ENERGY EFFICIENCY OF RAILWAY VEHICLES

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ABSTRACT

The railway vehicles in Switzerland consume, in addition to the traction energy, a high share of electricity for comfort purposes. About 20% to 40% of the electricity consumed by the vehicles is used for **h**eating, **v**entilation and **a**ir-**c**onditioning (HVAC). The goal of this project was to optimise the HVAC system of the vehicle EWII of the Swiss Rhaetian Railway (RhB) to reduce overall energy consumption without any detrimental impact on passenger comfort.

The project was originally initiated by the Physics Department of the University of Basel with financial support from the Federal Office of Energy and the Federal Office of Transport. Over the last three years, six vehicles of four different railway companies were monitored by the University of Basel. The Center for Integral Building Technology of the Lucerne University of Applied Sciences and Arts (HSLU) has built up models of the rail vehicles in a simulation program and carried out additional measurements (heating-up experiments, air tightness measurements and thermographic imagery) in order to assess their energy demand and to calibrate the model. Once the models were calibrated, the optimisation measures for the HVAC system and the vehicle hardware of the EWII could be defined and calculated.

By means of simulations, the highest heat losses in the vehicles could be identified. Two substantial reasons for the high energy demand in rail vehicles turned out to be the poor insulation of the wagon envelope and the lack of heat recovery in the ventilation system. Both are challenging to improve due to on-board space requirements for additional systems as well as the high expenses. The most feasible measures identified to reduce the energy demand were the reduction of the outdoor air flow rate by means of CO_2 control or the temperature setback at night and during high occupation periods. Measures of this type are considerably easier to implement and, result in important energy savings, especially the CO_2 control when no heat recovery is installed in the ventilation unit.

Simulation results have shown a saving potential for heating demand as important as 40% for railway vehicles in case of the combined implementation of the measures, control of the air flow rate as a function of the CO_2 concentration, the reduction of the wagon temperature set point by 2K and the night setback of the vestibules. For the whole EWII fleet of the RhB this would represent a possible energy saving potential of about 840 MWh/a.

Keywords: railway vehicles, energy efficiency, heating demand of HVAC systems, CO_2-control, measurements, simulations.

INTRODUCTION

The passenger railway vehicles in Switzerland consume, in addition to the traction energy, a high share of electricity for comfort purposes. Relevant factors influencing this share are the thermal properties of the housing, the implemented controls and the operational parameters such as the distance of travel and the immobilisation time. Three years ago, a research project was initiated by the Physics Department of the University of Basel with the objective of improving the energy efficiency of HVAC systems in public transports. Several vehicles of different railway companies were examined and a monitoring system was developed and placed in the train to measure temperature, heating and cooling energy, position (GPS) and meteorological data. The main objective was to define and quantify measures to reduce energy consumption of the HVAC without compromising the comfort quality for the passengers.

METHOD

The Center for Integral Building Technology of the Lucerne University of Applied Sciences and Arts (HSLU) has built up models of the rail vehicles in a simulation program. The following additional measurements were carried out in order to assess their energy demand and calibrate the models: heating-up experiments, air tightness measurements and thermographic imagery.

Heating-up experiment

The scope of the heating-up experiment was to define the active thermal mass and the heat coefficient of the vehicle housing. The vehicle was put in a railway depot with a constant ambient temperature and the inside heated up to about 40°C . The cool down behaviour of the vehicle was then analysed in order to extract the necessary information. Measurements of the heating-up experiment were used to correct the parameters such as thermal bridges or coefficients in the simulation model and calibrate the model up to the point of matching simulations results with data of the heating-up experiment.

Tracer gas measurements

Previous experiments had shown that the outdoor air flow rate of the ventilation system has a high impact on the accuracy of the simulation models of the vehicles. In order to assess precisely this variable, tracer gas measurements were performed. Basically, a room in the vehicle was filled up with a tracer gas, i.e. SF_6 until saturation was reached. The decay of concentration was then observed, when ventilation system was turned off. The decay is caused by either wall infiltration or by the supply of outside air through the ventilation system. Knowing the volume of the wagon and the gas concentration decay, the outdoor air flow rate can be calculated.

