EXPERIMENTAL INVESTIGATION OF CAR CABIN ENVIRONMENT DURING REAL TRAFFIC CONDITIONS

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In the paper, the authors refer to measurement of a car cabin heat load and indoor environment during driving in real traffic conditions. The primary aim was to obtain data for boundary conditions, model testing and results comparison of the 1D car cabin heat load model. The secondary aim was better understanding of cabin environment inside a car cabin under different operational conditions. As test vehicle Škoda Felicia Combi with dark blue painting was used and GPS data, parameters of ventilation, cabin environment and ambient environment were measured. Measurements were preformed for summer, autumn and winter conditions including parking and driving test circuits around Brno. Driving circuit included driving in the city, out of the city and on the highway D1.

Keywords: *car cabin environment, real traffic measurement, cabin heat load, 1D simulation*

1. Introduction

A car cabin environment is result of heat and mass transfer between cabin, ambient environment, ventilation air and persons seated in the cabin [1, 2]. The transfer of heat is realized by radiation (longwave/shortwave), conduction (throught the cabin walls) and convection. The moisture is transfered by supplied air and the other source is evaporation from persons inside the cabin [3]. The presented 1D model is designed to simulate thermal behaviour of a car cabin during real operational conditions. The model was implemented in Modelica language, which allows using a causal programming and the scheme in the Fig. 1 shows main interfaces, important data parameters and main inputs and outputs of

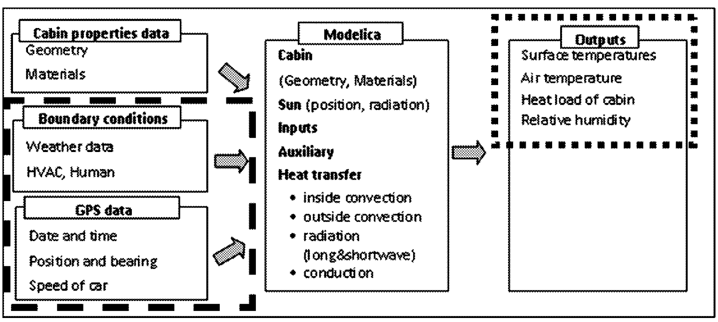

Fig.1: Flowchart of the car cabin model – input data (dashed box) and data for results comparison (doted box) obtained from real traffic measurements are highlighted

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the model. Heat loads of the car cabin depend on the weather data, HVAC system setup and on the position and bearing of the car (GPS data). These data are used by the model to calculate heat transfer inside and outside the car cabin, surface temperatures of the cabin exterior and interior, cabin air temperature, cabin air relative humidity and heat loads.

For testing of model functionality, comparison and validation of model outputs/results the measurements of the real car cabin environment was performed. The main purpose of the investigation was to obtain two groups of the data. The first group represents all data used as boundary conditions of the model (see Fig. 1 – dashed line box) and the second one represents data which characterized cabin environment and cabin heat load (see Fig. 1 – dotted line box).

2. Test car and measurement equipment

As test vehicle Škoda Felicia Combi with dark blue painting was used (see Fig. 2). The car was equipped by sensors which were divided into groups based on purpose of measured parameters. Placements of the sensors are marked by white numbers in Fig. 2, for a detailed description of used sensors see Tab. 1. Boundary conditions for simulations included measurement of weather conditions (ambient air temperature, air humidity and solar intensity), temperature of air from HVAC system, air temperatures in the trunk, the engine space and ambient air temperature under the car. Other sensors collected data for validation of the model predictions and they were split into two groups. The first one included sensors which measured surface temperatures and the second one included sensors which measured cabin environment (these sensors were located on the co-driver and the left rear seat).

