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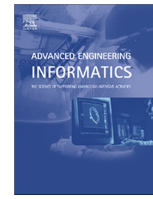

Identification of representative operating conditions of HVAC systems in passenger rail vehicles based on sampling virtual train trips

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ABSTRACT

Simulation-driven development and optimization of heating, ventilation and air-conditioning (HVAC) systems in passenger rail vehicles is of growing relevance to further increase product quality and energy efficiency. However, today required knowledge of realistic operating conditions is mostly unavailable. This work introduces methodologies and tools to identify representative operating conditions of HVAC systems in passenger rail vehicles. First a Monte-Carlo-simulation approach was employed to acquire a large set of close-to-reality HVAC operating conditions based on simulated train trips. Sampling simulated train trips bypassed the issue of unavailability of appropriate real-world data. Furthermore the approach allowed high flexibility in considering HVAC-relevant factors associated to different categories of trains, rail networks, operation profiles and meteorological conditions. Second, algorithms and methodologies such as *k*-means clustering and an adapted Finkelstein–Schafer statistical method were implemented to identify representative HVAC operating conditions from the sampled dataset. Final results comprise a set of time-independent HVAC operating points with associated frequencies of occurrence (ROC-points) as well as a set of time-domain signals for representative days (ROC-signals). These results are input for stationary or dynamic system-level simulations, which are used to support design decisions. The developed methodology was exemplarily applied to urban/suburban trains in Switzerland.

1. Introduction

1.1. Motivation and objectives

In passenger rail transportation typical heating, ventilation and air-conditioning (HVAC[1]) systems fitted to rail vehicles account for up to 30% of the overall energy demand [1]. A reduction of energy demand allowing decreased operating costs and lower environmental impact becomes increasingly important in the rail HVAC industry. Consequently it is the task of engineers to identify innovative, efficient, and feasible HVAC concepts as well as effective measures of HVAC optimization.

During real-world operation a rail HVAC system is exposed to a wide range of transient operating conditions. Reasons include varying thermal loads within the vehicle, changing meteorological parameters, and different operation profiles of a train. Thus it is essential to consider representative HVAC operating conditions (ROC) as a base for effective decisions on HVAC system design and optimization right from early phases of the system development process. However, today operating conditions being representative of a specific real-world application are mostly unavailable. Instead, the standards DIN EN 14750-1:2006-08 [2], DIN EN 13129-1:2003-01 [3], and typical customer requirement specifications define single stationary design points, which serve as the dominant criterion for HVAC design. These design points represent extreme operating conditions, which are typically rarely encountered in real-world operation. Vice versa, frequently encountered part-load conditions are usually considered insufficiently today.

Besides serving as an input to front-loading in system development, widely acknowledged representative operating conditions can support communication between system manufacturers, customers, and potentially legislative bodies. Driving cycles (such as the New European Driving Cycle) used to assess emission levels and fuel consumption of motor vehicles are a good example. In a similar way rail HVAC 'load cycles' would be valuable for a realistic,

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[1] Definition of specific abbreviations used in this article: HVAC – heating, ventilation and air-conditioning; ROC – representative operating conditions of HVAC systems in passenger rail vehicles; GTFS – general transit feed specification.

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transparent, and communicable assessment of different HVAC systems. Here energy efficiency (relative to investment costs) can be seen as a key parameter of HVAC system assessment.

This work introduces a methodology to identify representative rail HVAC operating conditions as a set of time-independent points (ROC-points) and as a set of time series (ROC-signals) of HVAC-specific variables. HVAC-specific variables may include ambient air temperature, ambient air humidity, heat flow of solar radiation, passenger occupancy, and train driving velocity. ROC-points are intended for application in stationary studies of HVAC systems, while ROC-signals address dynamic studies. Out of the basic HVAC operating modes including standby, pre-conditioning, and passenger-operation, the passenger-operation mode is seen as most important and therefore considered in the work at hand. The remaining HVAC modes are left to future studies.

As an objective, generated ROC themselves shall be independent of a specific HVAC implementation to allow comparability of different HVAC concepts and control strategies. Furthermore ROC must appropriately aggregate the total population of HVAC operating conditions, or – in a practical sense – a large number of samples drawn from that total population.

Generated ROC are intended to be used as inputs to numeric simulation models comprising a specific HVAC system in junction with a rail vehicle. Such models may be complex and computationally demanding. Simulation-based studies with these models and ROC as input shall yield results that give insight into the overall system performance. In theory, very similar results should be derived from simulations with the same models but with the total population of HVAC operating conditions as input. So the practical relevance of applying ROC is to obtain insight expressive of real-world conditions with available resources (an up-to-date desktop computer) and with reasonable effort (time to run complex simulation models).