Internal heat gains

All internal heat sources need to be known as a function of time. In the case of railway vehicles, the gains from lighting and from people need to be considered. Heat flow of electronic devices used by the passengers can be neglected. Lighting in the wagons is always switched on during operation and was assumed to be constant. Passenger occupancy strongly varies during the day and was not available as measured values for the whole time. For this reason, the occupancy was calculated by means of the measured CO_2 concentration in the wagon and the outdoor supply flow rate of the ventilation. This consideration improved the accuracy of the simulation model a lot against the assumption of a constant number of people over the operation period.

Simulation models

The vehicles were modelled and simulated in the software program IDA ICE. This software originates from the building sector and is widely used in research and engineering applications. The input data to the model consist in the geometrical and physical properties of the wagon, (especially the housing), the HVAC equipment including its control, the internal heat gains and the outside climate (temperature, solar irradiation and wind). The final model was calibrated with the help of the long term measurements by the University of Basel in combination with the stationary heating-up and tracer gas measurements and passenger countings. Once the models were calibrated, the optimisation measures for the HVAC units and the vehicle hardware could be defined and the highest energy saving potential in the vehicles could be identified.

Definition of Measures

In a first step, the energy flow diagram was generated. Ideas on how to optimise the wagon envelope and the operation of the HVAC system were gathered and evaluated in collaboration with the railway companies (Figure 1). The analysed measures were assigned to three categories: envelope, HVAC and operation. The measures were examined according to their energy saving potential and to the expenditure needed to implement the measures on an existing vehicle. The measures were classified into three levels, low, medium and high according to their expenditure. The lowest expenditure represents measures with small adjustments such as control and regulation of the HVAC systems. These measures can rapidly be implemented and are cost-efficient. Measures with medium expenditure affect additional or different HVAC components. The third category with the highest expenditure concerns the improvement of the opaque and transparent parts of the envelope.