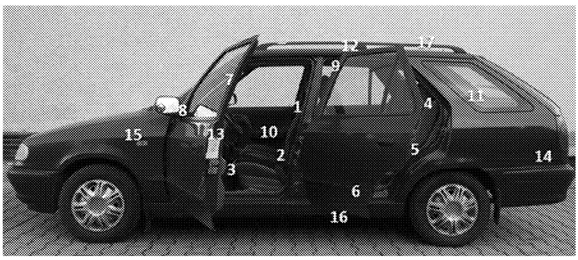

Fig.2: The test vehicle Škoda Felicia – numbers denotes sensor placements (see Tab. 1)

	Co-driver front seat			Rear seat on the left			Exterior and interior surfaces						Boundary conditions				
	Head	Torso	Feet	Head	Torso	Feet	Windshield	Dashboard	Roof int.	R. door int.	R. glass int.	Roof ext.	Outlets	Trunk	Engine space	Under car	Weather
Measured location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Air temperature	C	C	T	P	P	P	–	–	–	–	–	–	T	T	T	T	C
Surface temperature	–	P	–	–	–	–	P	P	P	P	P	T	–	–	–	–	T
Air velocity	C	–	–	–	–	–	–	–	–	–	–	–	C	–	–	–	–
Relative humidity	C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	C
Globe temperature	G	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Solar intensity	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	V

Tab.1: Sensor placement and measured quantities: C – Testo with combined probes, G – globe thermometer, P – resistance thermometer PT100, T – thermocouple, V – photovoltaic (PV) panel

The connection of sensors, Testo loggers, Programmable logic controller ELSACO and notebook Acer is shown in Fig. 3. Most of the sensors were connected with loggers and PLC by wires, but for measurements in inaccessible spaces (the trunk, engine space etc.) and for measurement on the car roof, wireless data transmission equipment was used.

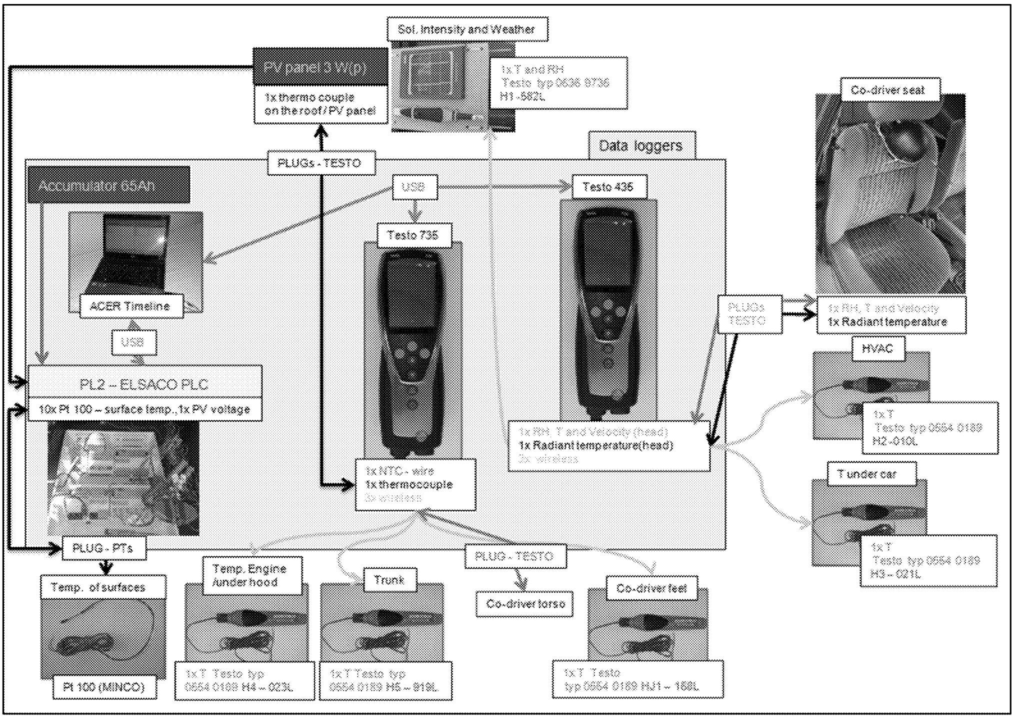

Fig.3: Schematic connection of measurement equipment

The position, bearing, speed and altitude of the car was measured by cell phone Nokia 6220 equipped with an internal GPS module and Sports tracker software was used for data logging. All data from measurements were synchronized by time code and post processed in Excel sheet with Visual Basic macros.

3. Main results from test circuit measurement

Measurements were performed for summer, autumn and winter conditions including parking and driving test circuits around Brno. Driving test circuit included driving in the city, out of the city and on the highway D1. The main results from parking test cases were presented in the paper [1]. Following paragraphs are focused on the main results of autumn and winter driving tests and data are presented in form of graph and averaged values to provide an overview about measurement results.

