Railvolution

The Professional Two-Monthly Magazine Of Rail Transport Worldwide

Volume 14 No. 2/14

Rail Tec Arsenal Offprint

EcoTram - Energy-Efficient Air-Conditioning For Trams

New HVAC Units And Additional Measures, Power Measurements, Outlook

EcoTram - Energy-Efficient Air-Conditioning For Trams

The two-phase research project EcoTram is aimed at substantially reducing the energy consumption of HVAC systems in trams. It runs from 2010 to 2014 and is carried out in cooperation with partners from Vienna using an ultra-low floor (ULF) tram as a test vehicle.

The **first project phase** was dedicated to extensive research and theoretical investigation of technical measures with the potential to curb HVAC energy consumption. In parallel, actual energy consumption was determined in extensive measurement runs. The results of these measurements were reported in Railvolution 6/10, pp. 42 - 44.

In the **second project phase** a test vehicle was retrofitted with three newly designed optimised HVAC units. Subsequent measurements showed that the energy consumption was reduced by up to 30 % - see Figure 1.

Photo: Siemens

Figure 1: The modified ULF A1 EcoTram during test runs in Vienna, here at Burgring in October 2013.

Principles Of Air-Conditioning

Practically all modern rail vehicles for passenger transport are equipped with air conditioning. The main purpose of the HVAC system is to ensure a high degree of thermal comfort for the passengers by providing heated or cooled fresh air. In most rail vehicles the HVAC system is designed as a compact unit installed on the roof, where the conditioned air is passed into the vehicle interior via a complex duct system using a fan.

Conventional HVAC units are equipped with an electrical heating register for heating and a compression chiller for cooling. Some vehicles additionally feature radiators or panel heaters in the passenger area. A control unit which measures the temperatures inside and outside the vehicle seeks to maintain a constant interior temperature irrespective of disturbances and additional loads. The HVAC system must thus be dimensioned taking into account various parameters such as maximum exterior temperatures, number of passengers, heat input through solar radiation and vehicle insulation. The thermal design loads also define the electrical power rating, which is between 30 and 60 kW per car depending on the vehicle type.

While the traction equipment requires energy only for acceleration, some of which may even be recovered during braking, HVAC systems consume energy throughout their operation. HVAC systems in rail vehicles thus require up to **30 %** of the overall energy, making them the second largest energy consumer after the traction unit.

EcoTram Project

The EcoTram research project was launched in Vienna in March 2010 in order to find solutions to these challenges. The **consortium** led by the Vienna University of Technology consists of Wiener Linien, Siemens, Vossloh Kiepe, Rail Tec Arsenal and SCHIG. The project is funded by the Climate and Energy Fund under the „New Energies 2020“ programme of the Austrian Research Promotion Agency (FFG) - see Figure 2.

The first project phase was dedicated to investigating and evaluating technical measures for reducing energy consumption. The measurements were carried out on a three-car ultra-low floor (ULF) tram manufactured by Siemens and operated by Wiener Linien, but nonetheless the results of the EcoTram project will also be applicable to other rail vehicles. The theoretical analysis was complemented by comprehensive measurements carried out in the climatic wind tunnel of Rail Tec Arsenal in May **2010**. Subsequently, a test vehicle was equipped with measurement sensors and instruments for a 15-month trial operation on the Vienna tram network.

The measurements in the climatic wind tunnel were designed to record and analyse the actual energy flows of the HVAC units under realistic climatic and operating conditions. This project phase resulted in a catalogue for assessing the saving potential of different measures in terms of energy and cost efficiency. The measurements allowed power consumption to be determined as a function of ambient conditions and thus also enabled the calculation of annual energy consumption - see Figure 3.

A range of measures was selected for implementation in a test vehicle in the second project phase, which started in **2012**. The vehicle was retrofitted with new, optimised HVAC units and subsequently tested in the Vienna climatic wind tunnel. The tests provided the basis for further improvements, which were again validated by comprehensive energy consumption measurements. The EcoTram vehicle has been in regular passenger operation on the Wiener Linien network (line 62) since summer **2013** to demonstrate its reliability and energy saving potential in service.

