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Reducing infection risk in electric public transport vehicles by thermal inactivation: Sensitivity, limitations and optimization

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Executive Summary
Thermal storage systems can increase the range of battery electric vehicles in public transport by providing the heating power for cabin heating. In cold climatic regions in particular, the heating demand accounts for a large proportion of the vehicle's energy requirements. However, the thermal energy that has to be provided for heating could also reduce the risk of infection from aerosols in the vehicle through thermal inactivation. The performance of such a system depends on the boundary conditions of the vehicle and the environment. This study uses a Modelica simulation model to demonstrate the application, control, optimization and limitations of thermal inactivation of airborne pathogens for the passenger cabin of a people mover.

Heavy Duty electric vehicles and buses, Health and Safety Considerations, Thermal Management, Energy Management, Modelling and Simulation

1 Introduction

The COVID-19 pandemic has shown the relevance of infection transmission by aerosols. Previous studies demonstrated, that the infection of several passengers by one index person is possible in public transport vehicles [1]. Reduction of the infection risk can be achieved by dilution of the aerosols with fresh air, by filtration through high efficiency filters or by inactivation of the infectious aerosols. However, increasing the fresh air supply increases the heating power demand significantly [2] while higher efficiency filters increase the pressure drop and thereby power demand of the HVAC system and require regular replacements [3]. For inactivation of aerosols generally UVC-light or plasma are used [4]. Another possible inactivation method is thermal inactivation, which was already investigated for the treatment of indoor air in buildings [5]. To achieve a thermal inactivation the recirculated air of the vehicle must be heated in the HVAC system to an appropriate inactivation temperature for an adequate exposure time. Compared to buildings, thermal inactivation could especially be suitable for public transport vehicles in flu season in winter, as they require high heating loads in comparison to their cabin volume due to big window areas and thin wall insulation. A previous study of Grübbel et. al. has already calculated a possible average infection risk reduction of up to 23.8% from October to March for a people mover concept in the City of Edmonton in Canada [6]. In this study, the sensitivity of infection risk reduction by thermal inactivation to the boundary conditions of the vehicle and environment, the inactivation characteristics of the microorganism, an optimization of the temperature control for thermal inactivation and a comparison to the risk reduction by fresh air exchange and HEPA-Filters are presented.

2 Methods

The performance of the thermal inactivation depends on the heating load and thereby the ambient temperature, as no additional energy should be used to achieve the infection risk reduction. Therefore, a thermal cabin model of a people mover, similar to the DLR U-Shift [7] is used to calculate the thermal inactivation with Modelica. The thermal cabin model considers all thermal loads of the vehicle, including occupants, ambient heat transfer, air supply and radiation as well as thermal masses as visualized in Figure 1. The model was validated using the measured temperature data of Torregrosa-Jaime et. al. of an battery electric Iveco ALTRA Daily minibus [8]. For validation purposes two electric 2000W heaters were used to heat up the vehicle cabin until it reached 50°C, which was stationary in a garage. Afterwards the heaters were turned off and the vehicle cabin cooled down until it was close to ambient temperature.

