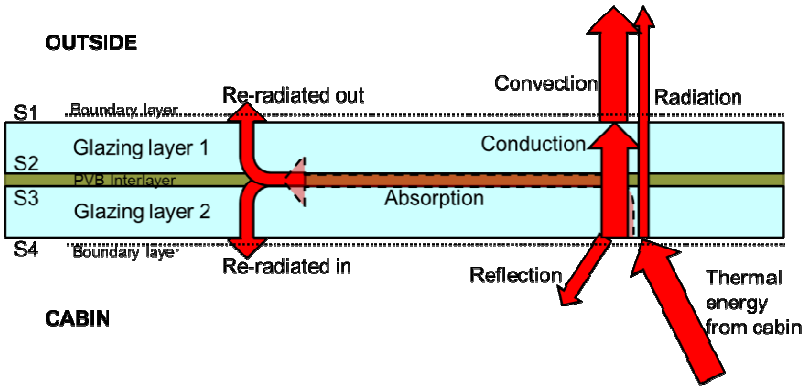
<u>Thermocouples on glazing</u>: Measure heat transfer across the glass.

The Solar Spectrum



Solar radiation from the sun according to AM 1.5

Solar radiation is either Short Wave or Long Wave:
Short Wave = 0-800nm Long Wave = 800nm+



ISO13837 defines the transmission of solar energy through vehicle glazing as follows:

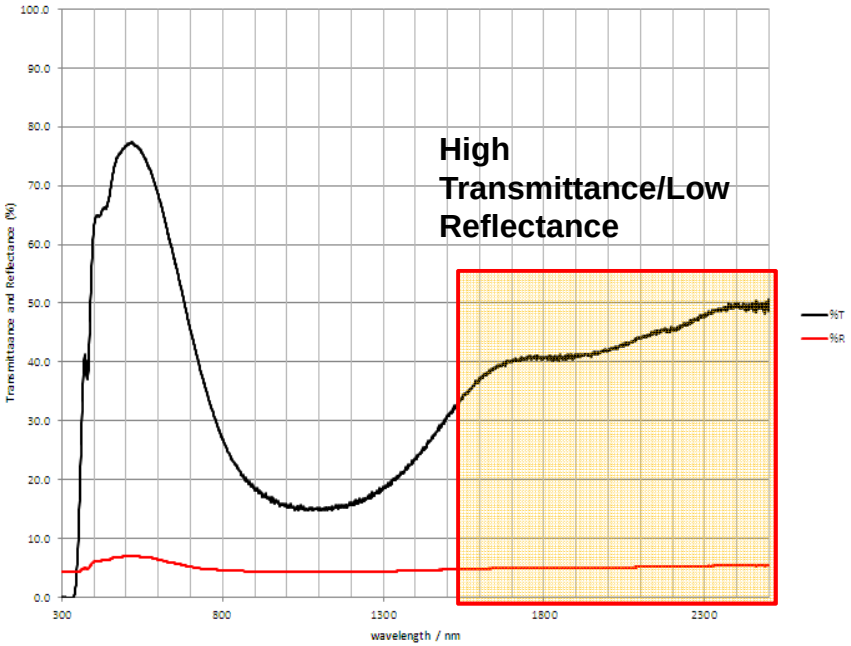
$$Tts = Tds + qi$$

Where:

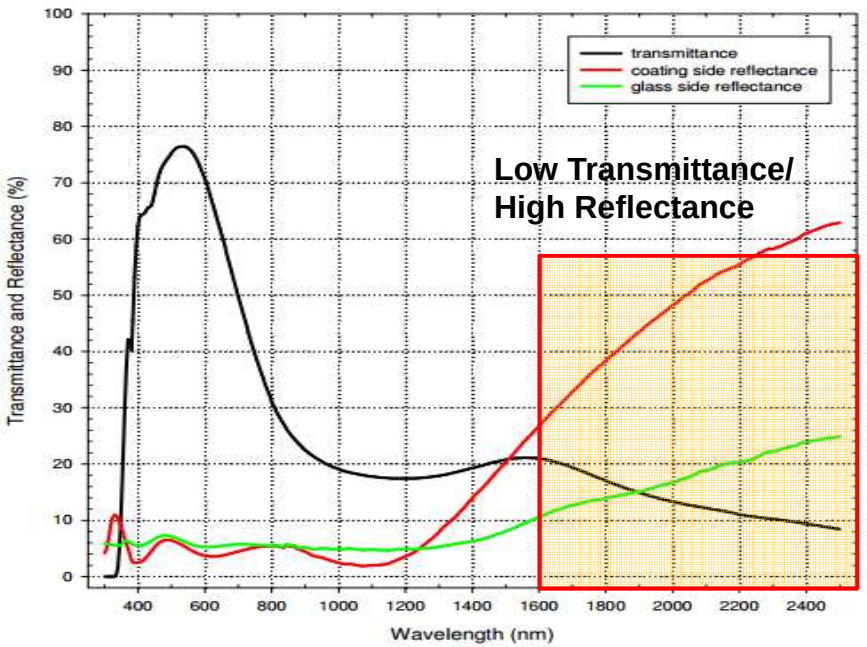
Tts = Total solar transmittance.
Tds = Direct solar transmittance.
Qi = Solar absorbance re-radiated into the vehicle.

Efficient Glazing Concepts

BASELINE – Standard Front Side Windows



PROTOTYPE – LowE Front Side Windows



- **Solar load into the cabin is significantly reduced with low emissivity (LowE) coating.**
- **LowE coating is typically placed on the inside of the glass, so that most heat is emitted to the outside of the glazing (ambient side).**
- **Infra-red reflective (IRR) coatings reflect Infra-red radiation away from the inner surface of the glass.**

Efficient Insulation Concept

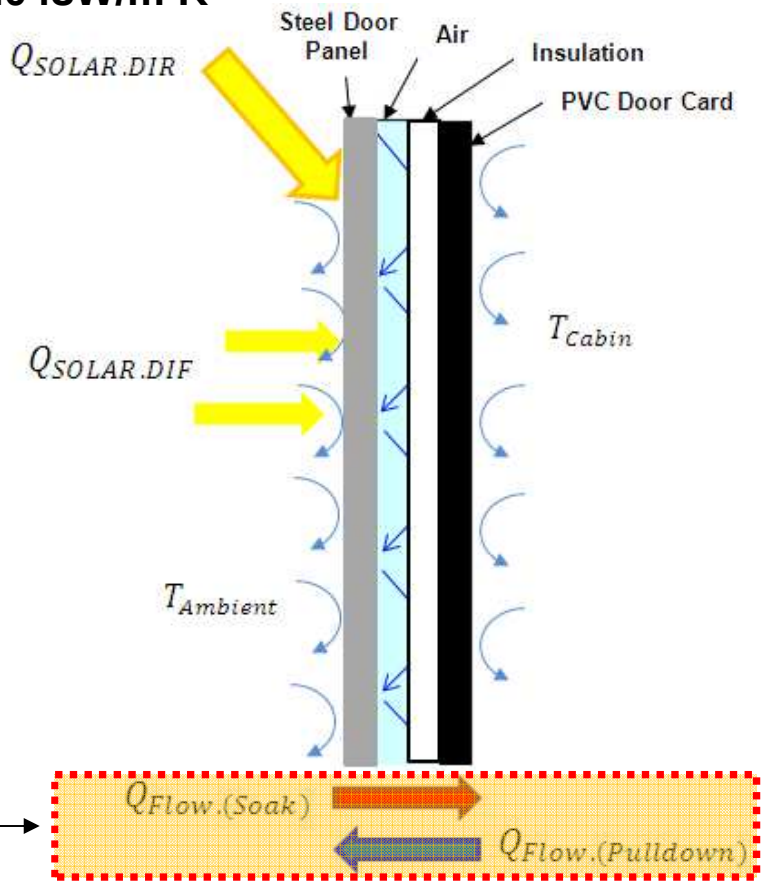
- **The effect of thermal insulation is to reduce temperature variations in the cabin.**
- **Expandable Polypropylene (EPP) used as insulation material.**
- **EPP has very low Thermal Conductivity 0.038-0.043W/m²K**

Material	K (W/m².K)	Cp (Kj/kg.K)	ρ (kg/m³)
Steel Door Card	52	0.49	7850
Insulation (EPP)	0.004	1700	2230
PVC Door Card	0.16	900	1300-1450
Air	0.0271	1.0	1.1-1.4