Picture: Siemens

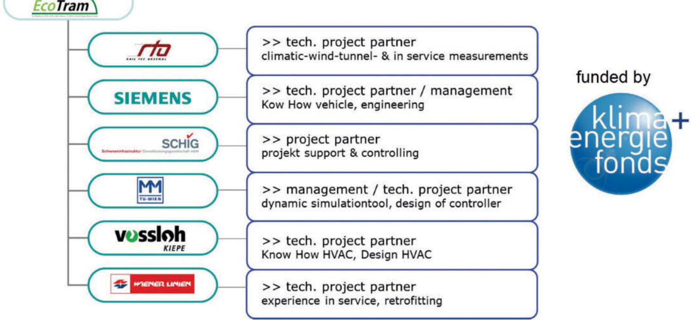


Figure 2: Partners in the EcoTram research project.

Picture: Siemens

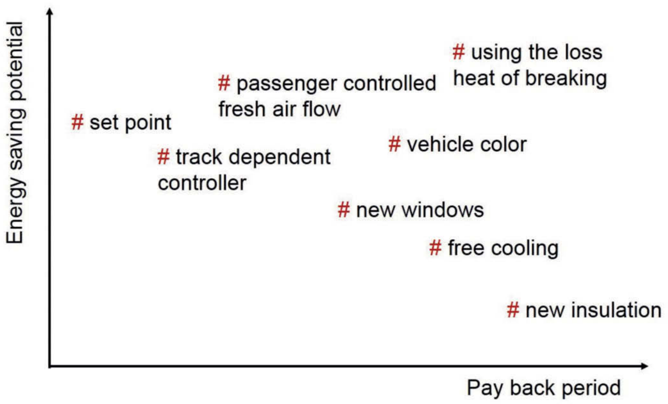


Figure 3: Different measures assessed in terms of their energy saving potential.

Description Of New HVAC Units And Additional Measures

Electrical energy can be saved by either reducing the heating or cooling demand or by more efficient energy generation. The following measures were implemented:

Steplessly Controlled Heating Register

The control unit and the heating register were replaced. Instead of the two-step control unit used previously, the heating register is now controlled by wear-free semiconductor technology enabling virtually stepless heating power control.
➔ The combination with a variable fresh air supply allows more dynamic and efficient control.

Variable Fresh Air Supply

The HVAC unit was equipped with a speed-controlled circulation fan and an additional fresh air damper.
➔ The amounts of fresh air and circulating air can be varied. This new feature improves efficiency by reducing the amount of fresh air that must be heated or cooled based on CO_2 concentrations.

CO_2 Control

CO_2 sensors measure the CO_2 concentration in the passenger area.
➔ Measurement of the CO_2 concentration makes it possible to determine the optimum amount of fresh air to be supplied and thus saves energy. Conventional devices use only one fresh air setting, which is considered for the maximum number of passengers.

Heat Pump

The use of a heat pump in a tram HVAC system is an entirely new approach. In heat pump mode the existing chiller compressor works in reverse and supplies heat energy from outside into the vehicle. The heat pump operates efficiently in the temperature range from +3 °C to +20 °C, substituting the electric heating register. A special challenge was to install the necessary valves in the limited space available and to eliminate the liquid separator.
➔ The heat pump has twice the efficiency of the heating register and thus helps to save energy in heating mode.

Picture: Vienna University of Technology

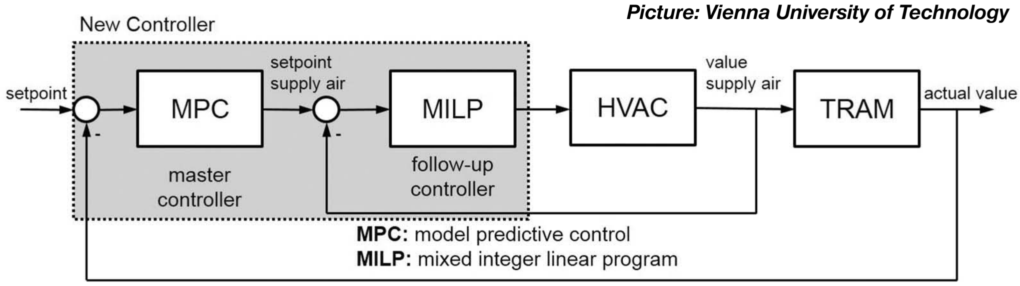


Figure 4: ***Scheme of the new controller.***

Compressor With Variable Voltage Supply

The compressor speed can be controlled in the range from 30 to 90 Hz via a variable frequency power source. Power can thus be precisely controlled in cooling and in heat pump mode without the need for a bypass.
➔ The HVAC unit provides more efficient operation, especially in cooling mode, as the cooling power supply can be adapted to the demand, thus obviating the use of a bypass valve, which usually dissipates excess cooling energy.