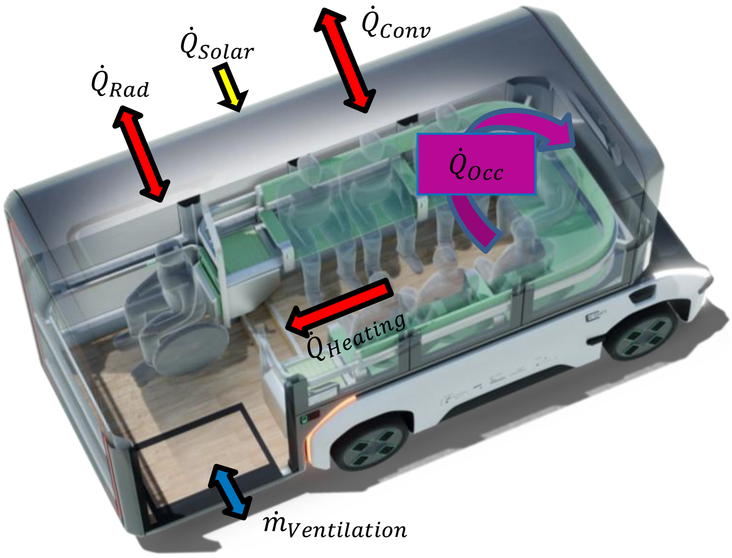

Figure 1 Simplified scheme of the cabin model

The parameters of the vehicle cabin for the validation of the model with the experimental data of the Iveco ALTRA Daily are listed in Table 1. The other parameters were set according to the publication of Torregrosa-Jaime et. al. [8]

Table 1 Cabin parameters of the Iveco ALTRA Daily for the validation of the thermal cabin model

Parameter	Value	Unit
V_Air	24.3	m^3
A_Walls	27.9	m^2
A_Roof	10.6	m^2
A_Floor	10.6	m^2
A_Seats	30	m^2
A_Glass	8.2	m^2

Then, the model was adapted with the following parameters to the cabin of a battery-electric people mover, similar to the DLR U-Shift cabin. The vehicle cabins are of similar size but the considered people mover has significantly larger window areas. The parameters are listed in Table 2.

Table 2 Cabin parameters of the people mover cabin

Parameter	Value	Unit
V_Air	20	m^3
A_Walls	20.6	m^2
A_Roof	11.8	m^2
A_Floor	11.8	m^2
A_Seats	25	m^2
A_Glass	24.1	m^2

After validation and adaption of the model the heating power P_H can be calculated in dependence of the the operating conditions of the vehicle.

In addition to the thermal storage, the system for the thermal inactivation of microorganisms in the ambient air of public transport vehicles consists of a fan, bypass and a thermal inactivation volume V_i in which the necessary inactivation temperature can be set. The bypass is necessary to control the outlet temperature of the thermal storage which fluctuates during the operation. The exposure time of the air can be calculated with the following equation:

$$t_{exp} = \frac{V_i(T_i - T_C)c_p\rho}{P_H} \tag{1}$$

Where T_i is the inactivation temperature, T_C the cabin temperature, c_p the specific heat capacity of air and ρ the density of air. The thermal inactivation can then be determined by the following first-order reaction equation:

$$\frac{C}{C_0} = e^{-kt_{exp}} \tag{2}$$

Here C_0 (TCID50/m^3) is the initial concentration of the aerosolized pathogen while C (TCID50/m^3) is the concentration after the inactivation. The exposure time t_{exp} results out of the size of the inactivation volume in the HVAC system, the inactivation temperature and the current heating power demand. Due to the higher airflow the exposure time decreases with increasing heating power. The rate constant k determines the temperature dependent speed of the inactivation and is given by an Arrhenius approach:

$$\ln(k) = -\frac{E_a}{RT} + \ln A \tag{3}$$

To model the rate constant k various models by Yap et. al. [9] and Hessling et. al. [10] for different Coronaviridae are used. The hygienic air exchange rate for the vehicle is then calculated as follows:

$$HAER = \frac{C_0}{C}\frac{3600P_H}{(T_i - T_C)c_p\rho}\frac{1}{V_C} \tag{4}$$

The relative infection risk reduction is calculated using the RiSiCo model [11], taking into account the air exchange rate, occupancy rate and cabin size in comparison to the bus operating without the HAER provided by thermal inactivation by the following equation:

$$RR_{inf} = \frac{\bar{\bar{n}}_{Aerosol}}{\bar{\bar{n}}_{Aerosol,ref}}\frac{V_C\,ACH}{V_{C,ref}\,HAER + V_C\,ACH}\,\frac{n}{n_{ref}}\,\frac{\tau}{\tau_{ref}} \tag{5}$$

