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# EcoTram Research Project: How Much Energy Is Used By The HVAC Of A Tram?

## *Measurements In The Climatic Wind Tunnel And In Service*

# How Much Energy Is Used By The HVAC Unit Of A Tram?

## Investigations In The Climatic Wind Tunnel And In Operation

**Practically all new rail vehicles for passenger transport are equipped with air conditioning. Higher passenger comfort, however, comes at the expense of increased energy consumption. But how much energy is actually used by an air conditioning unit in operation? Are climatic wind tunnel measurements suitable for calculating annual energy consumption and what are the advantages over in-service measurements? This article seeks to answer these questions.**

### Introduction

Full air-conditioning, which has long been state of the art in mainline rolling stock has also increasingly become an issue in urban and suburban rail transport over the past decade. In the past five years a rising trend in this respect can be observed for trams, where simple convection and fan heaters are being replaced by complex HVAC systems. Depending on requirements, the air is heated by means of a heating register or cooled by means of a refrigeration unit, while a fan ensures controlled fresh air supply. The large number of tram passengers and the prescribed fresh air rate per passenger result in a high energy demand for air conditioning.

Additionally, these vehicles are less well insulated than regular train vehicles due to restrictions in axle load. The **energy demand** for air-conditioning in trams must therefore not be neglected in relation to traction power. While traction power is only required for acceleration and speed maintenance, however, the HVAC unit is in constant operation throughout service hours. The electrical heating power installed in mainline, urban and suburban rolling stock amounts to roughly 4 to 7 % of traction power, while the corresponding percentage for trams is about 13 to 22 %.

There are different approaches and possibilities for reducing the energy consumption of the HVAC unit, such as fresh air supply dependent on passenger load, heat pumps, optimised control etc. The corresponding energy saving potentials and the application of climatic wind tunnel measurements have already been examined in [1].

**Energy saving** measures can be implemented in new vehicles and can also be retrofitted to existing systems. Operators will only decide to implement such measures, however, if they are not only environmentally beneficial but also economically sensible, meaning the investment and maintenance expenses must be paid back by savings in energy costs. It is very difficult to predict the exact amount of energy that a specific measure saves in operation, as this depends both on regional environmental and operating conditions. A frequently fully occupied vehicle in service in southern Europe will require different measures than a vehicle deployed in cooler regions.

### EcoTram Research Project

The research project EcoTram initiated in March 2010 is designed to examine these issues in more detail in order to find appropriate solutions. The project consortium led by the Vienna University of Technology comprises the key players Wiener Linien, Siemens, Vossloh Kiepe, Rail Tec Arsenal and SCHIG mbH. The project is funded by the „Klima- und Energiefonds“ under the „Neue Energien 2020“ programme of the Austrian Research Promotion Agency (FFG).

The **measurements** are carried out on a three-car ULF (ultra-low floor) tram manufactured by Siemens and operated by Wiener Linien. The aim of the project is to optimise the tram's heating, ventilation and air-conditioning unit in order to save energy. The results of the EcoTram project will be universally applicable. The theoretical examination of optimisation potentials is complemented by „static“ and „dynamic“ measurement series. The „static“ measurements were carried out in the climatic wind tunnel of Rail Tec Arsenal in May 2010. Subsequently, the test vehicle was fitted out for „dynamic“ operation on the Vienna tram network over a period of about 6 to 8 months.

*Figure 1:* ***A ULF tram inside the climatic wind tunnel.***

The measurements in the **climatic wind tunnel** were designed to record and analyse the actual energy flows of the heating and air conditioning appliances under realistic climatic and operating conditions (see Figures 1 and 2). During operation, route and load-dependent influencing factors are recorded over an extended period of time and validated with the measured values. A comprehensive simulation model of the vehicle's thermal behaviour is being developed by the Vienna University of Technology to provide a sound basis for a variety of case studies. This approach is designed to demonstrate and quantitatively assess the relationships between environmental conditions, operating parameters, vehicle bodyshell, air conditioning and heating equipment.

The results of the research project enable a comprehensive **assessment** of different measures in terms of their energy and cost efficiency. This for the first time allows measurements carried out in the climatic wind tunnel to be directly compared with those obtained in service. A follow-on project will combine all findings obtained from the EcoTram project to build an energy-saving prototype.