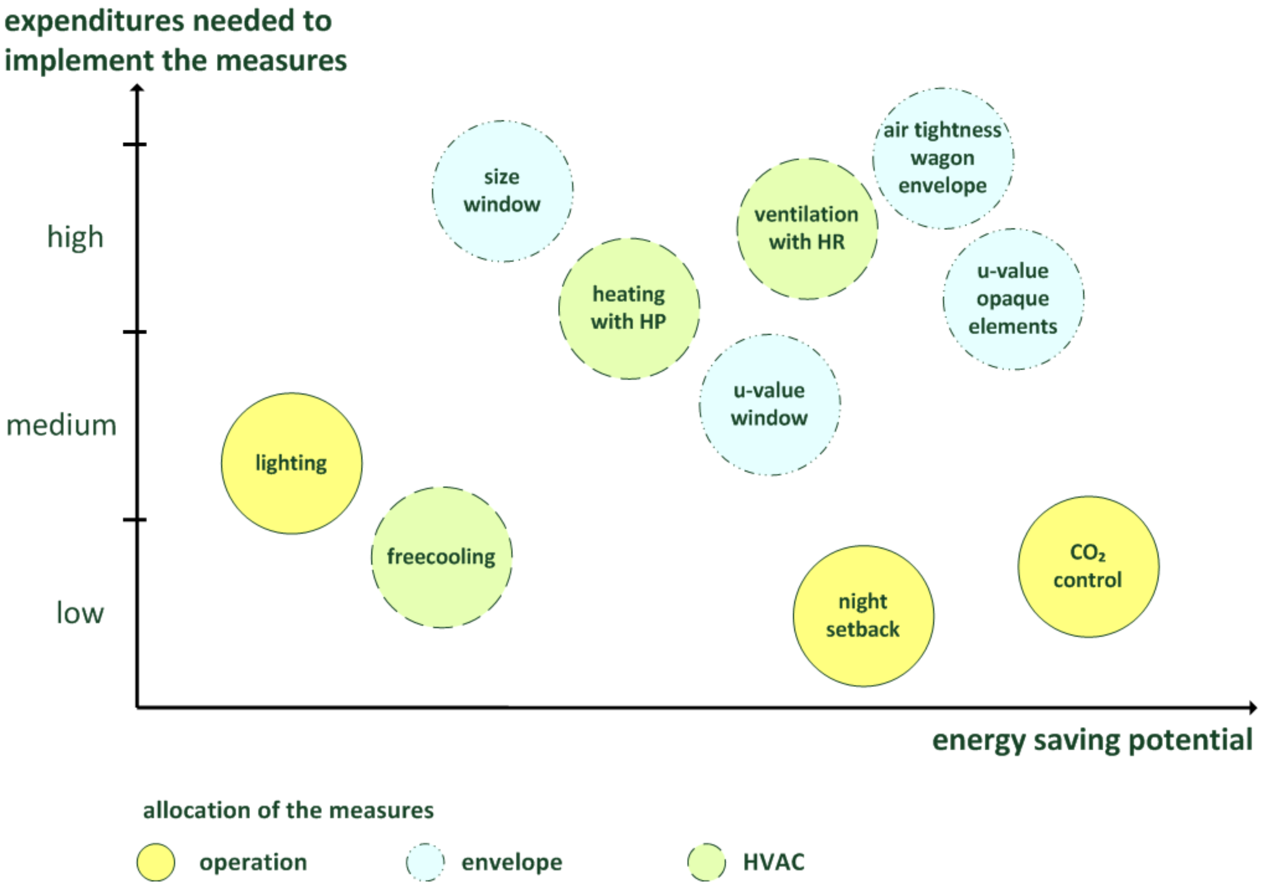

Figure 1: Qualitative cost-benefit assessment for the different measures (the assessment was performed by railway experts).

In a second step, defined measures were tested on the model of a specific wagon, the EWII of the Swiss Rhaetian Railway (RhB), and their energy saving potential was assessed.

RESULTS

Energy flow diagram

The energy flow diagram in Figure 2 shows the energy balance of the EWII of the Swiss Rhaetian Railway (RhB) on the base of the climatic data of the year 2011, i.e. the total heat gains (on the left) and heat losses (on the right) of the wagon for comfort purposes without considering the traction energy. “Solar” stands for solar heat gains through windows, “Light” the heat gains from lighting and “People” for heat gains from the passengers. The passenger room is conditioned by heating of the ventilation supply air, whereas the vestibules at the entrances are heated by radiators. The radiators have a three-stage manual control without temperature sensor. For this reason, the effective heat input of the radiators lead to a high uncertainty in the simulations.

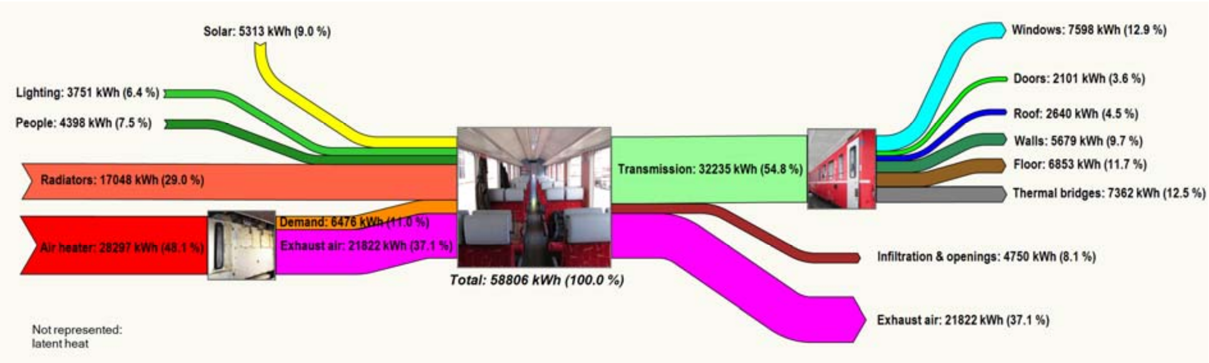

Figure 2: Energy flow diagram of the EW II (RhB) based on the simulations.