Refrigerant

The conventional refrigerant 134a was replaced with 407c to achieve higher efficiency in heat pump mode.
➔ The saving effect of the refrigerant will be very low. It had to be replaced primarily because of the heat pump.

Sun Protection Films

In cooling mode, about 1/3 of the cooling capacity is required for compensating the heat introduced into the vehicle by solar radiation. The transmission value of the window panes plays a major role in this respect. As it was not possible to replace single-glazing with double-glazing for reasons of weight, the windows were fitted with sun protection films. These films block three times more solar radiation and transmit less heat into the vehicle interior. Although the passenger area receives less light, there was no negative feedback from passengers during trial operation.
➔ The sun protection films reduce the cooling load in summer. The negative effect of a higher heating demand in winter should be lower than the energy savings in summer.

Vehicle Colour

Preliminary investigations have shown that the surface temperature of white painted surfaces is around 20 K lower than that of black painted surfaces. As the operator did not want to repaint the vehicle for the trial runs, white films were applied which transmit less heat into the vehicle than the usual grey-red paint.
➔ As a result of the white colour, the vehicle requires less cooling power in summer, having a similar effect to the sun protection films on the windows.

HVAC Control Unit

Conventional HVAC systems are equipped with a controller which uses a finite state machine model for controlling the interior temperature, without however taking into account the energy efficiency of heating or cooling power generation. The small number of settings for the fan, compressor and heating register results in a total 72 switching states, while new and more sophisticated HVAC systems have 1.2 million switching states.

The new two-step model **predictive controller** was developed by the Institute of Mechanics and Mechatronics of the Vienna University of Technology. The master controller uses the measurement data to calculate the heating or cooling power required to maintain the desired interior temperature. The slave controller is optimised for selecting the most efficient switching state for the HVAC units from a characteristic map, which was determined in extensive tests in the Vienna climatic wind tunnel.
➔ The controller is the heart of the new HVAC units and helps to save energy across the entire temperature range by providing optimal control of all HVAC components - see Figure 4.

The HVAC manufacturer Vossloh-Kiepe was faced with the **challenge** of designing a new unit with the same dimensions, weight and air connections - see Figure 5. It would have been possible, for example, to extend the temperature range of heat pump operation by using larger heat exchangers. Siemens was responsible for developing a new power supply solution for the HVAC system. The units were previously supplied with 600 V DC for the heating register and 400 V 50 Hz for the fan and compressor.

As the new system is equipped with a variable speed compressor, however, it requires a variable frequency **power supply** from 30 to 90 Hz. As it was not possible to install an additional converter due to weight and space restrictions, the project team decided to split the existing redundant converter and turn one half into a variable frequency converter. This required only some software modifications and the installation of additional cables. The redundancy demanded by the tram operator Wiener Linien was maintained by using a coupling relay for emergency operation.

These measures made it possible to provide the necessary power supply without the need for a new converter. All modifications were carried out in the Ottakring tram depot under the supervision of Wiener Linien.

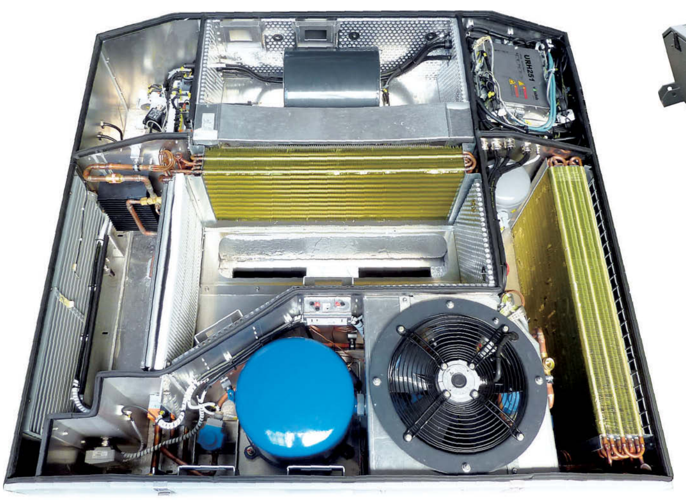


Figure 5: ***HVAC unit HKL 338-ECO.*** ***Photos: Vossloh Kiepe***

Power Measurements In The Climatic Wind Tunnel

After the vehicle had been retrofitted and the new HVAC units installed, the power consumption of the HVAC units was measured in the climatic wind tunnel to verify the energy savings achieved. Every unit was supplied with 600 V DC for the heating register, 400 V 50 Hz for the fans and 400 V