*Figure 2:* ***Installed equipment for passenger load simulation inside the ULF tram.***

### Measurements In The Climatic Wind Tunnel And In Service

The measurements in the climatic wind tunnel provide a sound basis for the project. The advantage over in-service measurements is that it is possible to change only a single parameter in order to determine its influence on the power consumption of the HVAC unit. The following parameters were **simulated**:

- passenger load: heat load of approx. 120 W per passenger,
- speed: average wind speed,
- solar radiation: average radiation simulated by solar array,
- external temperature and relative humidity: in the range between -20 °C and +32 °C.

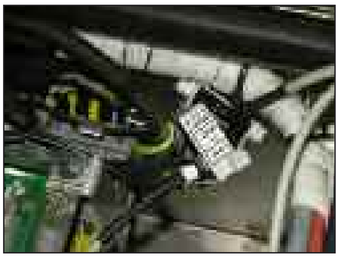

*Figure 3:* ***Example of current transformer for power measurement inside the HVAC system.***

The power consumption of the HVAC units was measured by separately recording the power consumption of each heater and each cooling device of the three HVAC systems. A comprehensive range of measuring instruments and sensors (see Figure 3) were installed in the vehicle to validate the data obtained in the climatic wind tunnel and to gather extensive operating data.

The **in-service** measurements include the following relevant operating data and environmental parameters:

- power consumption of HVAC units and vehicle,
- external and internal temperatures,
- relative humidity,
- intensity and direction of solar radiation,
- speed and position,
- number of passengers and door opening cycles,
- system data of HVAC units.

The vehicle has been in regular service on the Wiener Linien network since June 2010, continuously recording the specified data. The measurement equipment sends a **daily status** report via SMS so that the captured data need only be read out once a month. The routes covered so far are shown in Figure 4.

## Power Curves Resulting From The Climatic Wind Tunnel Tests

The data obtained from the measurements in the climatic wind tunnel allow the power consumption of the HVAC units to be determined for different parameters as a function of external temperature. For this purpose, temperature ramp tests were carried out with a gradient of 3 K/h. For each test, the external temperature was first increased from 0 °C to +28 °C, then held at +28 °C and then again reduced to 0 °C in order to detect any hysteresis effects in control behaviour or power consumption. Additional temperature ramp tests were carried out with varying passenger load and solar intensity.

The **results** of the tests are shown in Figure 5. The power consumption of the heaters decreases with increasing external temperature. In the transition range, electrical power is required only for fan operation. As temperatures continue to increase, the compressor cuts in, first operating in cyclic mode. A further increase in cooling demand leads to permanent operation of the compressor and electrical power consumption increases in proportion to refrigerant pressure. The four curves clearly show the strong influence of solar intensity and passenger load on power consumption. The additional heat from the passengers and solar radiation reduces the power consumption of the HVAC unit in heating mode, while increasing the cooling demand already at slightly elevated temperatures.

## Optimisation Potential In Temperature Control

The climatic wind tunnel tests revealed some interesting phenomena that are counterproductive from a purely energetic perspective. Figure 6 shows the power consumption of the three HVAC units for one increasing and one decreasing temperature ramp carried out under the same conditions. The diagram also shows the internal temperatures, which in both cases correspond to the setpoint values. In heating mode the difference in power consumption is approx. 1.5 kW at the same temperature, which is due to the **thermal inertia** of the overall system. In cooling mode the difference amounts to approx. 6 kW, which is too large to be due to thermal inertia.

More detailed investigations showed that the differences in power consumption are inherent in the system. While increasing temperatures cause the compressor to operate in cyclic mode, falling temperatures do not lead to cyclic operation of the compressor, as the excess cooling capacity is dissipated via the bypass. This control behaviour may be conducive to achieving an optimal internal temperature, but is not the best solution from an energetic point of view.

*Figure 4:* ***Tram routes (green line) shown in Google Earth©.***

Another interesting effect observed during the climatic wind tunnel tests is shown in Figure 7. The **compressor** was switched off at an external temperature of 15 °C. This was obviously too late, with the result that the HVAC unit had to briefly activate the heater in order to maintain the set internal temperature. The power consumption in this case was 0.25 kWh. Although this effect provides no significant saving potential, it nevertheless shows that climatic wind tunnel measurements reveal details that are not accessible through calculations.