3.1. Autumn test circuit – 13. 10. 2011

The first group of data describes boundary conditions. The weather conditions during autumn driving test were dry and cloudy. Solar intensity on the horizontal plane (roof) was from 95 to 550 W/m^2, ambient air temperature (measured on the roof) was from 11 to 15 °C (see Fig. 4) and relative humidity was 60 %. Maximal speed of the car was 111 km/h (the test circuit included highway D1) and average speed was 58.1 km/h (see Fig. 4), the route led from Brno to Vyškov and back.

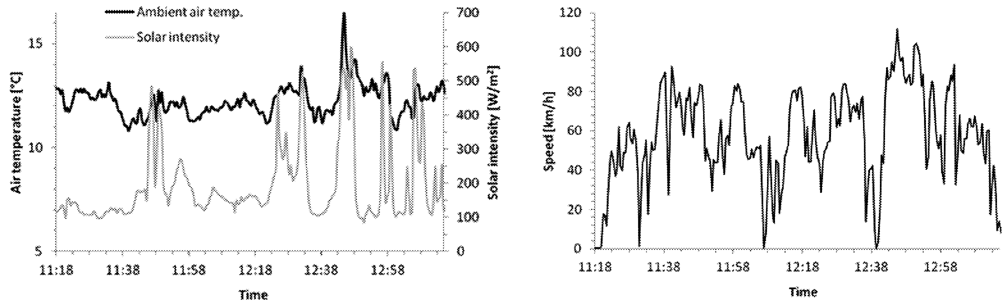

Fig.4: Ambient air temperatures and horizontal solar radiation (on the left) and car speed (on the right) – autumn driving test

During driving circuit the car cabin was occupied by two persons, the ventilation was switched on and the fan controller was set up on the 2nd level. The air was distributed to the cabin from middle outlets with the horizontal direction of outlets flaps and from the defrost outlet under windshield. Average volumetric flow of ventilation air was 27.3 l/s and its temperature started on 21 °C and oscillated from 23 to 31 °C (see Fig. 5). The oscillation of temperature and volumetric flow of ventilation air is connected with actual car speed, engine power and intensity of solar radiation.

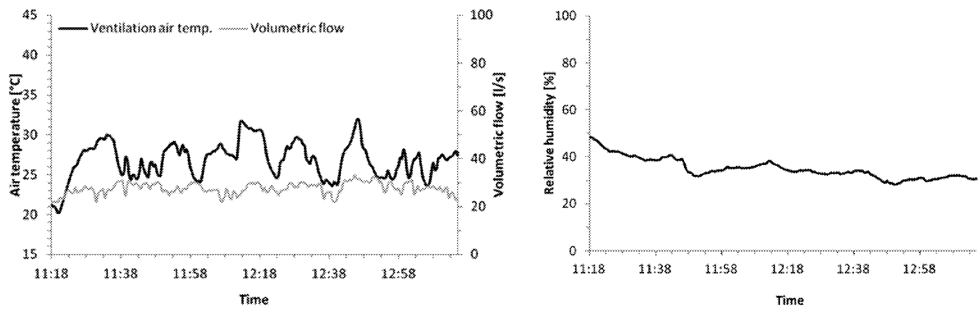

Fig.5: Ventilation air temperature and volumetric flow (on the left) and relative humidity in the cabin(on the right) – autumn driving test

Air velocities at outlets were about 3.0 m/s, however far from the outlets air velocities was much lower, at the head level of co-driver it was 0.11 m/s. Due to the fact that the primary flows were non isothermal and cabin environment was affected by intermittent solar loads air temperatures in the cabin oscillated between 20 and 30 °C (see Fig. 6). From the figure can be seen that, the head-feet temperature difference at star (time 11:25) was about 4.1 °C for co driver seat and dropped to the 2.5 °C (time 12:30) as result of air mixing inside the cabin. There is also seen difference between responses to heating at feet level against head and torso level. The response at feet level was slower and it took more than half of hour to reach the value close to torso temperature.