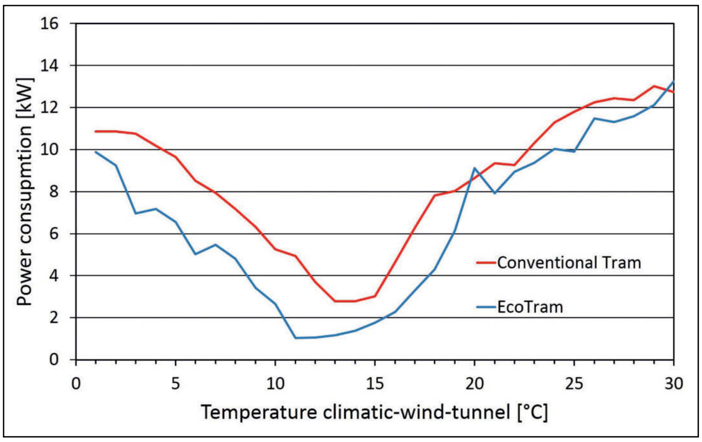


Figure 6: ***Power consumption of the conventional (red) and new (blue) HVAC units.***

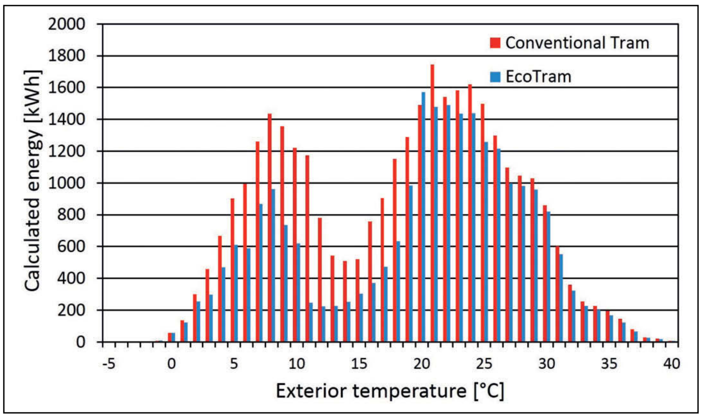


Figure 7: ***Energy consumption of HVAC units with reference to the frequency distribution of exterior temperature for the period September 2010 to August 2011.***

with variable frequency for the compressor for cooling and heat pump operation. The voltage and current measurements provided the basis for calculating power **consumption**, i. e. the energy required for HVAC operation. The power consumption of the 24 V control unit was neglected.

The measurement values were continuously recorded by an autonomous data acquisition system both in the climatic wind tunnel and during in-service operation. In addition to power consumption the system also recorded interior and exterior temperature, humidity and solar radiation, operating parameters of the HVAC units and the position and velocity of the vehicle.

Prior to the energy consumption measurements, the **heat pump** was extensively tested and optimised with a special focus on determining the characteristic map of the heat pump. The switching process between heating and cooling and the lower operating limit also presented technical challenges. In the subsequent ramp tests the air temperature was increased continuously from 0 °C to +28 °C at a rate of 3 K/h, while all other parameters were kept constant. These tests were carried out under different conditions of solar radiation, wind speed and passenger number.

These measurements allowed to plot power consumption of the HVAC units as a **function of exterior temperature**, as shown in Figure 6. The same measurements had also been carried out with the conventional HVAC units of the ULF tram in 2010 and thus provide a good opportunity for comparison. It can be seen that the energy consumption of the optimised HVAC units is clearly below that of conventional units; with the exception of the 20° range, where the predictive controller tends to heat and cool simultaneously due to its special design. This may be negative from an energy point of view, but it permits precise control of cooling air supply, whereas a pure cooling system might introduce too much cold air into the vehicle interior.

The measurement curves indicate potential **energy savings** of 32 %. However, this figure does not take into account the actual temperature distribution over the year. It is therefore more sensible to calculate annual energy consumption based on a measured temperature classification. For this purpose, the power consumption measured for each degree of temperature is multiplied by the number of hours in which that temperature was measured and added up to obtain a value for energy consumption. This approach is based on the assumption that the average values for the number of passengers and tram velocity are constant and that solar radiation correlates with the exterior temperature.