The main goal of the insulation is to:

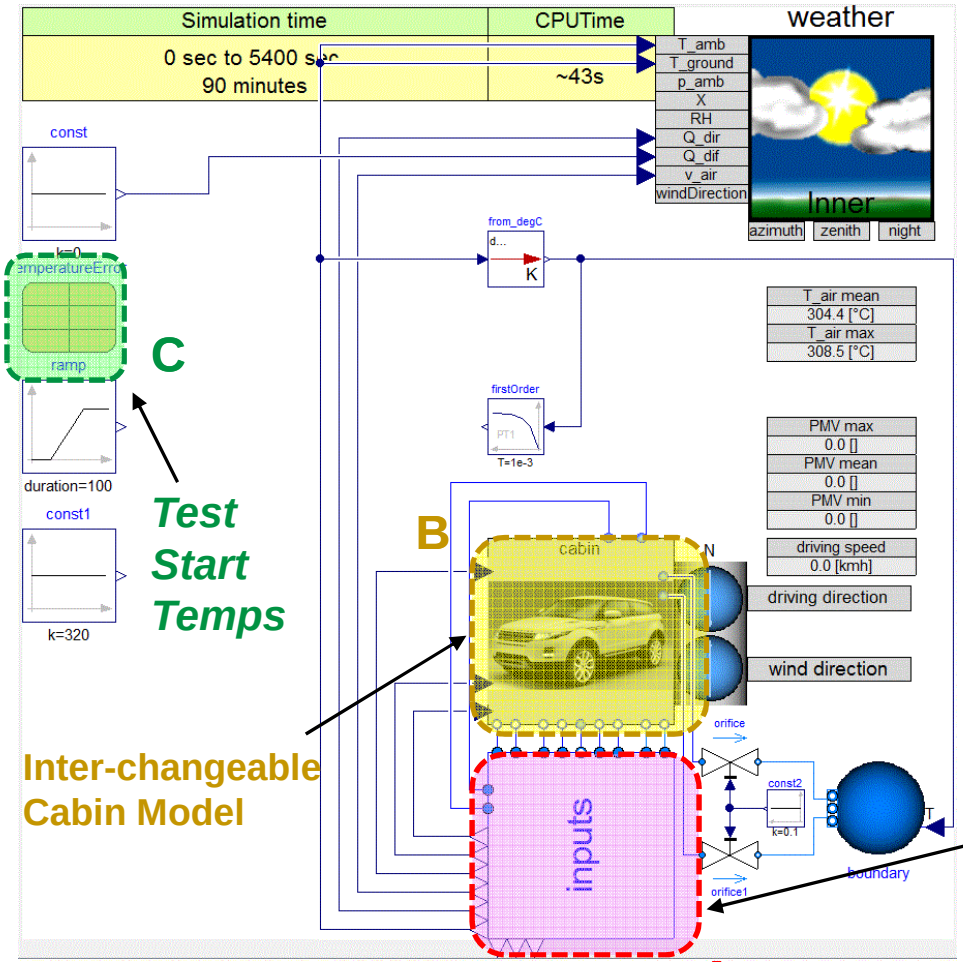
- Prevent radiant heat entering the cabin through the panels/walls.
- Contain cabin heat from a warm-up condition during cold ambient temperatures.

- During soak conditions heat transfer goes from outside to inside.
- During pull-down heat transfer goes from cabin to outside.