Other boundary conditions were: air temperature under the car 17.5 °C, in the engine space 23.5 °C and in the trunk 17.4 °C. Air temperature in the trunk was lower than in the

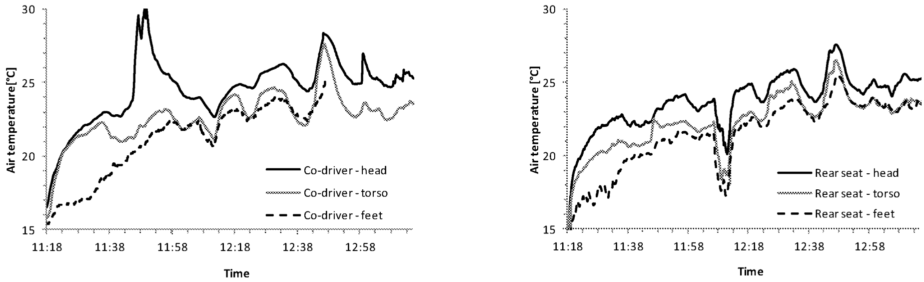

Fig.6: Air temperatures inside cabin at the co driver seat (on the left) and at the rear left seat (on the right) – autumn driving test

cabin because the space of the trunk was covered by shell thus the cabin-trunk circulation of air was very low.

The second group of data was used for comparison and validation of the model results (see Fig. 5 – on the right and Fig. 7) :

- Relative humidity inside cabin 27 % (at co-driver's head)
- Surface temperature of cabin exterior : roof 16.0 °C
- Surface temperatures of cabin interior : roof 23.0 °C, seat 22.3 °C, right side door 20.1 °C, dashboard 24.5 °C, right side window 17.1 °C and windshield 17.4 °C

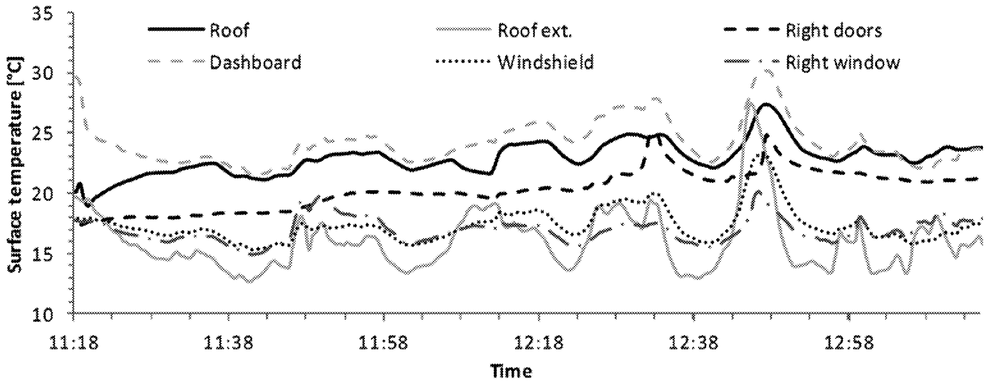

Fig.7: Surface temperatures – autumn driving test

The coldest interior surfaces were windows, due to the low thermal resistance of glass and part with highest temperature was dashboard affected by solar radiation. The temperature of exterior surfaces and interior glassed surfaces was result of combination of car speed and intensity of solar radiation. For example, the temperature of roof exterior dropped after start from initial temperature 20 °C to the 8 °C in 20 minutes mainly due to higher outside convection caused by higher car speed, but also reflect intensity of solar radiation (peeks in graph).

3.2. Winter test circuit – 26. 1. 2012

The first group of data describes boundary conditions. The weather conditions during winter driving test (26th January) were cold and dry, the sky was overcast. Solar intensity on the horizontal plane (roof) was 48 W/m^2, ambient air temperature was 0.5 °C (see Fig. 8

on the left) and relative humidity 57 %. Maximal speed of the car was 86.8 km/h and average speed was 54.6 km/h, the route led from Brno to Vyškov and back (see Fig. 8 on the right).