Taking into account the climatic conditions of the period September 2010 to August 2011 the energy consumption results in: **conventional vehicle 33.15 MWh, EcoTram 24.7 MWh**. Based on these calculations the three HVAC units of the EcoTram II test vehicle require on average 26 % less energy than those of conventional vehicles, i. e. the new HVAC units use an average of 5.7 kW instead of 7.7 kW - see Figure 7.

In-Service Measurements

The tram has been in operation on the Vienna tram network (line 62) since July 2013. All measurement data are continuously recorded during operation. These measurements aim to test the tram's reliability in service and to verify the energy saving potential measured in the climatic wind tunnel. The experiences of the past nine months have shown that the HVAC units function reliably; only the defrost function of the heat pump had to be adjusted. The operator did not register any increase in complaints from the passengers.

Valuable information was also gathered about heat pump operation. Due to the sheltered urban setting and mild winter temperatures the heat pump could be used as the only heating source over extended periods of time.

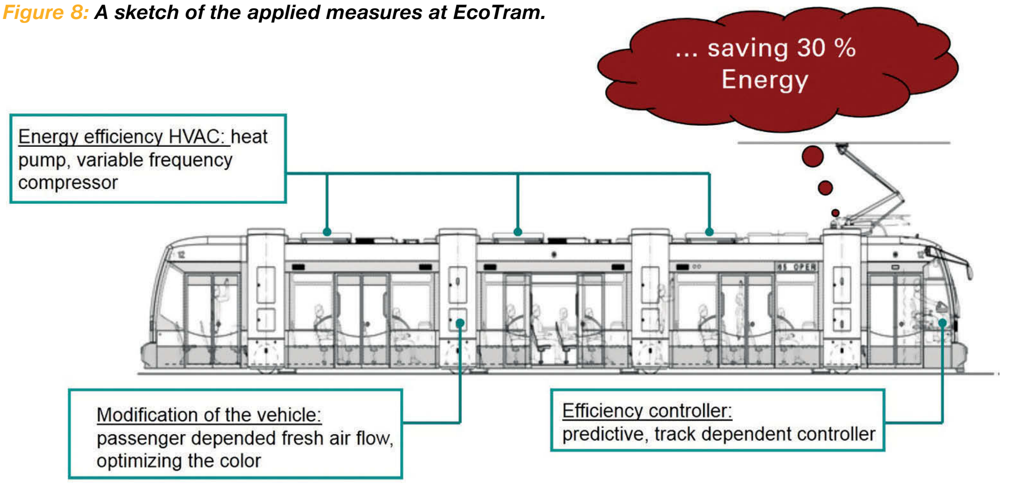
The power consumption in service is now being compared with the climatic wind tunnel tests and the measurements carried out on the conventional vehicle in 2010. Despite the long reference periods (15 and 9 months, respectively), this comparison is relatively difficult due to substantial differences in the ambient conditions. The **main difference** is to be found in the frequency distribution of the exterior temperature and thus also the power consumption of the HVAC units. Nonetheless, the saving potential of the EcoTram II as compared to the conventional vehicle is clear in principle. In view of this, the extensive measurements carried out under similar conditions in the climatic wind tunnel have turned out to be extremely valuable for the comparison of energy consumption.

Results/Outlook

The EcoTram research project will be completed successfully in May 2014. It provides the basis for further developments in the design of the heat pump and the refrigeration cycle for dual use as well as new HVAC control methods. The Vienna climatic wind tunnel provided valuable assistance in the optimisation and assessment of the new developments. In addition to providing important technological findings for the partners involved, the project also achieved its main objective by demonstrating that modern HVAC systems can reduce the power consumption for tram air-conditioning by up to 30 %.

It should be noted in particular that many measures taken in the redesign of the HVAC unit and the vehicle can be implemented **easily and cost-efficiently** since many components are already available and can be readily adapted - see Figure 8. This applies not only to trams but also to other types of rail vehicles. It is to be hoped that the railway industry and operators will implement these findings in their new vehicles in order to improve both their profitability and environmental sustainability.

Figure 8: ***A sketch of the applied measures at EcoTram.***



Gregor Richter
Project manager
Rail Tec Arsenal

Pictures, unless otherwise cited, by Rail Tec Arsenal