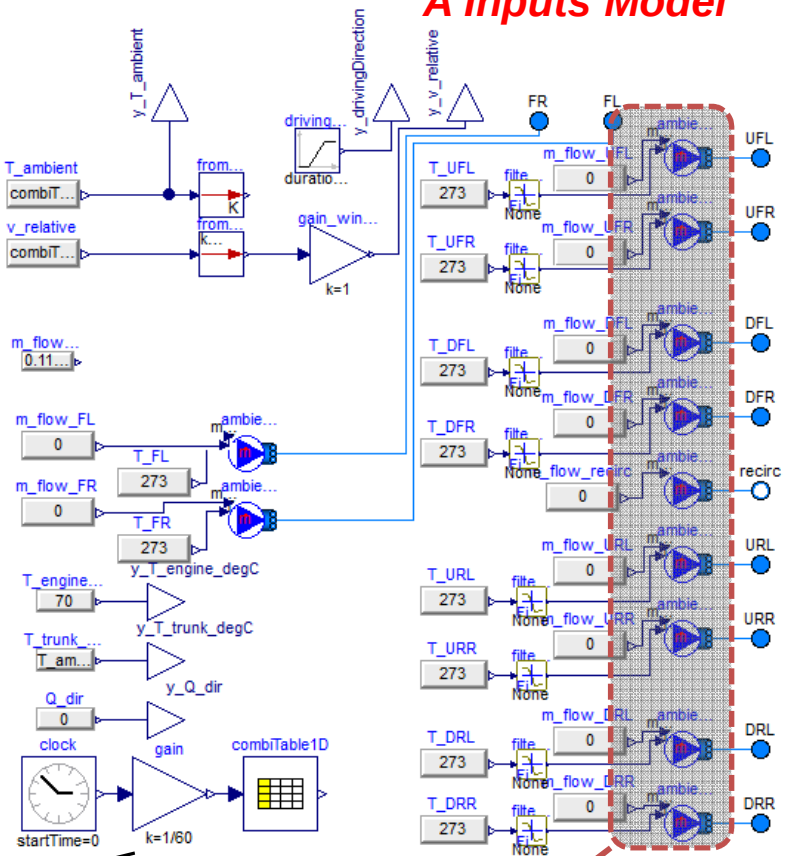


Modelling the Cabin

Experiment Model



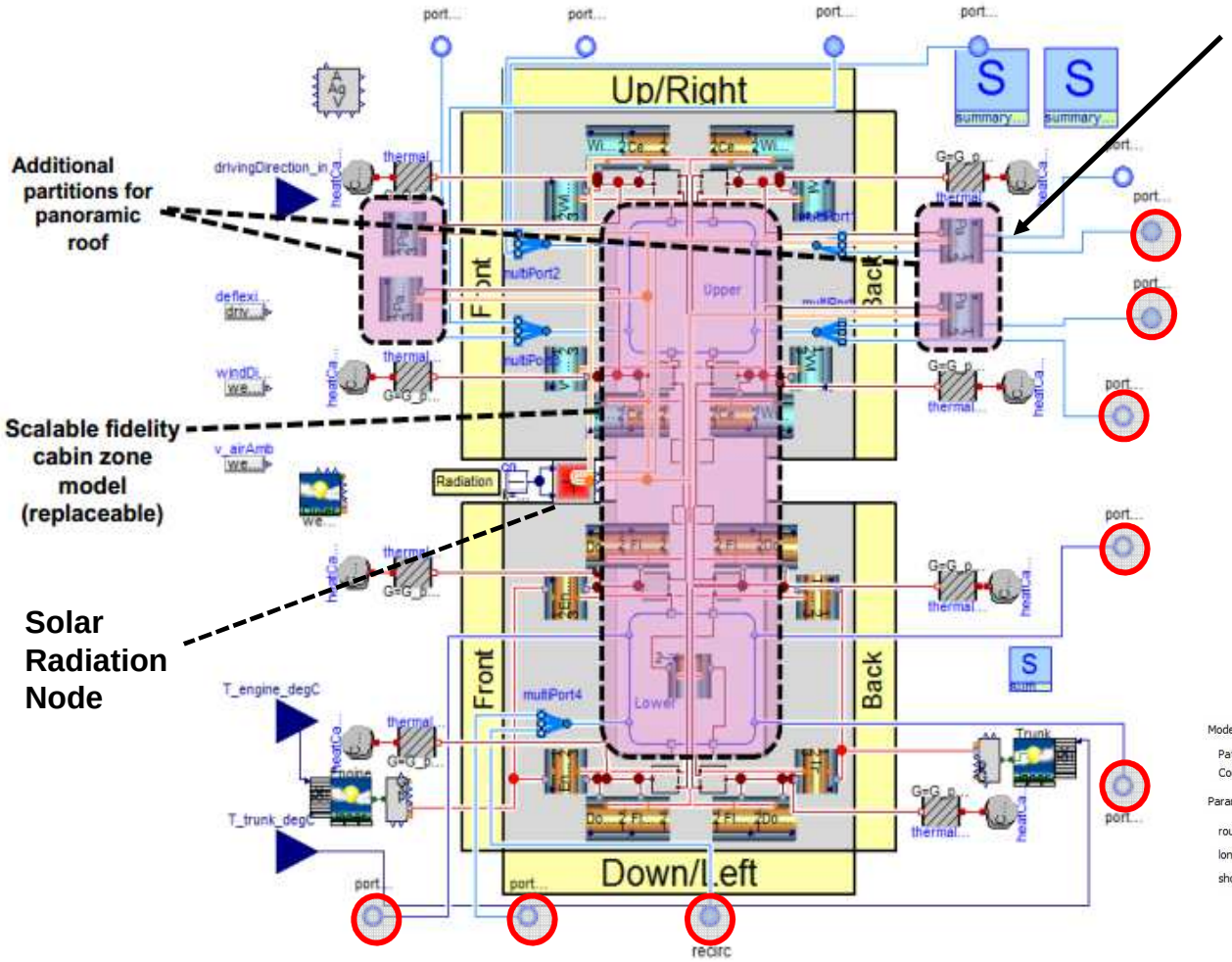
A Inputs Model



Test data fed into relevant zones of the cabin

Creating a Physical Cabin Model

B Scalable Cabin Model



PARTITION DATA

Model
Path HumanComfortLib.Zones.Fundamentals.Records.Partition.LayerSetup.AutomotiveCabinHull
Comment
Parameters

n	4		Number of layers
s	{0.75,145,0.75,2.5}	m	Layer thickness
material	{1,2,1,3}		Layer material

Materials

material1	redeclare SteelDoorPanel material1
material2	Air(...)
material3	redeclare PlasticDoorTrim material3
material4	MaterialBase(...)

Model
Path HumanComfortLib.Zones.Fundamentals.Records.Partition.LayerSetup.Material.Glass
Comment
Parameters

lambda	0.86	W/(m.K)	Thermal conductivity
d	2300	kg/m3	Density
c	780	J/(kg.K)	Specific heat capacity

Model
Path JLR_HVAC.CabinModelling.DataRecords.Materials.L538.Ceiling.Base_glazing.SingleGlazedGreen_2_1mm_PanoRoof
Comment Surface characteristic for 2. 1mm green single glazed L538 panoramic roof - Base
Parameters

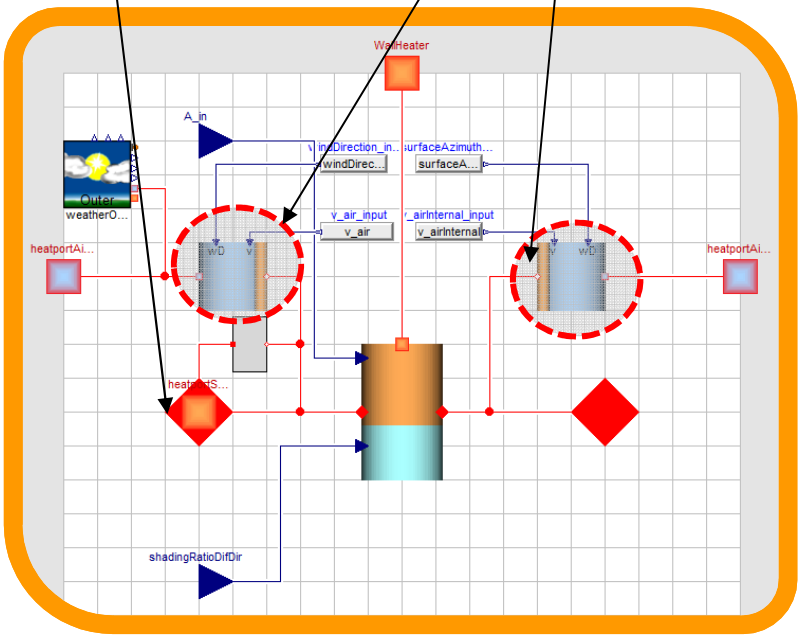
roughness	IdealSmooth_Glass(...)	Surface roughness
longWaveRadiation	Glass(...)	Long wave emission
shortWaveRadiation	SingleGlazedClear_3mm(...)	Short wave radiation absorption

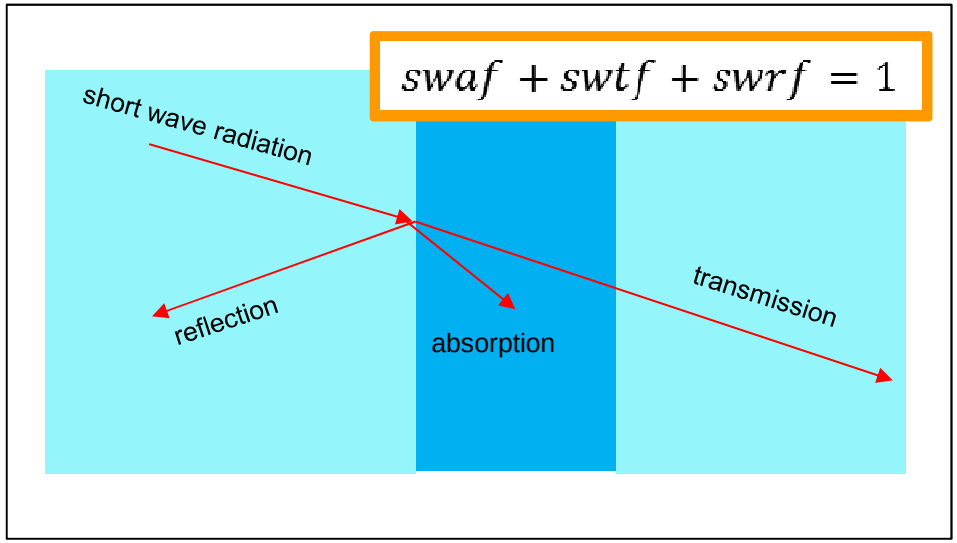
Modelling the Glazing

Solar radiation: transmittance, absorption, reflectance and emissivity factors: lwef, swaf, swtf

Convection Model for Inside and outside surfaces

Baseline Car	Type	lwef	swaf	swtf
Front Windshield	Green Laminated	0.84	0.405	0.537
Panoramic Roof	Green Laminated	0.84	0.790	0.167
Front Side Window	Mon	0.84	0.446	0.491
Rear Side Window	Mon	0.84	0.446	0.491
Rear Windshield	Mon	0.84	0.472	0.467
Prototype Car	**Type**	**lwef**	**swaf**	**swtf**
Front Windshield	Lam/IRR	0.84	0.275	0.323
Panoramic Roof	Lam/LowE	0.21	0.931	0.0239
Front Side Window	Mon/LowE	0.21	0.528	0.417

