

# Measurements of Energy Used for Vehicle Interior Climate

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## ABSTRACT

Fuel consumption of vehicles has received increased attention in recent years; however one neglected area that can have a large effect on this is the energy usage for the interior climate. This study aims to investigate the energy usage for the interior climate for different conditions by measurements on a complete vehicle. Twelve different NEDC tests in different temperatures and thermal states of the vehicle were completed in a climatic wind tunnel. Furthermore one temperature sweep from 43° to -18°C was also performed. The measurements focused on the heat flow of the air, from its sources, to its sink, i.e. compartment. In addition the electrical and mechanical loads of the climate system were included. The different sources of heating and cooling were, for the tested powertrain, waste heat from the engine, a fuel operated heater, heat pickup of the air, evaporator cooling and cooling from recirculation. It was found that a separation of the sources and sink was possible and increased the understanding of the energy usage. Further the study showed that the sources were very dependent on the powertrain and that ambient conditions and thermal state of the vehicle, i.e. thermal load, had a very large impact on the needed energy.

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## INTRODUCTION

Focus on fuel consumption has increased in the automotive industry during the last couple of years due to customer demand. This customer interest is caused by rising fuel prices and the environmental debate. In addition the growing concern has led many governments to create and implement regulations regarding fuel consumption and emissions, especially on greenhouse gases.

The increased attention has led to many improvements in, e.g. engine efficiency, aerodynamics and road load friction, areas which have a large effect on certification cycles. Other areas, which are excluded or have negligible impact in certification cycles, can have a large effect on real-world fuel consumption. One of these neglected areas is the system for interior climate [1].

There have been many different ways to analyze fuel consumption, energy consumption or power usage of the climate system. For example complete vehicle testing is common for CO<sub>2</sub> emission tests focusing on the air-conditioning (AC), see [2,3]. This kind of test directly measures the impact on emissions by the AC; it does not explain any mechanism behind the result. Further it does not look on the complete energy usage of the climate system and is very

dependent on the powertrain. An additional drawback is the difficulties that arise when emissions are measured. Another direct approach, made by de Moura and Tribess [4], was when different compressors were compared regarding fuel consumption. Test benches for AC-systems are rather common and have been used extensively by both car manufacturers, subcontractors and suppliers. Gaveau and Clodic [5] made extensive tests on an AC-system by varying different parameters and measuring, among other things, compressor power and fan power. Gado et al. [6] made several tests of the AC-system focusing on transient states.

In recent years a lot of effort has been made on models that simulate fuel consumption, however in most models auxiliary loads, as the climate system, are not modeled at all instead they are added as a constant load; see for example [7]. This approach does not answer more specific questions regarding the climate systems. Other types of models, made especially for modeling the climate system, are also available and their focus has been on performance, not on energy usage. Some specialized models have focused on energy usage but only on some components of the total climate system or on a very narrow part of the different relevant conditions. One example of a more specialized model is presented by Kiss et al. [8].



Therefore the complete energy usage for the interior climate has not been thoroughly investigated and there is a lack of knowledge about the effect of different conditions. Additionally, newer more efficient engines have less or no waste heat available. This increases the challenges for future climate systems and the need for knowledge.

The objective of this study is to investigate the energy usage for the interior climate, more precisely the heating and cooling sources and sinks and their size. In addition the electrical and mechanical loads used for the interior climate will also be studied. The investigation will be made for different conditions such as temperature, sun load and thermal state of the vehicle, i.e. thermal loads.

## METHOD

Several tests were performed, with different conditions, on a regular Volvo S60 in a climatic wind tunnel.

### Test Facilities

All tests were carried out in a climatic wind tunnel capable of varied conditions. See [table 1](#) for information about the tunnel specifications.

Table 1. Climatic wind tunnel.

|                                  |                            |
|----------------------------------|----------------------------|
| min/max air temperature          | -40°C - 50°C               |
| relative humidity                | 5 – 95% RH                 |
| sun intensity                    | 600 – 1200W/m <sup>2</sup> |
| max velocity wind                | 200km/h                    |
| max velocity chassis dynamometer | 250km/h                    |
| max load, chassis dynamometer    | 320kW                      |
| max torque, chassis dynamometer  | 14kN                       |

### Test Object

The tested vehicle was a Volvo S60, D5 and model year 2012, see [figure 1](#). It had a 2.4l diesel engine, Electronic Climate Control (ECC), AC-system with a variable displacement compressor and a Fuel Operated Heater (FOH). Additionally an electrical heater of a Positive Thermal Coefficient type (PTC) was installed. Modification of the vehicle was made so that either the FOH or the PTC could be used for heating but in the test presented here only the FOH was used.