Typically the railway industry is a project business. HVAC systems are engineered to meet the specific demands of a given train service provider (the customer). As a consequence a one-time definition of an overall standard load profile would be insufficient. Hence the required methodology and tools shall allow flexible capturing of project-specific boundary conditions including the regional climate and the train network of future operation. To achieve the objectives the following steps were carried out in this work:

- Development of a simulation model on thermal loads of a passenger rail vehicle.
- Acquisition of data to appropriately describe real-world influencing factors.
- Application of a Monte-Carlo-simulation approach for sampling close-to-reality HVAC operating conditions based on virtual train trips.
- Development of a methodology to identify a set of points (ROC-points) and a set of signals (ROC-signals) of representative HVAC operating conditions from the sampled data set.

In the present work ROC-points describe the distribution of operating conditions encountered in the sampled trips. Here frequencies of occurrence define weighting factors. Time-dependence is not regarded for ROC-points. On the other hand, ROC-signals are constituted by sets of related time-domain signals of variables characterizing HVAC operation. Each set is associated to an appropriate weighting factor and its signals are defined for one full day. For both, ROC-points and ROC-signals, weighting factors are relevant regarding the computation of yearly energy demand: The demand of the HVAC system as derived from simulating one day of ROC-signals or one ROC-point is multiplied by the corresponding factor. Finally the sum of the energy demand values is an approximation of the overall yearly energy demand.

In simulation-based studies on HVAC systems it depends on the research question and the overall system concept, whether ROC-points or ROC-signals shall be applied. Basically ROC-points are the input to stationary simulations, whereas ROC-signals are used for dynamic simulations. The key question is whether time-dependence and storage effects are of relevance or not. For instance, if charging/discharging cycles of a thermal energy storage are to be analyzed, ROC-signals are required.

This paper is structured as follows: First a brief overview of HVAC system boundaries and related work on ROC is given. In Section 2 key variables are defined and the methodology and input data for the random sampling process are described. In Section 3 the methodology for the identification of ROC is outlined. For demonstration, the methodology and tools developed were applied to generate ROC for urban/suburban trains operating in Switzerland. Results are given in Section 4 followed by a discussion and conclusion in Section 5.

1.2. Overview of loads and influencing factors on a rail HVAC system

Fig. 1 schematically shows a passenger rail vehicle with HVAC system. As it can be seen the typical air flows between vehicle and the HVAC unit result in a closed loop. The scheme also indicates key influencing factors on thermal loads, which are to be compensated by the HVAC system.

The time-variance of different influences may differ greatly throughout operation: As an example, the ambient temperature influencing heat influx (in cooling mode) or heat loss (in heating mode) basically changes slowly in the course of a day. On the other hand, heat loads imposed by solar radiation may change rapidly as the exposure of vehicle side walls and windows varies depending on the orientation of the train track in relation to the sun. Switching between travelling on the surface versus in a tunnel generally imposes abrupt changes of influences. At stations door opening goes along with infiltration of ambient air and possibly fast shifts of passenger occupancy. Passengers cause sensible and latent thermal loads and require a certain volume flow of ambient air supply to compensate CO_2-production of the human metabolism. The influence of convection at the outer vehicle skin and the impact of solar radiation vary because the relevant outer heat transfer coefficient depends on driving velocity.

1.3. Related work on representative operating conditions of rail HVAC systems

In [4] technical recommendations on the specification and verification of energy consumption of rolling stock are presented. There the primary focus lies on traction. The new draft standard prEN 13129:2013 [5] incorporates a set of signals characterizing HVAC operation throughout one day of winter, summer, and intermediate season respectively. However, climatic zones are not differentiated here. The approaches in [4,5] do not sufficiently represent ROC with respect to applications aimed at in the present work.

Small sets of 6–12 operating points associated to weighting factors are proposed in [1,6].[2] These small sets of points aim at minimal effort in physical testing in climatic chambers. In contrast, the work at hand focuses at a more detailed set of representative points for application in stationary numeric simulations and at signals for dynamic numeric simulations. Considering the methodology in [1] a random selection process comparable to a common approach used to identify driving cycles is incorporated. As a reference a compre-

[2] Ref. [6] was elaborated in cooperation with the German Railway Industry Association (VDB).