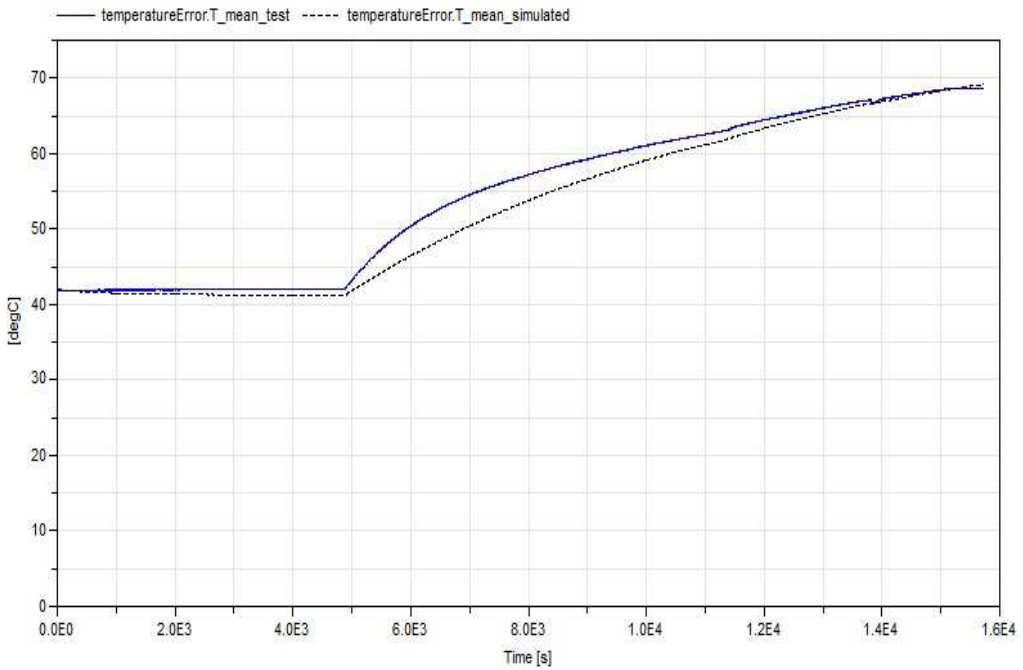


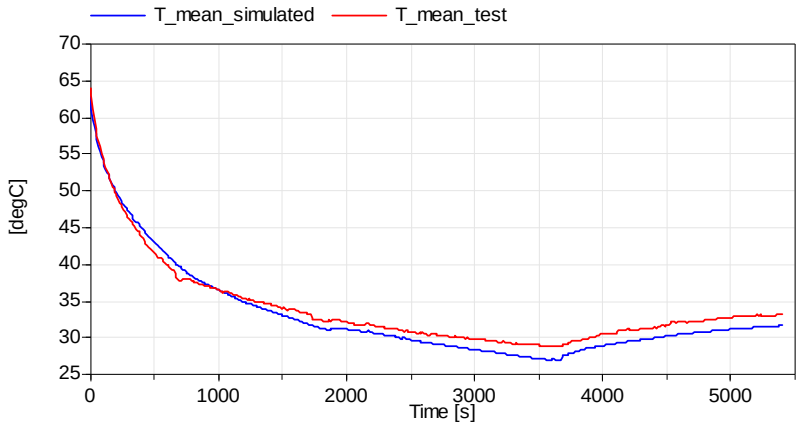


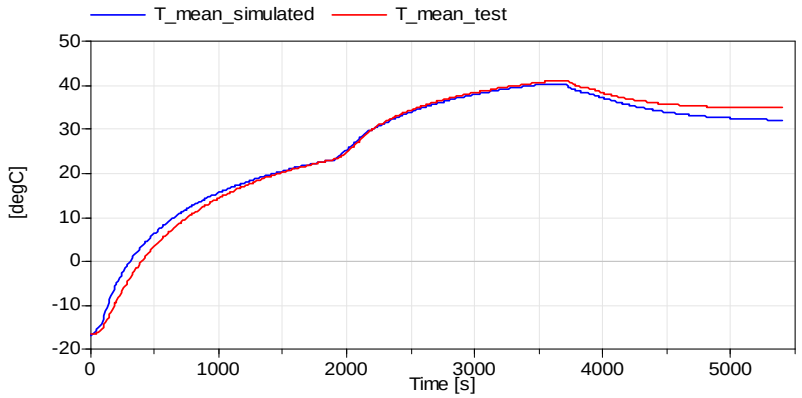
Correlating Baseline Test Data
Cabin Only (Test Inputs)

On optimisation of the thermal masses we achieve the temperature profiles shown in Figure 1.1. We achieve the following end-of-test discrepancy between the measured and simulated data:

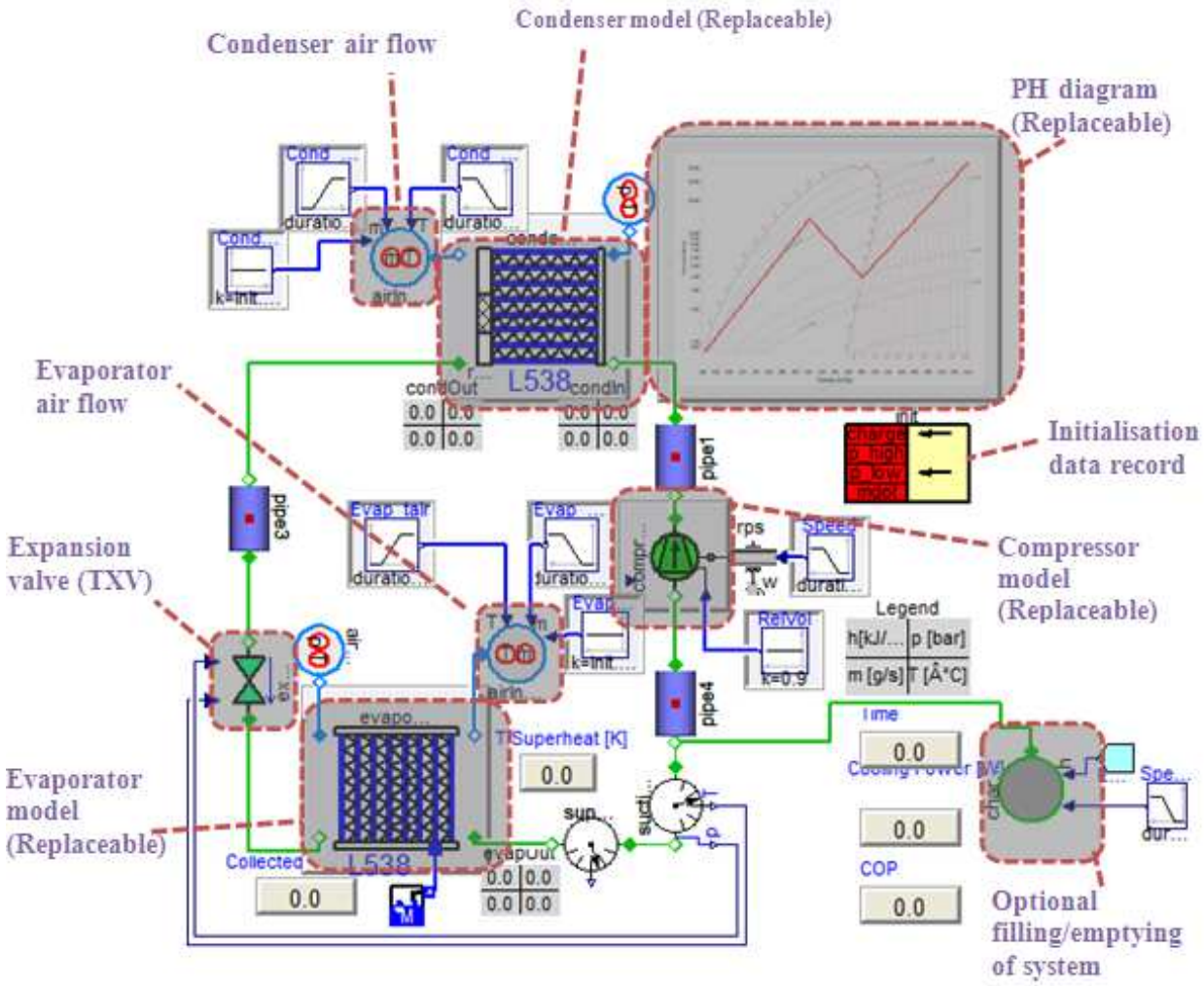
Warm up:	2.9 degC
Pull down:	1.5 degC
43degC Soak:	0.5degC