This control behaviour can be observed not only under simulated conditions in the climatic wind tunnel, but sometimes also under service conditions. Figure 8 shows data measured during in-service operation. It depicts both the external temperature and the power consumption of the heater and the cooling device of the HVAC unit of one module. The power consumption exceeds 3 kW, indicating that the compressor was in operation at that time. The heater was active shortly after the compressor was switched off by the control unit.

## Power Consumption Of HVAC Unit During In-Service Operation

Further results of the in-service measurements are depicted in Figure 9. The diagram shows the mean power consumption of all three HVAC units, the power consumption of the HVAC units as a percentage of that of the entire vehicle and the mean external temperature for each month. These data can be used to answer the question posed at the beginning of the article as to the **percentage of power** actually used for air-conditioning. For example, the HVAC unit accounted for 34 % of total vehicle power consumption in July. This is remarkable since the installed electrical cooling capacity, including fans, corresponds to only 4 % of the installed traction power.

## Comparison Of Power Consumption Measurements

The results of in-service measurements were subsequently compared with the results obtained in the climatic

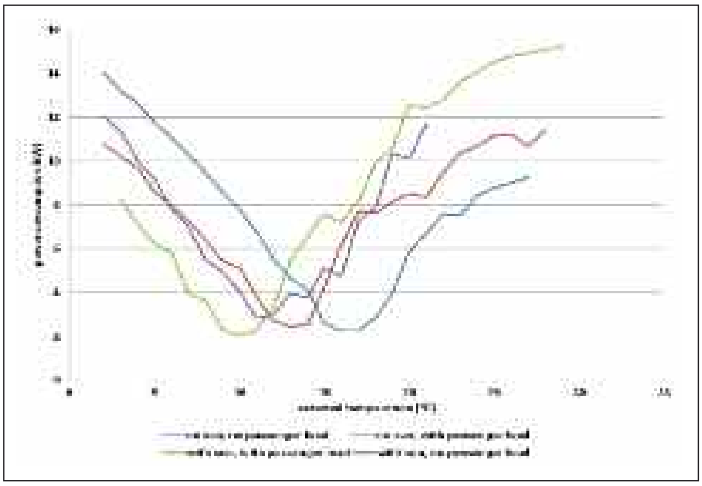

*Figure 5:* ***Mean power consumption of the three HVAC units in the climatic wind tunnel.***

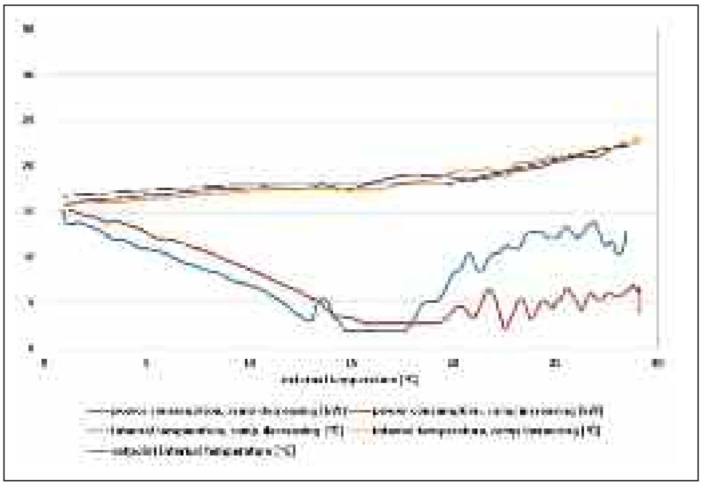

*Figure 6:* ***Power consumption of HVAC units for increasing and decreasing temperature ramps (0 °C <-> 28 °C) in the climatic wind tunnel.***