Figure 1. Tested vehicle, Volvo S60.

## Performed Tests

A large range of different tests were performed with the intention to investigate several different conditions. In this paper the focus will be on tests made with the New European Driving Cycle (NEDC) but for different temperatures and states of the vehicle compared to the certification cycle. The ambient temperature interval was from -18°C to 43°, compared to standard NEDC which normally is between 20° to 30°C, and the vehicle was either initially the same temperature as the ambient or in steady state. For more information regarding the test cycle see [\[9\]](#) and for performed tests see [table 2](#). If the test was a cool down with sun load the vehicle was soaked before the start of the test to an average air temperature in the compartment of 60°C. The definition of steady state was that both the engine and the compartment reached its normal operating temperature, for those conditions, before the start of the test. In other words, no heating up or cooling down of the compartment, the engine or any other components during the test. In all NEDC-tests a driver was present in the compartment.

A second type of test was also made; a long temperature sweep from 43°C to -18°C, divided into two sessions, with constant wind and vehicle velocity of 50km/h. The temperatures changed one degree approximately every sixth minute, this resulted in quite stable interior climate during the test. There was no driver present in this type of test, instead a throttle control was mounted in the car. The control dissipated approximately 100W heat which is roughly equal to one person.

In all tests the ECC was set on auto climate and a temperature of 22°C on both driver and passenger side, which is a common customer setting. The dew point (DP) was controlled during the tests, see [table 2](#) for specific levels.

Table 2. Performed tests.

| No: | Test          | Climate                                 | State        |
|-----|---------------|-----------------------------------------|--------------|
| 1   | NEDC with FOH | -18°C, -20°C DP                         | heat up      |
| 2   | NEDC with FOH | -18°C, -20°C DP                         | steady state |
| 3   | NEDC with FOH | -10°C, -14°C DP                         | steady state |
| 4   | NEDC          | 2°C, 0°C DP                             | heat up      |
| 5   | NEDC with FOH | 2°C, 1°C DP                             | heat up      |
| 6   | NEDC with FOH | 2°C, 1°C DP                             | steady state |
| 7   | NEDC          | 24°C 12°C DP                            | steady state |
| 8   | NEDC          | 24°C, 13°C DP, 1000W/m <sup>2</sup> sun | steady state |
| 9   | NEDC          | 43°C, 25°C DP, 1000W/m <sup>2</sup> sun | cool down    |
| 10  | NEDC          | 43°C, 25°C DP, 1000W/m <sup>2</sup> sun | steady state |
| 11  | NEDC          | 43°C, 25°C DP                           | cool down    |
| 12  | NEDC          | 43°C, 25°C DP                           | steady state |
| 13  | temp. sweep   | 43°(-)18°C, 18°(-)22°C DP               | steady state |

## Measured Variables

The vehicle was prepared with sensors for measuring temperatures, voltages, currents, pressures, flow rates and revolutions. ECC parameters were also measured, i.e. the status of the climate control was continuously monitored. The most important sensors and calculations are presented here.

## Coolant Circuit

In the coolant circuit the flow rate, the temperatures out from the engine, after the FOH and after the compartment heat exchanger was measured. This made it possible to measure the heat transfer in the heat exchanger and also the heat transfer from the sources, the engine or FOH. Note that the engine is loosely defined; it includes all heat sources that release heat to the coolant. See [figure 2](#) for a simplified overview of the coolant circuit.

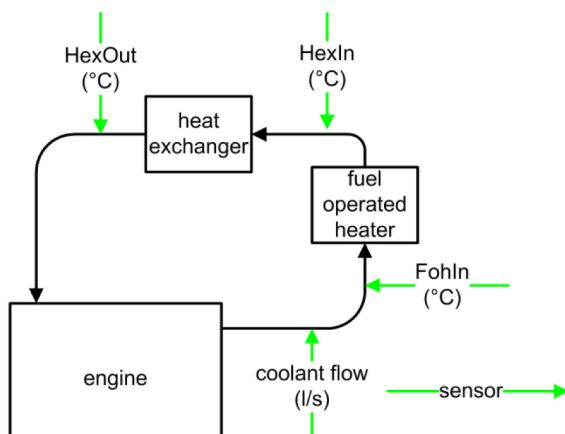


Figure 2. Simplified overview of the climate part of the coolant circuit.