Parameterised Air Conditioning Model



AC System Components

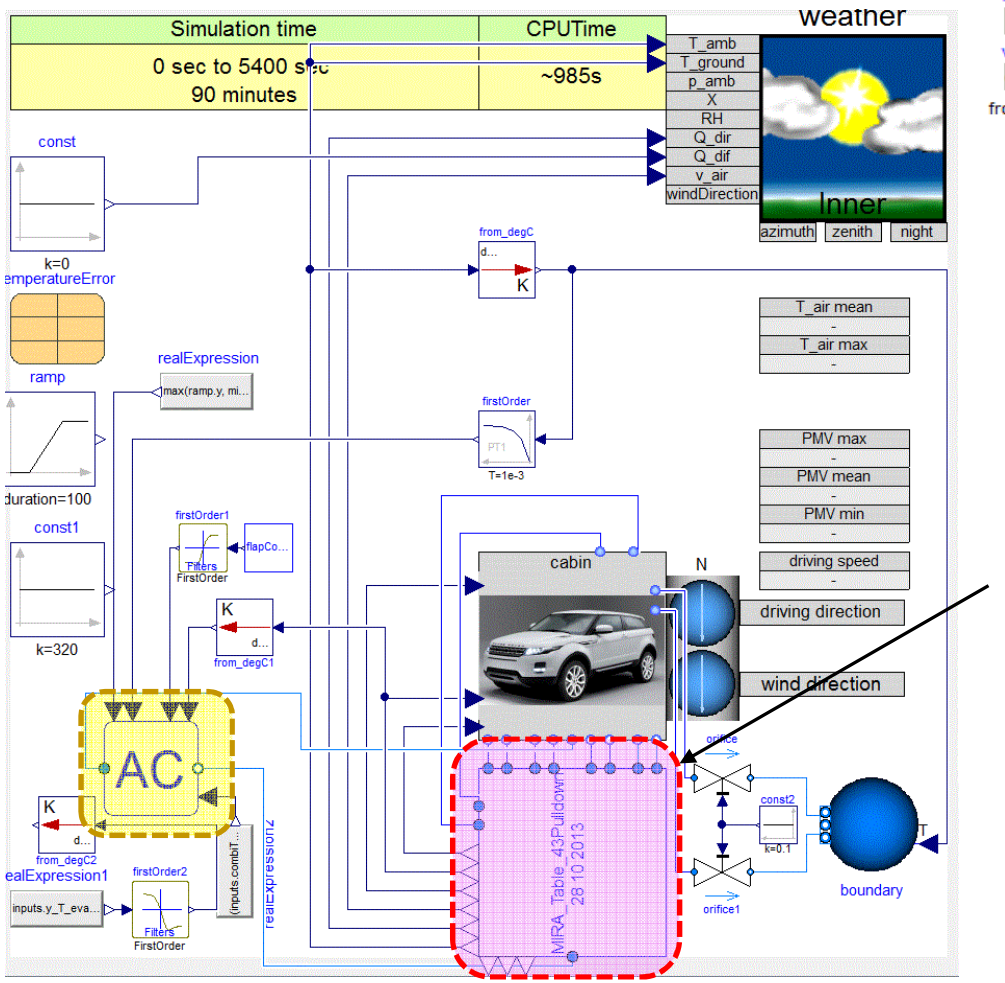
- AC Compressor
- Condenser
- Evaporator
- TXV
- Refrigerant (R134a)

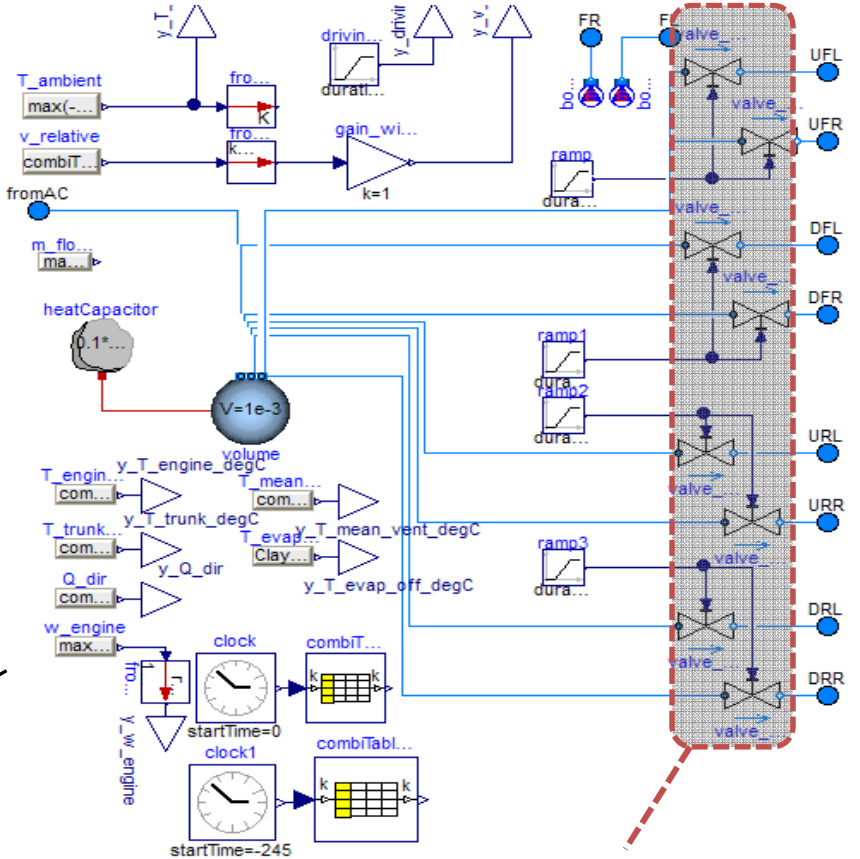
Compressor model is table based and includes:
:

- Volumetric Efficiency
- Isentropic Efficiency
- Effective Efficiency

Integrating Cabin & AC Model

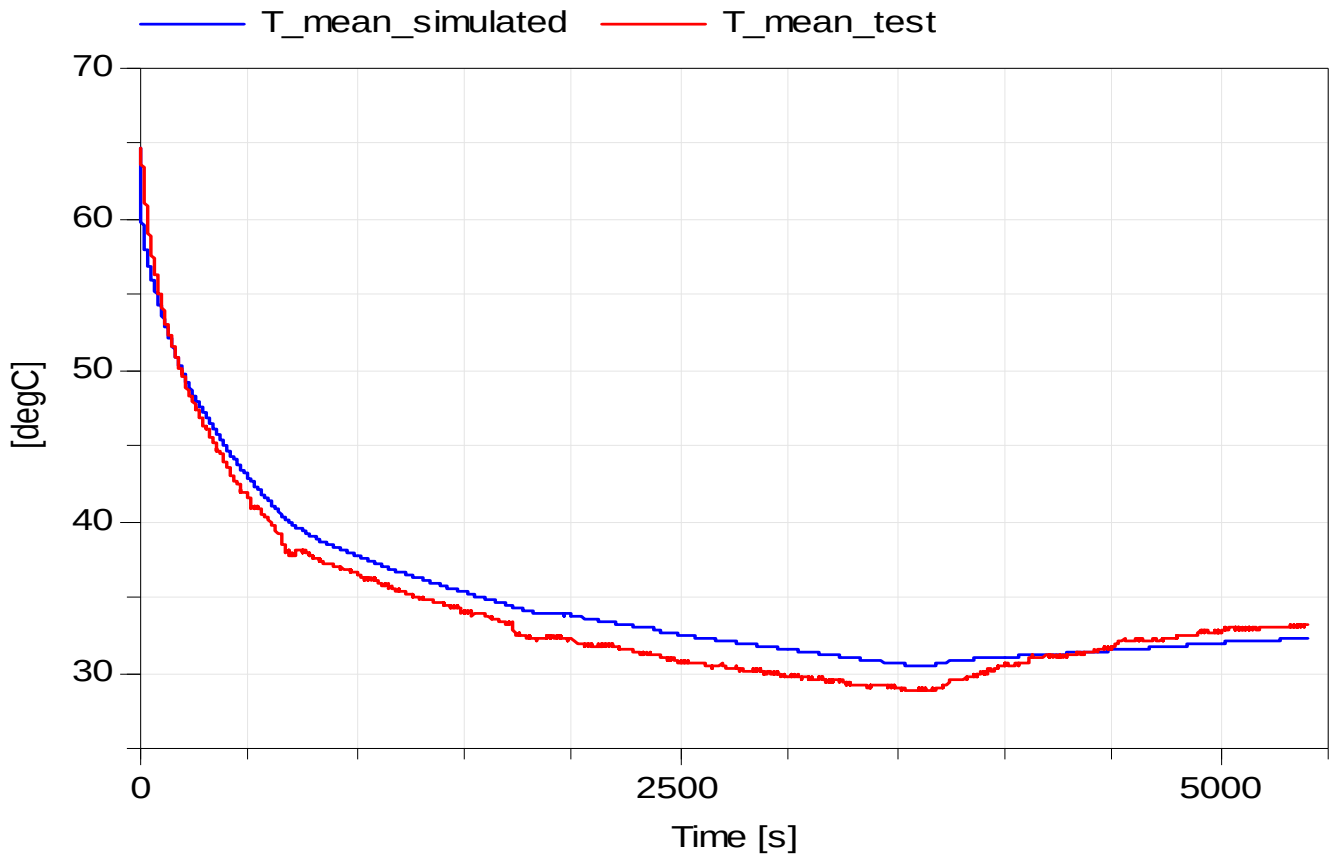
Experiment level of Integrated AC & Cabin Model





Fluid Ports from AC to Cabin (no test data).