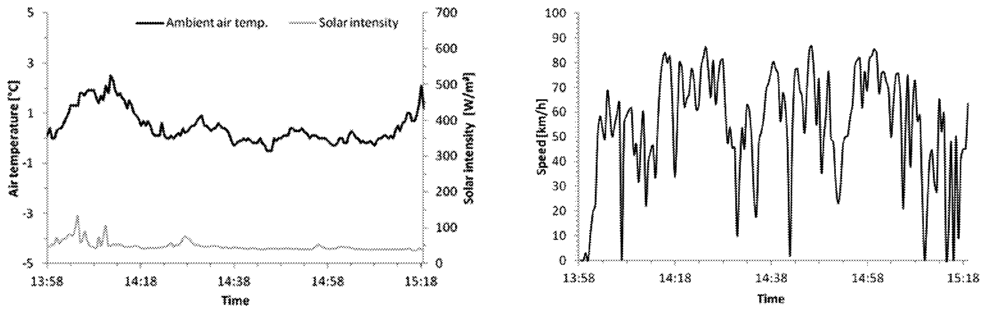

Fig.8: Ambient air temperatures and horizontal solar radiation (on the left) and car speed (on the right) – winter driving test

During driving circuit the car cabin was occupied by two persons, the ventilation was switched on and the fan controller was set up on the 2^{nd} level. The air was distributed to the cabin from middle outlets with the horizontal direction of outlets flaps and from the defrost outlet under windshield. Volumetric flow of ventilation air was 27 l/s and its temperature started on 10 °C and after 10 minutes it value was stabilized on 36 °C (see Fig. 9).

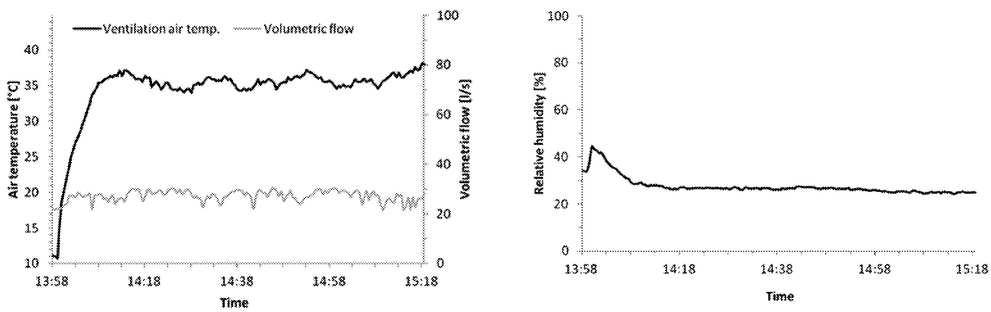

Fig.9: Ventilation air temperature and volumetric flow (on the left) and relative humidity in the cabin(on the right) - winter driving test

Air speeds at outlets were about 3.3 m/s, however far from the outlets air speed was much lower, at the head level of co-driver it was 0.13 m/s. Due to the fact that the primary flows were non isothermal and strongly affected by buoyancy the strong vertical air temperature difference was observed at the beginning of the test (see Fig. 10). From the figure can be seen that, the head-feet temperature difference dropped from 11.4 °C (time 14:10) to the 5 °C (time 15:18) as result of air mixing and temperature stratification inside the cabin. There is also seen significant difference between responses to heating at feet level against head and torso level. The response at feet level was very slow and it took more than one hour to reach the stable value close to 16 °C. In contrary at torso and head level the response time was quite short; the air temperatures reached stable values in few minutes after stabilization of ventilation air temperature. Since only central and defrost outlets were opened, the main stream flowed between front seats to the rear seat. From this reason the response time was shorter in case of rear seat against co-driver seat.

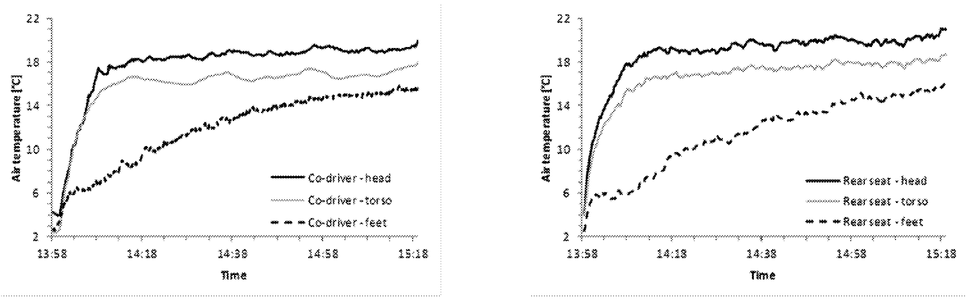

Fig.10: Air temperatures inside cabin at the co driver seat (on the left) and at the rear left seat (on the right) – winter driving test

Other boundary conditions were: air temperature under the car 5.5 °C, in the engine space 11.3 °C and in the trunk 5.6 °C. Floor and firewall are obviously well insulated, thus temperature in engine space and under the car have not great impact to the cabin environment. Air temperature in the trunk was much lower than in the cabin because the space of the trunk was covered by shell thus the cabin-trunk circulation of air was very low.