Where $\bar{\bar{n}}_{Aerosol}$ is the aerosol exhalation rate, ACH the air changes per hour, n the number of passengers and τ the duration of the travel. As we assume that $\bar{\bar{n}}_{Aerosol}$ and τ stay constant the equation reduces to:

$$RR_{inf} = \frac{V_C\,ACH}{V_{C,ref}\,HAER + V_C\,ACH} \tag{6}$$

The inactivation temperature T_i in the inactivation volume is either set to fixed value, or controlled by a PI controller in Modelica to account for the varying heating power P_H. The PI controller is programmed so that 99% of the initial pathogens are inactivated according to the model. This could increase the performance of the system compared to a fixed inactivation temperature. As fixed inactivation temperatures values between 90°C and 150°C are investigated. The size of the inactivation volume was determined by a simulation study and defined in dependence of the maximum heating power of the HVAC system as follows:

$$V_i = 1.5 \frac{cm^3}{W} P_{H,max} \tag{7}$$

To assess to potential effectivity of the system models for thermal inactivation from Yap and Hessling et. al. are evaluated for different locations. Furthermore, the sensitivity to changes in cabin temperature and air changes per hour (ACH) of the model are discussed and the energy consumption is compared to other possible methods of air quality improvement.

3 Results

Figure 2 shows the result of the thermal validation of the cabin model. The temperature curve of the simulation shows general agreement with the measured temperature from Torregrosa et al.. The R^2 value was calculated at 96.8% while the RSME is 1.26K. The biggest deviation appears with 3.5K at the end of the cooling down phase were the experimental data also shows some irregularities.

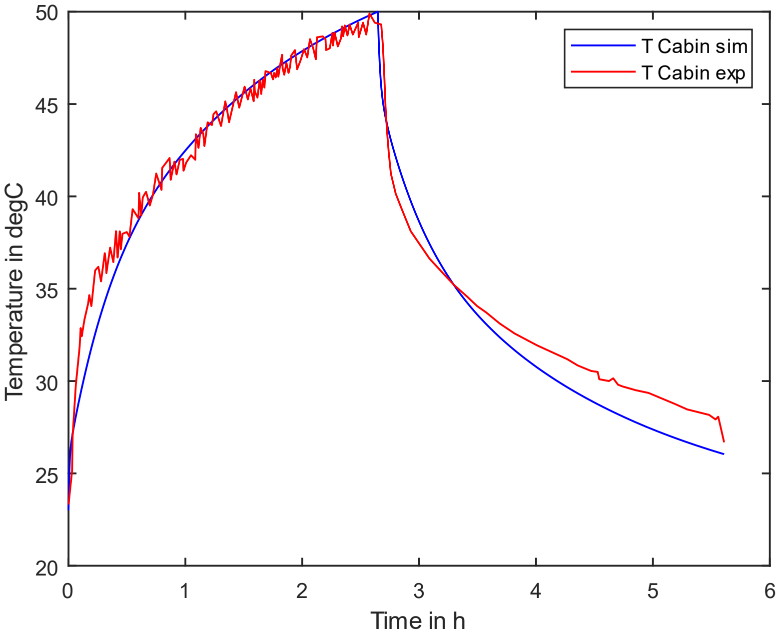

Figure 2 Comparison between the experimental and simulated cabin temperature of the IVECO mini-bus

In Figure 3 the daily averaged Hygienic Air Exchange Rate (HAER) is visualized for operating the People-Mover in Göteborg and Stuttgart from beginning of October to the end of March. The thermal inactivation is modelled for SARS-CoV-2 according to Yap et. al. [9]. The daily HAER varies as it is directly dependent on the heating power required. Therefore, the highest HAER is achieved for days with the lowest ambient temperatures. This shows the strong dependence of the possible thermal inactivation on the ambient conditions. The seasonal average HAER in Göteborg is 9.0 and in Stuttgart 7.4 for a variable inactivation temperature controlled by an PI controller from October till the end of March. This results in an infection risk reduction of 18.4% and 15.6% respectively. This shows the influence of the location on thermal inactivation. Compared to a fixed inactivation temperature of 130°C the HAER was increased by 5.5% and 8.1%.