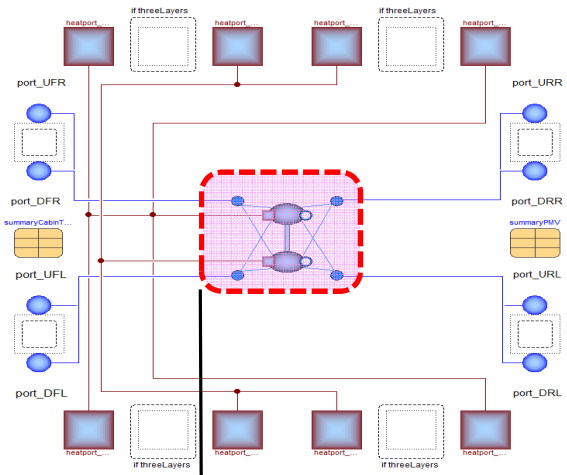
Correlating Baseline Test Data
Integrated AC loop & Cabin

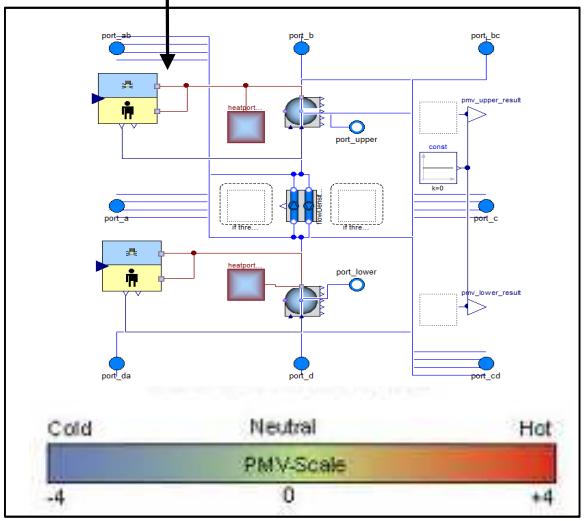


- Temperature error between test data and simulation 1-1.5°C
- Pull-down & Warm-up Tests with integrated AC & Cabin run 82% faster than real time.

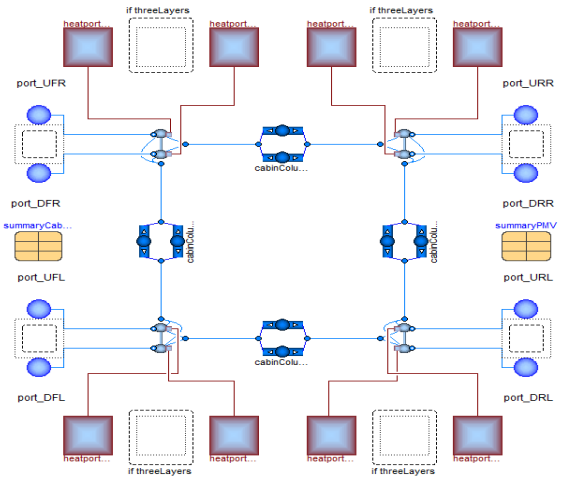
Scalable Fidelity Cabin Zones

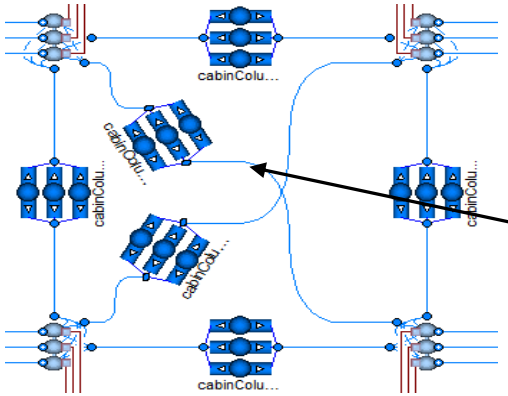
2 Zones (1 upper & lower Zone)



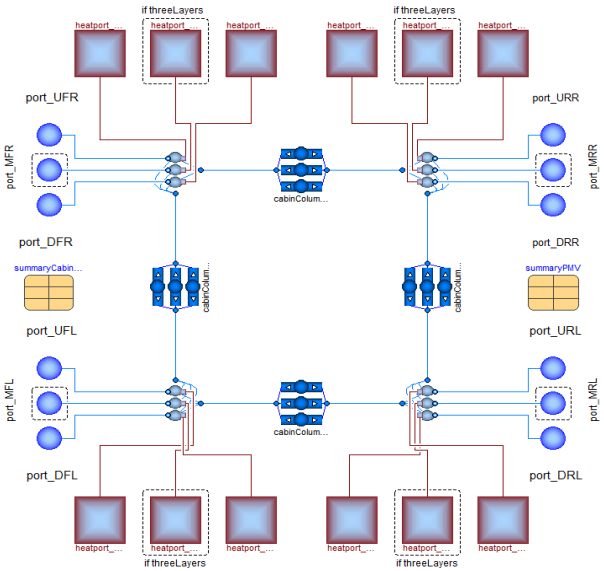


8 Zones (4 upper & 4 lower Zones)





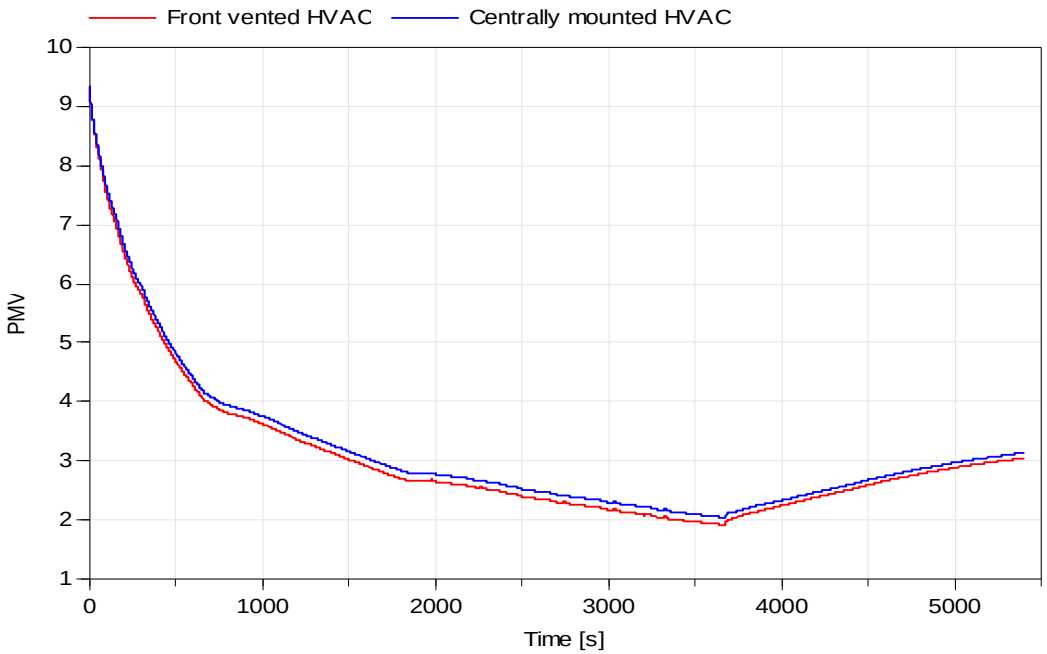
12 Zones
(4 upper, 4 middle, 4 lower Zones)

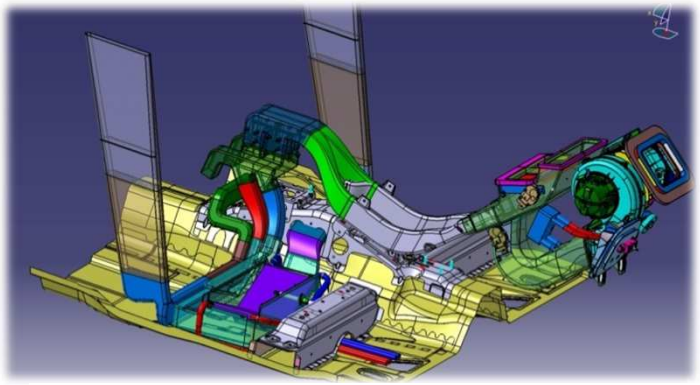


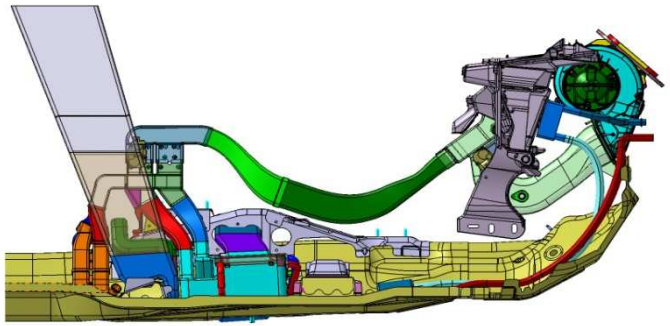
Diagonal air flow paths (front to rear) can also be applied to the cabin model.