The second group of data was used for comparison and validation of the model results (see Fig. 9 – on the right and Fig. 11):

- Relative humidity inside cabin 27 % (at co-driver's head)
- Surface temperature of cabin exterior: roof 2.2 °C
- Surface temperatures of cabin interior: roof 18.5 °C, seat 15.8 °C, right side door 11.4 °C, dashboard 14 °C, right side window 7.1 °C and windshield 6.1 °C

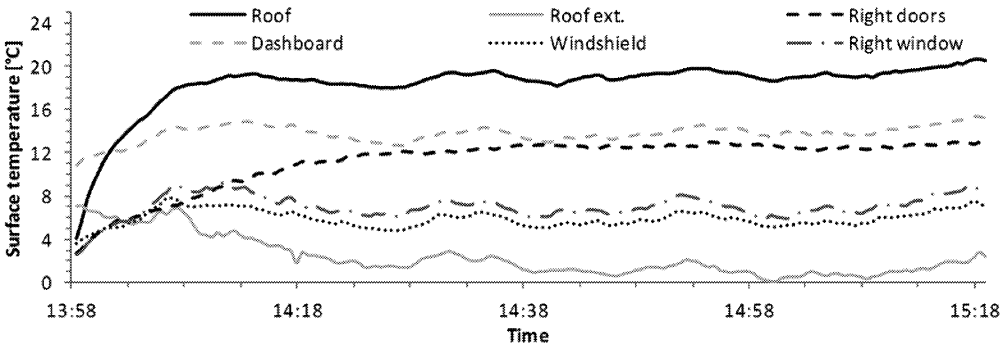

Fig.11: Surface temperatures – winter driving test

During winter driving circuit the coldest interior surfaces were windows, due to the low thermal resistance of glass. The temperature of exterior surfaces and interior glassed surfaces was dependent on the car speed. For example, the temperature of roof exterior dropped after start from initial temperature 7 °C to the 1 °C in 30 minutes mainly due to higher outside convection caused by higher car speed.

4. Conclusions

The mobile measurement system was designed for measurements of boundary conditions and car cabin environment during real driving tests. Measurements presented in the paper were performed in the real traffic conditions and revealed main characteristics and behaviour of cabin environment. From obtained data authors concluded that the car cabin environment is strongly affected by ambient environment and especially solar radiation is parameter with high impact on cabin heat load. Temperature of exterior surfaces and interior glassed surfaces depends mainly on combination of the car speed, intensity of solar radiation and ambient temperature. During winter test the strong vertical temperature stratification was observed and the mixing between head and feet level space was very low. That was main reason for very slow response of temperature of air at feet level to heating when it took more than one hour to reach the stable temperature. Together with results presented in the paper [4] authors collected the set of data for testing, calibration and results comparison of 1D car cabin model, which is designed for prediction of car cabin environment.

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References

[1] Wachsmuth C.U.H.: Precooling Strategies for Passenger Vehicles. Wolfsburg, 2009, Disertation, Nelson Mandela Metropolitan Univeristy

[2] Farrington R.B., Rugh J.P., Barber G.D.: Effect of Solar-Reflective Glazing on Fuel Economy, Tailpipe Emissions, and Thermal Comfort, National Renewable Energy Laboratory Report, Washington, 2000

[3] Zhang H., Dai L., Xu G., Li Y., Chen W., Tao W.: Studies of air-flow and temperature fields inside a passenger compartment for improving thermal comfort and saving energy, Part I: Test/numerical model and validation, In: Applied Thermal Engineering (29), Elsevier 2009, p. 2022–2027

[4] Pokorný J., Fišer J., Jícha M.: Calibration of the Heat Balance Model for Prediction of Car Climate, In: Experimental Fluid Mechanics 2011, Conference Proceedings Volume 2, Liberec, Technical University of Liberec, 2011, p. 928–931, ISBN 978-80-7372-784-0

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