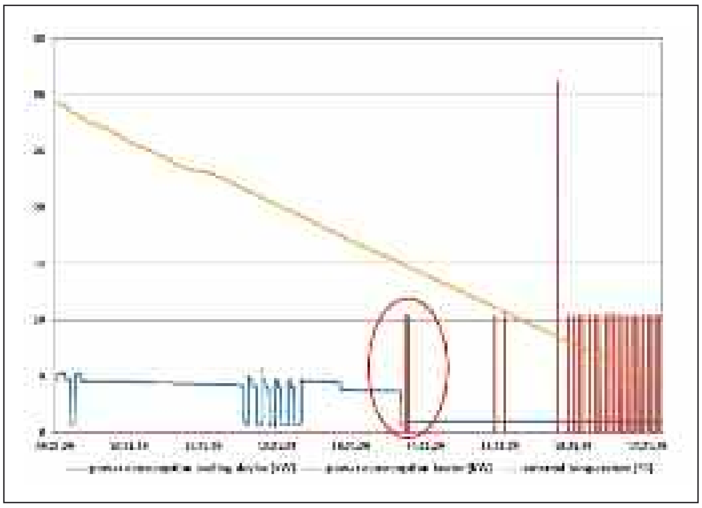

*Figure 7:* ***Noticeable heater activation at 15 °C during decreasing temperature ramp in the climatic wind tunnel.***

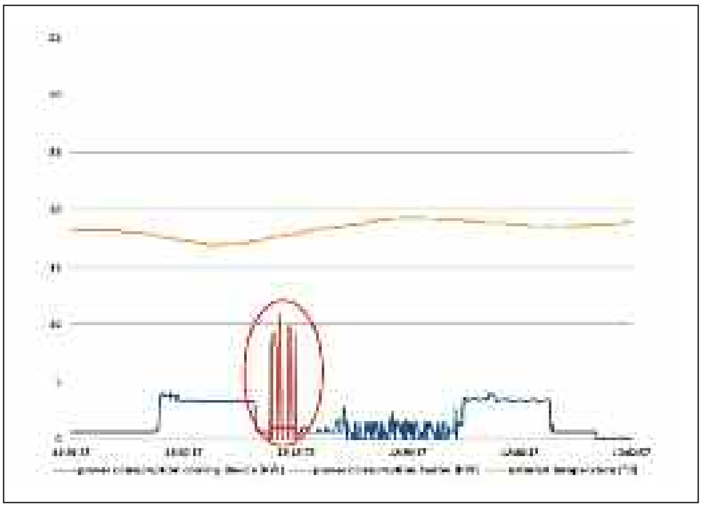

*Figure 8:* ***Effect of counter-heating also occurs during in-service operation.***

wind tunnel (see Figure 5). A power curve was generated by plotting all instantaneous power values measured for the three HVAC units as a function of external temperature. The parameters additionally recorded during in-service operation - passenger load and solar intensity - were used to calculate a **realistic power curve** for the climatic wind tunnel tests. Both curves are shown in Figure 10. The two curves match very well in the transition range, which is of particular interest. The difference between in-service operation and climatic wind tunnel tests is slightly higher in heating mode. The results for this temperature range, however, are not yet meaningful as the in-service measurements are so far limited to the period from June to October.

## Calculation Of Annual Energy Consumption

Operators increasingly demand information about the expected annual energy consumption of new rail vehicles. A simple and practical solution is to calculate the annual energy consumption from data measured in the climatic wind tunnel, which, as shown above, are in good agreement with in-service values. For this purpose, the power consumption for each degree of external temperature is multiplied by the duration of that temperature and then accumulated (see Figure 11).

The data measured in the climatic wind tunnel resulted in an energy consumption of 9,700 kWh for the months June to October, which is a deviation of only 3 % from the value of 9,400 kWh recorded during in-service operation. The difference is smaller than expected, indicating that the calculation of energy consumption based on climatic wind tunnel measurements produces **realistic results**. The method developed is designed to reproduce the climatic and operating conditions in service as realistically as possible, but does not claim to predict actual consumption values with 100 % accuracy. The focus is rather on assessing and comparing the energy efficiency of different HVAC systems under reproducible and comparable conditions.

## Summary And Outlook

Modern rail vehicles use a significant amount of electrical energy for air-conditioning. For example, the HVAC system of the tram investigated in the EcoTram project accounted for 34 % of total energy consumption of the vehicle in the month of July. It was also demonstrated that the power consumption measurements in the climatic wind tunnel are in very good agreement with the values measured during in-service operation.