## Air Distribution System

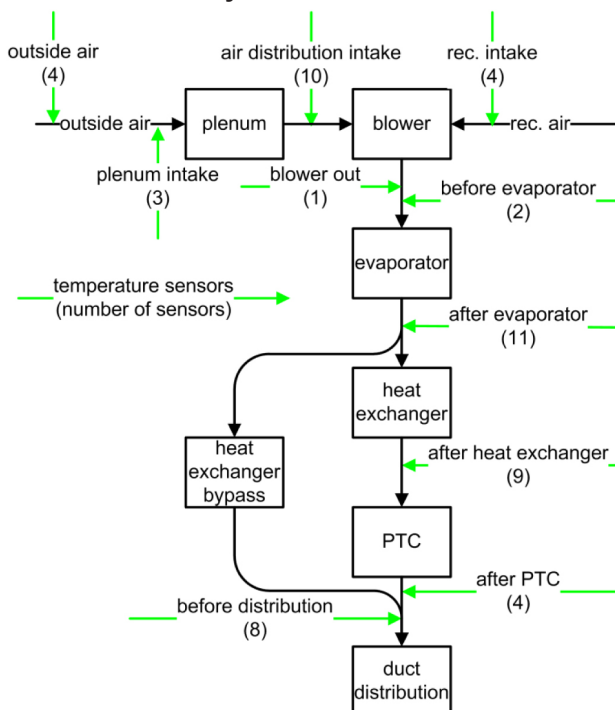


Figure 3. Simplified overview of the air distribution with temperature sensors. Number of sensors in parenthesis.

Most temperature sensors were mounted in the air distribution system. See [figure 3](#) for an overview of the location of the sensors. In addition to the figure, sensors were mounted at all the duct outlets in the compartment and several temperature sensors on the outside of the vehicle. Two humidity sensors were also used, one located on the outside of the vehicle and one at the recirculation intake.

## AC-System

The AC-system was prepared with pressure and temperature sensors at various locations. This made it possible to observe that the system worked properly. For these tests the most important sensor was the torque sensor mounted on the compressor axle. With the torque and the speed it was possible to calculate the power of the compressor.

## Electrical Measurements

Several important components for the climate system use electrical power for its functions. In general both the voltage and current were measured for the blower, blower control and cooling fans with control. The vehicle was equipped with a double electric fan for the radiator cooling, here called cooling fan. In all tests presented in this paper the condenser cooling for the AC-system was the requester of all cooling fan loads, i.e. the engine never needed extra cooling.

Some electrical loads were not measured; instead values from specifications and other tests were used. This applies to the climate coolant pump, the FOH and the compressor clutch and control.

## Passenger Compartment

Several temperature sensors were mounted in the compartment, measuring among other things the air temperature both at head level and feet level both in front and rear. Additional sensors were installed at the compartment evacuation in the rear.

## Airflow

The airflow was measured separately before the test for different settings on the air distribution, recirculation, temperature and blower speed with the vehicle at standstill. These measurements were used to make a correlation between flow rate and blower voltage combined with the air distribution settings. Because the flow rate and temperatures, i.e. the heat transfer for the heat exchanger, in the coolant circuit was known it was possible to compare it to the heat transfer on the air side. If the heat transfer rates were consistent between the two sides the airflow correlation was most likely acceptable. The effect of ram pressure was controlled by the ECC, i.e. reducing the blower voltage with increasing velocity of the vehicle to keep the same airflow. Many small effects on the airflow are ignored, such as increased pressure drop due to wet evaporator and the air leakage characteristics.

## Calculated Variables

### Heat Flow

The heat flow for bulk or macroscopic motion of a fluid can be defined as:

$$\dot{Q} = \dot{m}C_p\Delta T \quad (1)$$

Note that [equation \(1\)](#) is a simplification of the rate equation of the first law of thermodynamics. The main assumptions were that there is no difference in potential or kinetic energy, no work and that the internal energy did not depend on pressure, i.e. only temperature dependence [10].