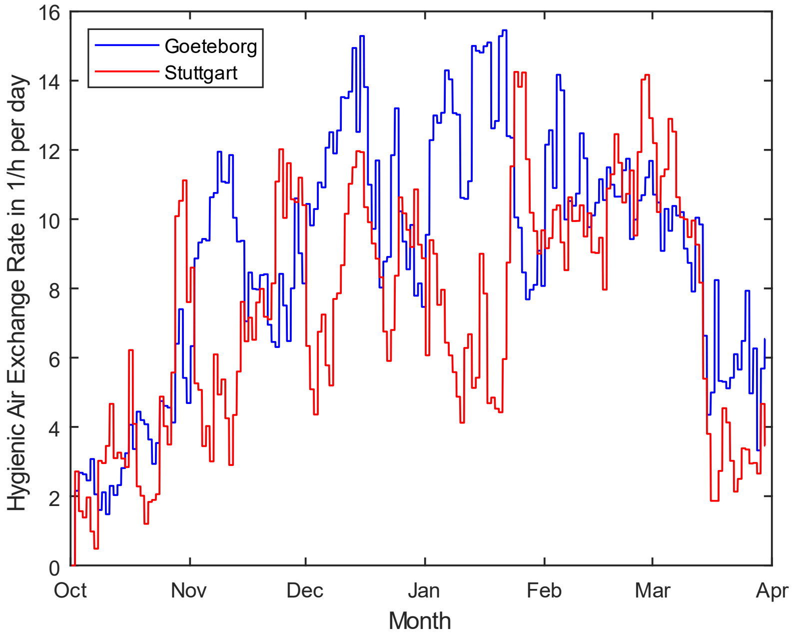

Figure 3 Daily average HAER in Stuttgart and Göteborg

To further discuss the impact of the inactivation temperature, T_i is varied between 90°C and 150°C for operating the people mover in Göteborg using the model of Yap et. al. for SARS-CoV-2. As displayed in Figure 4 the seasonal HAER reaches its maximum with 8.9 at 120°C inactivation temperature. The PI controlled inactivation temperature offers a by 1% increased HAER of 9 as previously mentioned and offers the benefit of a constant and controlled inactivation efficiency.

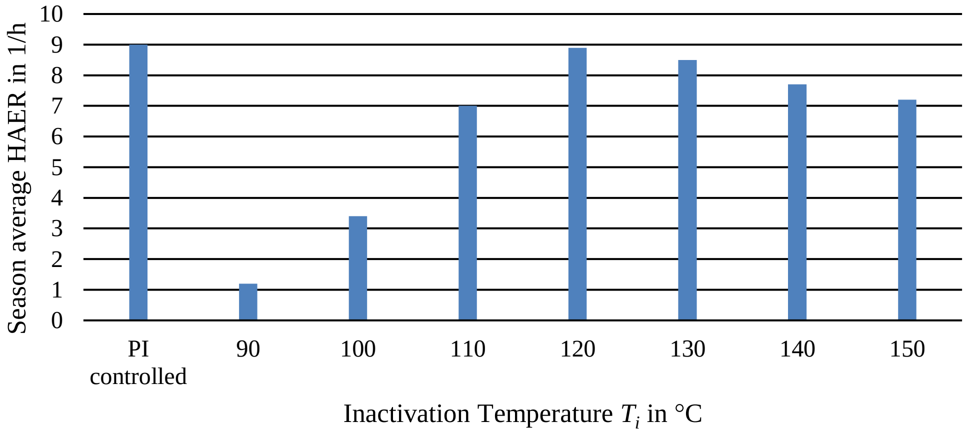

Figure 4 HAER for operating the people mover in Göteborg in dependence of the inactivation temperature; ACH=40