Centrally Mounted HVAC

Plot of mean PMV for all occupants for front vented HVAC (red) and centrally vented HVAC (blue).

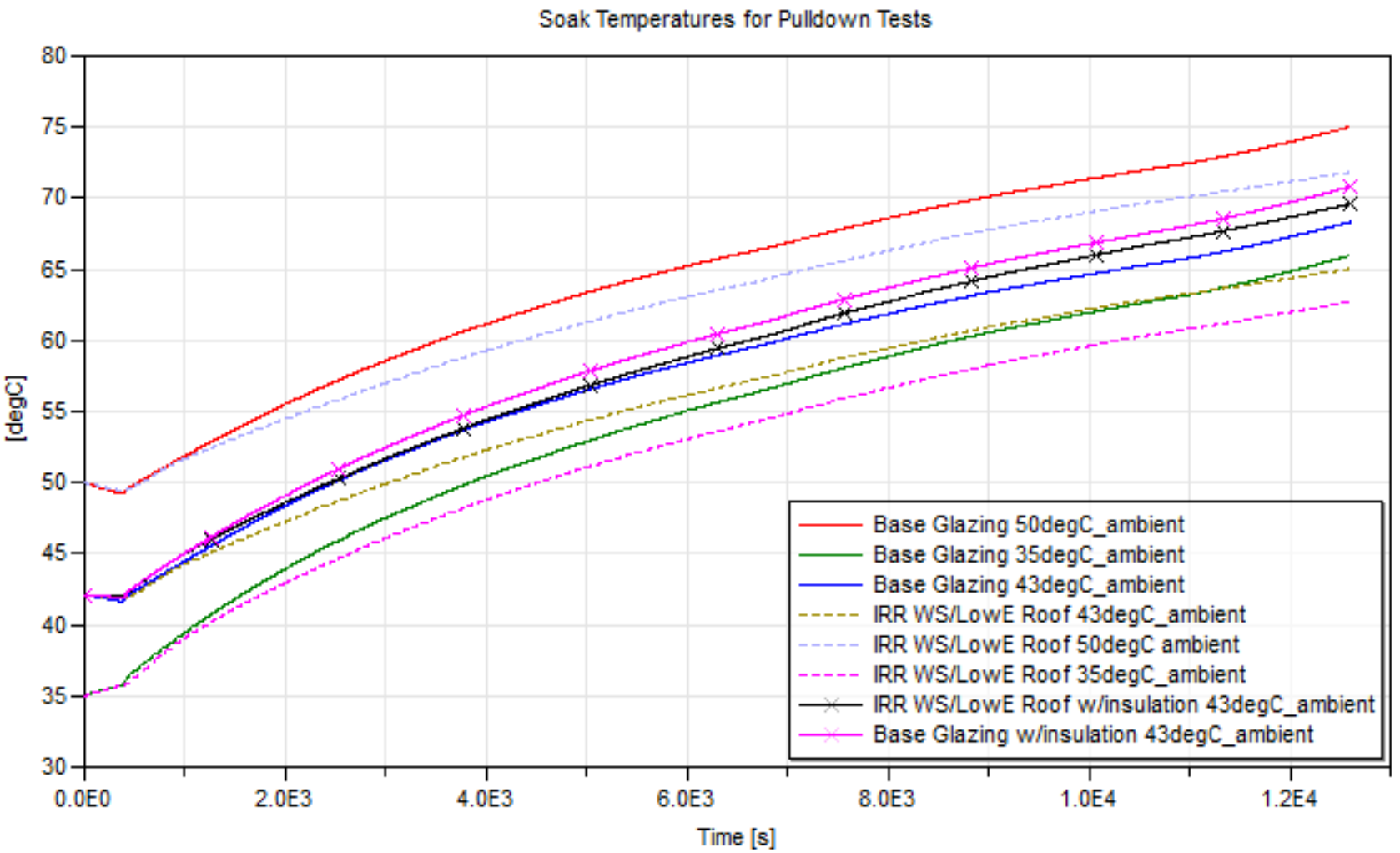




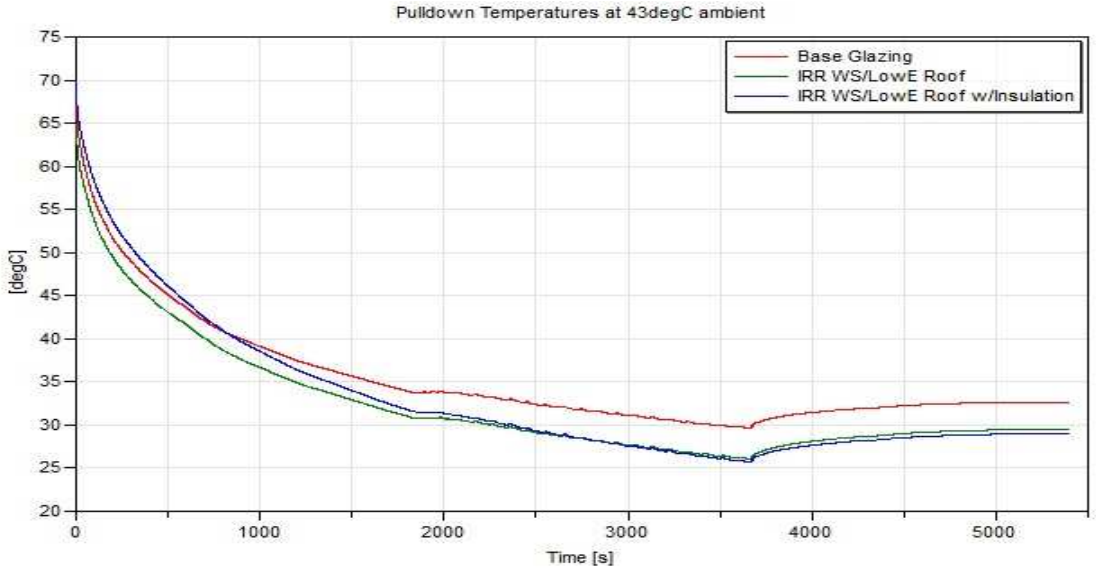


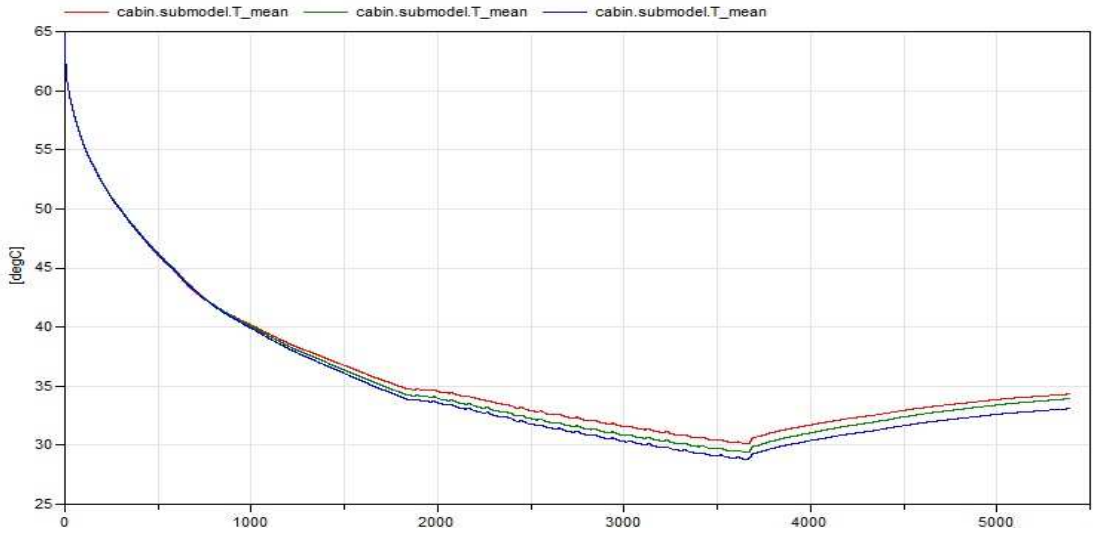
- **Centrally mounted HVAC system achieved by adding upper vents to the rear zones and re-routing the air flow to these as well as the upper front vents.**
- **Design currently showing to have minimal effect on thermal comfort, cross sectional area of the ducting is currently too large.**