For the calculations the fluid was either air or coolant, see section Definitions/Abbreviations for explanation of expressions. All the calculations on the air side assumed constant heat capacity,  $C_p$ , however on the coolant side the heat capacity was dependent on temperature. The heat flow into the compartment with the air was divided into three different parts, see [equation \(2\)](#). As a reference temperature, for the heat flow calculations of the air, the ambient temperature was used. Heat flow into passenger compartment with the air:

$$\dot{Q}_{a\text{ in}} = \dot{m}_{a\text{ HX}}C_p(T_{\text{PTC}} - T_{\text{amb}}) + \dot{m}_{a\text{ byp}}C_p(T_{\text{evapR}} - T_{\text{amb}}) + \dot{m}_{a\text{ leak}}C_p(T_{\text{evapF}} - T_{\text{amb}}) \quad (2)$$

The heat flow out of the passenger compartment with the air, [equation \(3\)](#):

$$\begin{aligned} \dot{Q}_{a\text{ out}} &= \dot{Q}_{a\text{ rec}} + \dot{Q}_{a\text{ amb}} \\ \dot{Q}_{a\text{ rec}} &= \dot{m}_{a\text{ rec}}C_p(T_{\text{rec}} - T_{\text{amb}}) \\ \dot{Q}_{a\text{ amb}} &= \dot{m}_{a\text{ uncont}}C_p(T_{\text{cabavg}} - T_{\text{amb}}) + \dot{m}_{a\text{ cont}}C_p(T_{\text{cabevac}} - T_{\text{amb}}) \end{aligned} \quad (3)$$

For the coolant circuit the presented heat transfer were based on where the heat in the heat exchanger came from, i.e. it was not compared to a reference temperature. Therefore it was possible to have cases where there was no waste heat from the engine used by the climate system, although compared to the ambient the engine did release waste heat.

Heat pickup was defined as the temperature increase of the air before the evaporator, see [equation \(4\)](#). This was mainly due to warm surfaces at the inlet but also include, for example, temperature increase caused by the blower.

$$\dot{Q}_{a\text{ heatpickup}} = (\dot{m}_{a\text{ tot}}T_{\text{evapF}} - \dot{m}_{a\text{ osa}}T_{\text{amb}} - \dot{m}_{a\text{ rec}}T_{\text{rec}})C_p \quad (4)$$

The cooling on the airside over the evaporator was calculated for both sensible, [equation \(5\)](#), and latent heat, [equation \(7\)](#).

Sensible:

$$\dot{Q}_{a\text{ sens}} = (\dot{m}_{a\text{ tot}} - \dot{m}_{a\text{ leak}})C_p(T_{\text{evapF}} - T_{\text{evapR}}) \quad (5)$$

For the latent heat, i.e. condensation, the humidity sensors were used. The amount of humidity was calculated for the outside air and recirculated air from temperature and relative humidity. It was assumed that all the air passing the evaporator was cooled to the average temperature and that the dew point was decreased to this temperature if higher. The amount of condensed water can be seen in [equation \(6\)](#).

$$\dot{m}_{w\text{ cond}} = \dot{m}_{w\text{ osa}} + \dot{m}_{w\text{ rec}} - \dot{m}_{w\text{ evap}} \quad (6)$$

[Equation \(6\)](#) was valid only if  $\dot{m}_{w\text{ cond}} \geq 0$ , otherwise  $\dot{m}_{w\text{ cond}} = 0$ . The latent heat:

$$\dot{Q}_{a\text{ lat}} = 1000\dot{m}_{w\text{ cond}}(2500.8 - 2.36T_{\text{evapR}} + 0.0016T_{\text{evapR}}^2 - 0.00006T_{\text{evapR}}^3) \quad (7)$$

### Compressor Load

Compressor torque was measured using a torque sensor on the compressor shaft. The compressor power was calculated as in [equation \(8\)](#).

$$\dot{W}_{\text{comp}} = \frac{2\pi}{60}(\omega_{\text{eng rpm}}k_{\text{ratio}}\tau_{\text{comp}}) \quad (8)$$

## RESULTS

The results are divided into three parts, first averages for each of the 12 performed NEDC tests, then a more thorough and time-resolved examination of two transient tests: no 1, heat up in  $-18^\circ\text{C}$  and no 9, cool down in  $43^\circ\text{C}$  with  $1000\text{W}/\text{m}^2$  and soaked compartment. Finally the steady state temperature sweep is presented.

### NEDC Averages

In [table 3](#) and [figure 4](#) the average electrical and mechanical loads are presented for all the different NEDC tests. It can clearly be seen that the two largest electrical loads were the blower and the cooling fan. In most conditions, except cool downs, the average blower power was not especially high, see for example test 1. The level was low because either there was no need for a large airflow or the airflow was limited by available heat.

Test no 7 was most similar to a standard NEDC. In this test the average electrical power was 177W and mechanical power was 962W.