The results show that 55% of the heat losses are going through the envelope of the wagon (transmission losses) and 37% through the exhaust air of the ventilation system. Infiltration (incl. door openings) are responsible for 8% of the total heat losses. This shows that two substantial reasons for the high energy demand are the poor insulation of the wagon itself and the high outdoor air flow rate with a lacking heat recovery of the ventilation system. Not represented in figure 2 is the energy saving potential due to the reduction of the internal temperature set point and to the reduced operation times, inducing a proportional reduction of the energy flows.

Possible measures with their energy saving potential

A total of seven different measures were simulated for the EW II and the energy saving potential of each measure is shown in Figure 3. The five options represented on the left side are single measures (not cumulated), whereas the two options on the right side are a combination of left hand measures. Since the heat gains from lightning, people and solar irradiation are identical in all options, only the heat demand of the radiators and air heaters are represented.

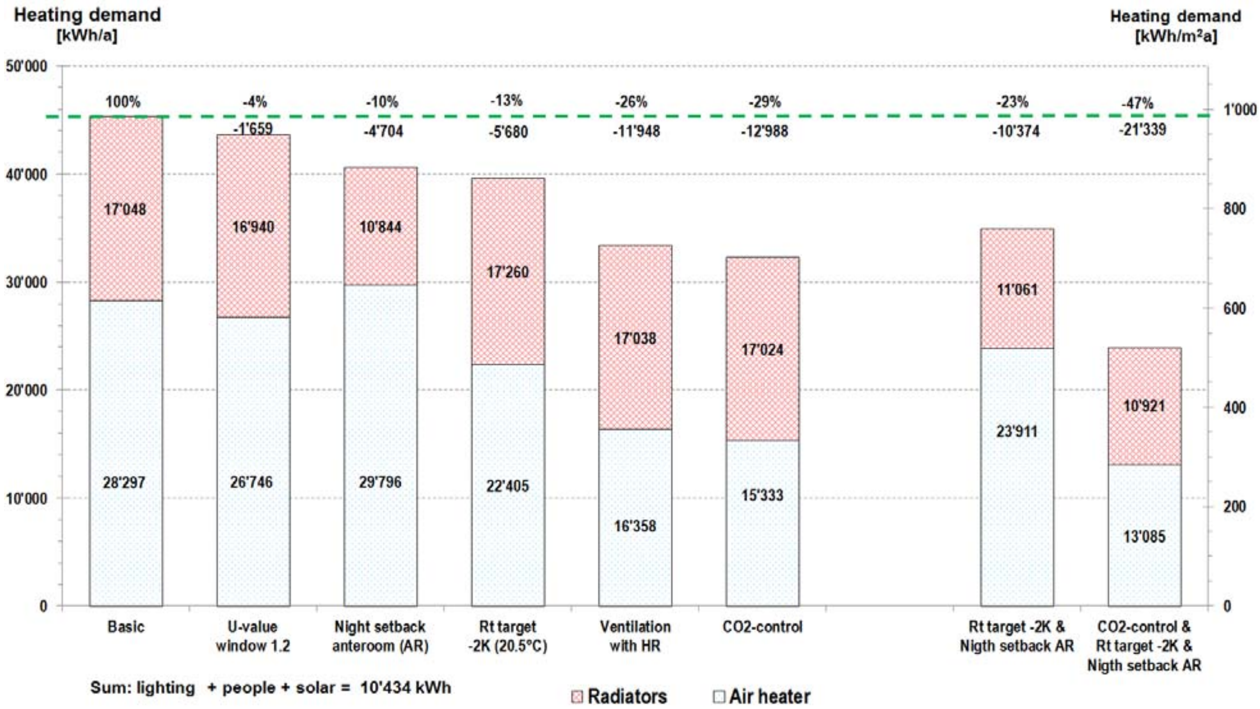

Figure 3: Heating demand of the EW II (RhB) after implementing different measures. The five options represented on the left side are single measures (not cumulated), whereas the two options on the right side are combined measures.

In the basic case, the U-value of the windows equals 3.1 W/m^{2}K. In the first option, this was reduced to 1.2 W/m^{2}K. This measure results in a 4% reduction of the heating demand.

In the second option, the air temperature of the two vestibules is reduced the same way (night set back) as in the passenger room. An anti-freeze protection to a set point of 6°C is assumed. This measure saves up to 10% of the heating demand.

The reduction of the indoor air temperature in the wagon from 22.5°C to 20.5°C (option 3) reduces the heating demand by 13%.

Another possibility to diminish heating demand is to implement a heat recovery (HR) in the ventilation system. The antifreeze protection for the HR was considered by limiting the exhaust air temperature to 1°C. The installation of a heat recovery system would allow 11’948 kWh or 26% of the heating demand to be saved.

The demand control of the outdoor air flow rate as a function of the CO_2 concentration (option 5) has shown even a slightly higher potential than the HR system. The set point has been set to a maximum of 1’000 ppm CO_2 concentration. This way, the heating demand can be reduced by around 29%.

The heating demand can be reduced further if more than one measure is implemented. The combination of the reduction of the wagon temperature by 2 K (option 2) and the night setback of the vestibules (option 3) can reduce heating demand by 23%.