In addition to the inactivation temperature, the HAER of thermal inactivation also depends on the air exchange with fresh air. An increased number of ACH increases the heating power required to keep the cabin at the defined comfort temperature of 20°C. However, as the general ACH is higher, this reduces the possible additional risk reduction due to thermal inactivation. Different sources for air exchange rates for buses can be found in the literature. The Association of German Transport Companies (VDV) requires a minimum air exchange rate of 15 m^3/h per passenger [12]. In the people mover under consideration, which is designed for a number of 15 passengers, this results in a minimum air exchange rate of 11.25 per hour. The RAL German Institute for quality assurance requires a minimum air exchange rate of 15/h for comfortable coaches at an outside temperature of -20°C and a cabin temperature of 20°C [13]. Shinoara et. al. [14] measured the ACH for an IVECO bus operating in Japan at 8.5 1/h during summer in stop & go operation with regular door openings. However, the ACH of door openings is dependent on the temperature difference. A calculation of the air exchange through a door opening of 20s every 90s using an approximation according to the DIN 2078 resulted in a maximum air exchange rate of 30 air changes per hour for a constant temperature difference of 20K between the indoor and outdoor environment for the considered people mover with one door. This overestimates the air exchange through door opening due to the assumption that it occurs instantaneously and the temperature difference stays constant. Nevertheless, an air exchange rate of 40 air changes per hour was considered as the upper limit. This is the sum of possible leakages, the minimum requirement for air exchange during operation and door openings as a worst-case scenario for the design of the heating capacity. This air exchange rate was also used to dimension the inactivation volume and determine the previous HAER. In order to determine the influence of the air exchange rate on thermal inactivation, this parameter is varied from 10 to 40 air changes per hour for the operation of the people mover in Gothenburg using the thermal inactivation model Yap et. al. for SARS-CoV-2 and an PI-controlled inactivation temperature. Furthermore, the possible infection risk reduction through the HAER is calculated and displayed in Figure 5. This clearly shows that the HAER also increases as the ACH rises. This is to be expected, as a larger fresh air supply also causes a higher heating output as soon as the outside temperature is below the cabin temperature. The higher heat output increases the air flow rate through the thermal inactivation system. However, the potential risk reduction due to thermal inactivation is greatest with the lowest fresh air supply, although the HAER is also lowest here. The reason for this is that the HAER increases the total air change in the vehicle proportionally more at low ACH. This is due to the fact that heat loss through air exchange with the environment only accounts for part of the heating output. The heat loss through heat conduction, convection and radiation remains unaffected by this.

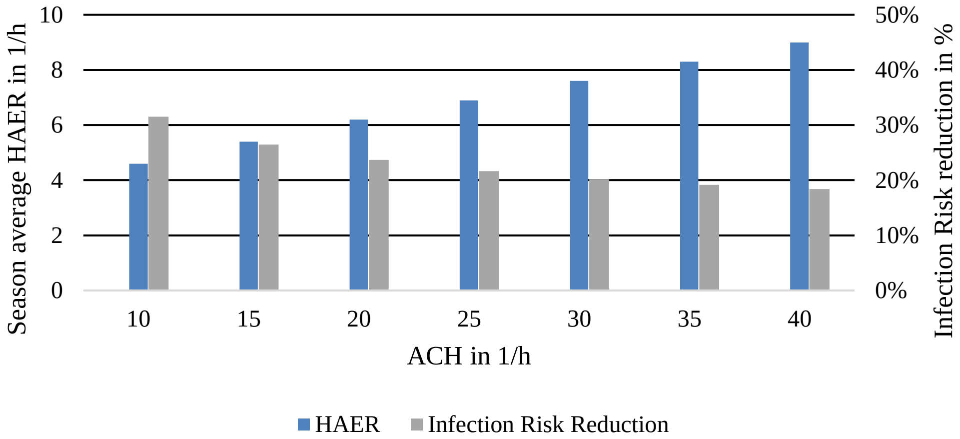

Figure 5 HAER and infection risk reduction in dependence on ACH; T_i: PI-controlled