Effect of Efficient Glazing on Soak Temperatures



Effect of Efficient Glazing on Pull-down Temperatures





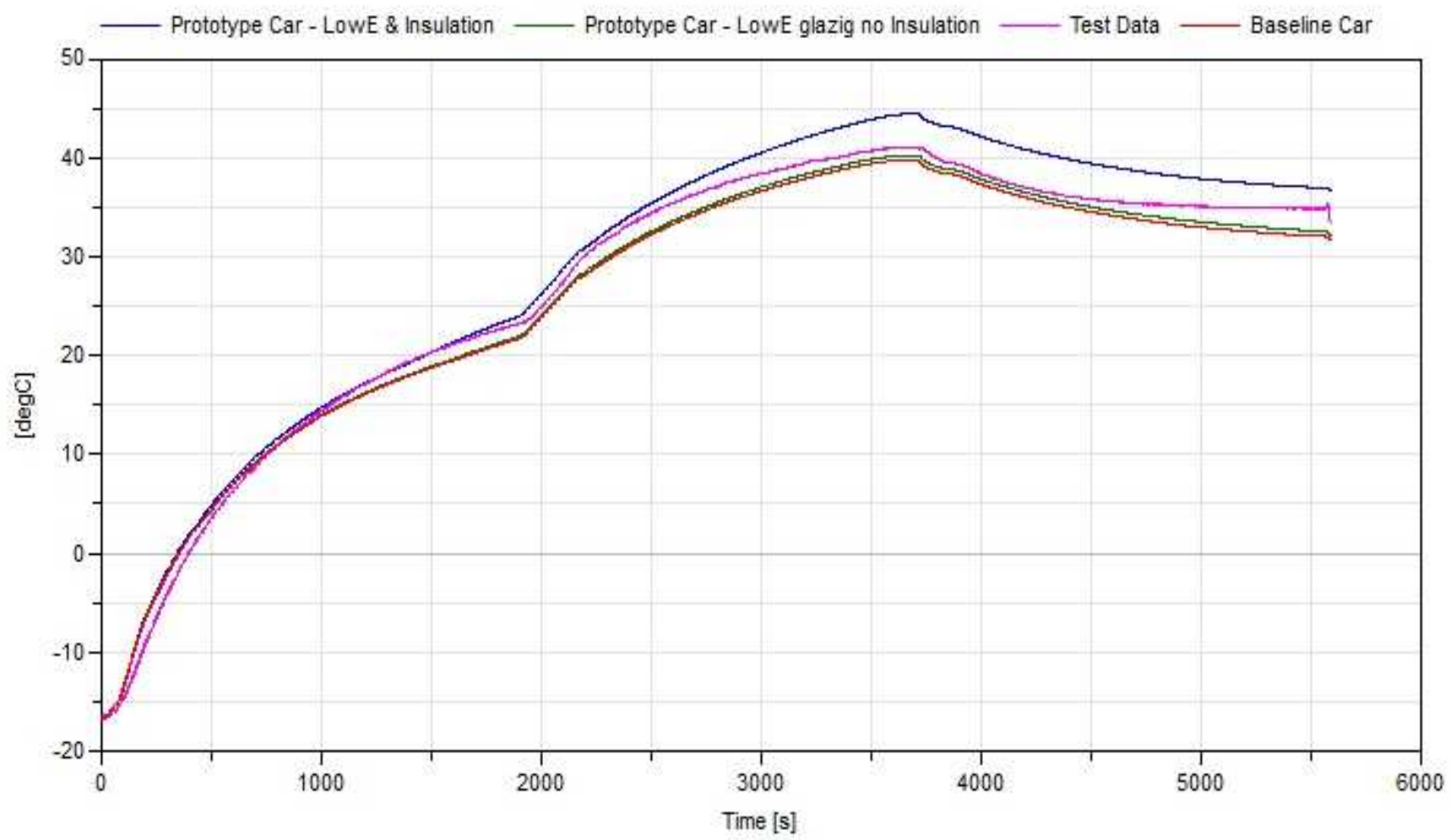
Case 1: T_Start = T_Soak(Final)

- Temperature of cabin is initialized at temperature at the end of the vehicle soak for each condition.
- Greater benefit of LowE glazing and insulation technologies in this case

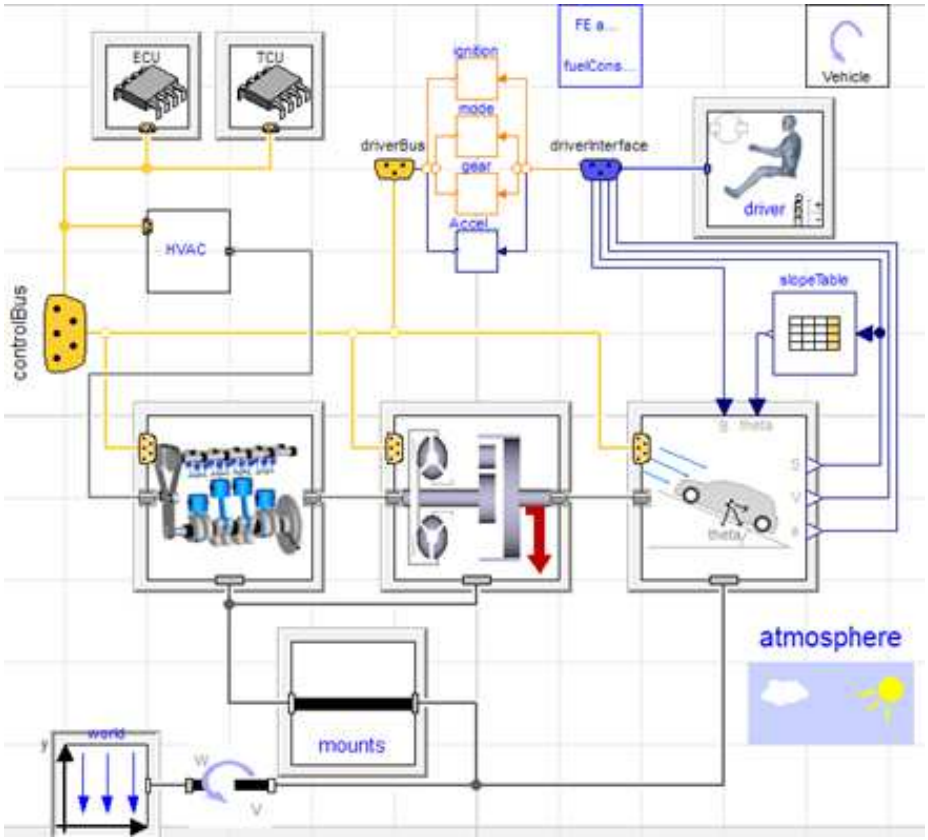
Case 2: T_Start = 65°C (Constant)

- Temperature of cabin is initialized at a fixed temperature at the start of the test
- Reduced benefit of LowE glazing and insulation technologies in this case, this would apply when soaking to a fixed temperature.

Effect of Efficient Glazing on Warm-up Temperatures



Vehicle Model



Baseline Results

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

Driver Model:
The driver model feeds in the test cycle profile, required accelerator pedal position and required brake pedal position to the control bus.

Engine Model:
Table based and uses MEP and BSFC table data to calculate the fuel flow which is dependent on throttle angle

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:
Simplified model which includes the final drive ratio, friction brakes, wheels, vehicle mass, car resistance (including aero and rolling resistance)

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.

Conclusions & Next Steps

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 pull-down, 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 cabin model with integrated AC loop correlates well with the baseline with 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 pull-down.

Future Targets

- Conclude Fuel Economy Benefits of Glazing and Insulation Technologies.
- Benefit of Cabin Air Re-Circulation on HVAC energy reduction.
- Effect of heated contact surfaces on energy consumption and thermal comfort.

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