If these two measures are combined with the CO_2 control of the air flow rate (option 5), the heating demand can be reduced by 47%, which corresponds to a saving potential of 21’000 kWh per year.

DISCUSSION

By means of a heating-up experiment and tracer gas measurements, a simulation model that reproduces the thermal mass, the heat losses through the envelope and the HVAC system of trains could be built up and validated. The heat demand of the specific railway vehicle (EWII of the RhB) could be represented and several improvement measures could be simulated.

The results have shown that the single measure which reduces the most the heating demand (-29%) is the demand control of the outdoor air flow rate as a function of the CO_2 concentration. This can be implemented at relative low expenses by integrating CO_2 sensors and a fan speed control in the ventilation system. The installation of a heat recovery in the ventilation system has fairly the same reduction potential as the CO_2 control, but leads to much higher expenses, since it requires the installation of additional components, which is difficult on existing wagons due to shortage of space. The improvement of the envelope insulation was not further analysed since this measure is only feasible in a total revision of the wagon. This measure is costly and requires space inside the wagon, which is hardly available.

By the simulations it could be shown that the simultaneous implementation of three relative easy and cost-effective measures in the wagon (the CO_2 control of the air flow rate, the reduction of the wagon temperature by 2K and the night setback in the vestibules), can reduce the heating energy demand by more than 40%. The implementation of these measures to all 40 EWII wagons of the RhB in operation would reduce their annual heating energy consumption by 840 MWh. The annual electricity consumption of the entire SBB passenger fleet is about 1’200 GWh [4]. Assuming that about 20% of this energy is used for the HVAC system, and 30% of it can be saved by the presented measures, about 70 GWh of electric energy could be saved annually for the SBB passenger fleet.

There are several other types of public transportation vehicles like buses, trams, air planes or ships, which presumably present a great energy saving potential for their comfort installations. These will also have great importance in future electric cars, since the heating and cooling demand highly affects the distance range of the vehicle. By means of thermal simulations, it is possible to calculate the energy demand of the comfort facilities of these transportation vehicles in detail and to assess different energy efficiency measures.

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