The data measured in the climatic wind tunnel provide a sound **basis for calculating** the amount of energy used for air-conditioning in a specific period. For this purpose, the power consumption of the HVAC system is continuously recorded during a temperature ramp. These measurements allow the energy efficiency of different systems to be compared under reproducible conditions. Climatic wind tunnel tests additionally provide the unique opportunity to discover phenomena that open up new possibilities for improving the control strategy and thus also the energy efficiency of HVAC systems.

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***Photos and diagrams:***
***Rail Tec Arsenal Wien***

*[1] G. Haller; Measuring the energy efficiency of air conditioning systems: analysis and calculation of energy consumption, saving potentials; Railvolution 2/08.*

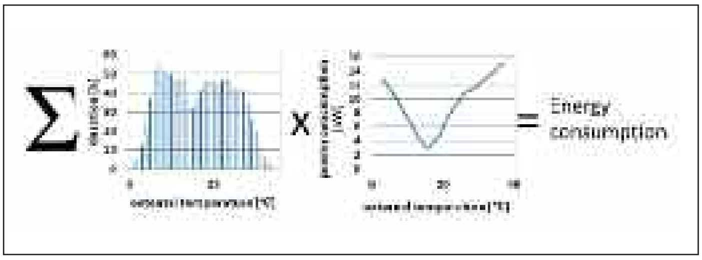


*Figure 11:* ***Calculating the energy consumption by cumulated duration of external temperatures.***

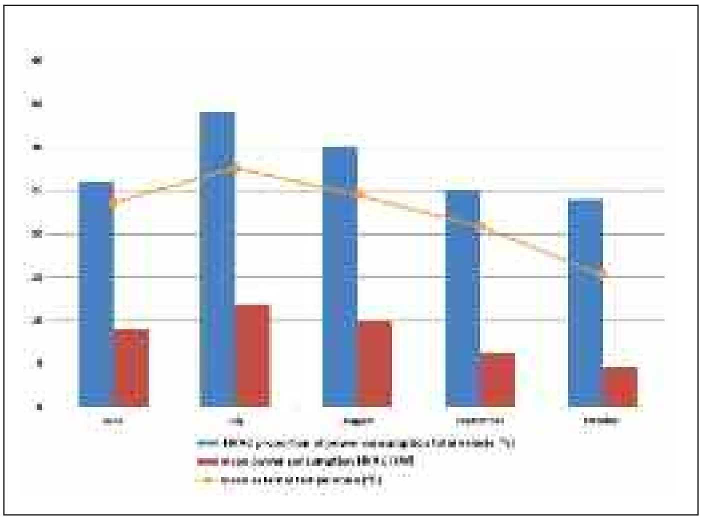

*Figure 9:* ***Comparison of mean power consumption per month.***

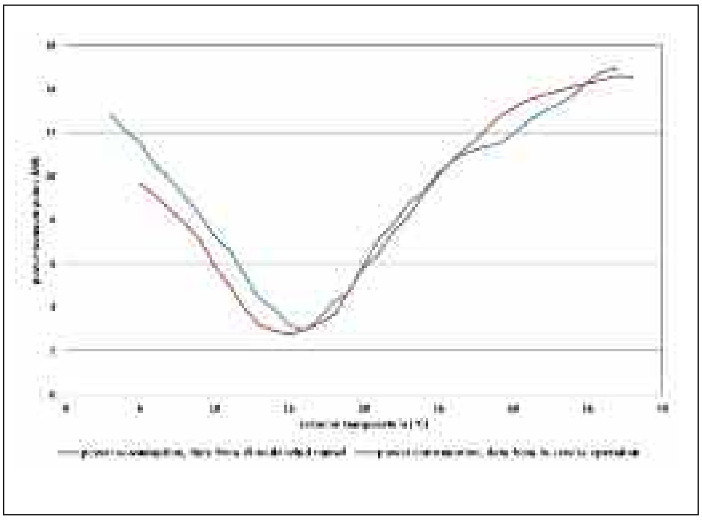

*Figure 10:* ***Comparison of power consumption during in-service operation and in the climatic wind tunnel.***