An advantage of thermal inactivation is that no additional power is required, only thermal energy already used to heat the cabin. The risk reduction through thermal inactivation when heating the cabin in winter is based on a reduction in potentially infectious aerosols. This can also be achieved by other technical measures such as additional air exchange with fresh air or the use of HEPA filters. However, additional air exchange increases the heat output required to heat the cabin. HEPA filters offer the advantage of not increasing the heating power demand, but require an increased fan drive power, as they cause a pressure drop in the ventilation system. Simulations were carried out to assess these effects. The additional air exchange was added to the ACH and the additional power requirement for cabin heating was calculated. Furthermore, the necessary additional fan drive power was calculated for the integration of a HEPA filter with a pressure loss of 500 Pa at an overall fan efficiency of 50% according to the recommendations by the International Energy Agency [15]. The results are shown in dependence of the previously discussed original ACH for operating the people mover in Göteborg in Figure 6.

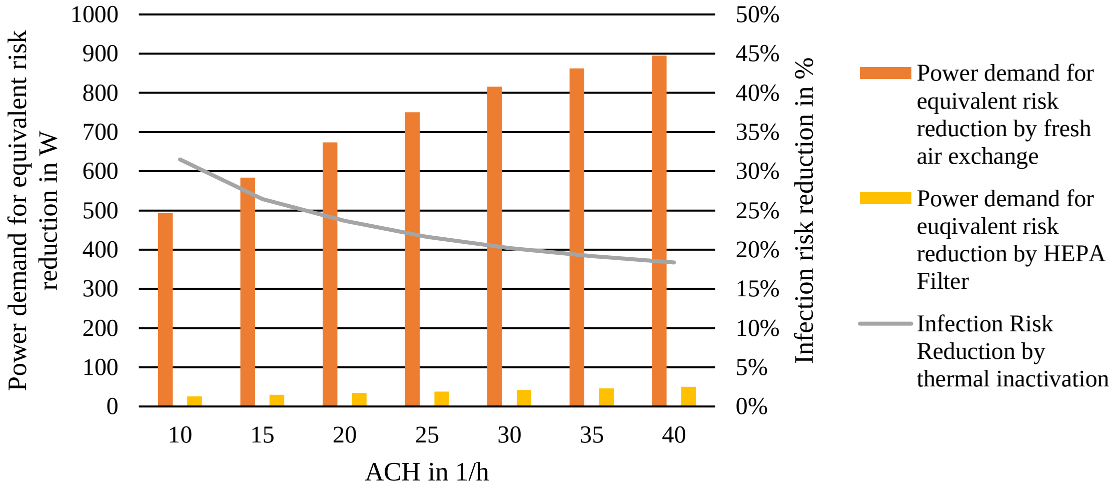

Figure 6 Infection risk reduction by thermal inactivation and power demand for comparable infection risk reduction by fresh air exchange and HEPA-filter in dependence on original ACH; T_i: PI-controlled

The power demand of the overall HVAC system for an equivalent risk reduction by fresh air exchange is increased by 14.4 to 16.5%, the relatively highest additional power requirement is caused at the lowest original ACH. Thermal inactivation can therefore significantly reduce the energy requirement of the HVAC system while maintaining the same risk of infection. In contrast the HEPA filter only increases the power demand by 0.8%. The fan power required to operate the HEPA filter is negligible in relation to the required heating power.

The HAER and possible infection risk reduction are not only sensitive to the location and vehicle boundary conditions but also to the inactivation characteristics of the potential pathogen. In Figure 7 the seasonal average HAER and possible infection risk reduction for operating the People Mover in Stuttgart Vaihingen are shown for three different models for SARS-CoV-1, MERS-CoV and SARS-CoV-2 from Yap et. al. [9] and Hessling et. al. [10] respectively with the maximum ACH of 40:

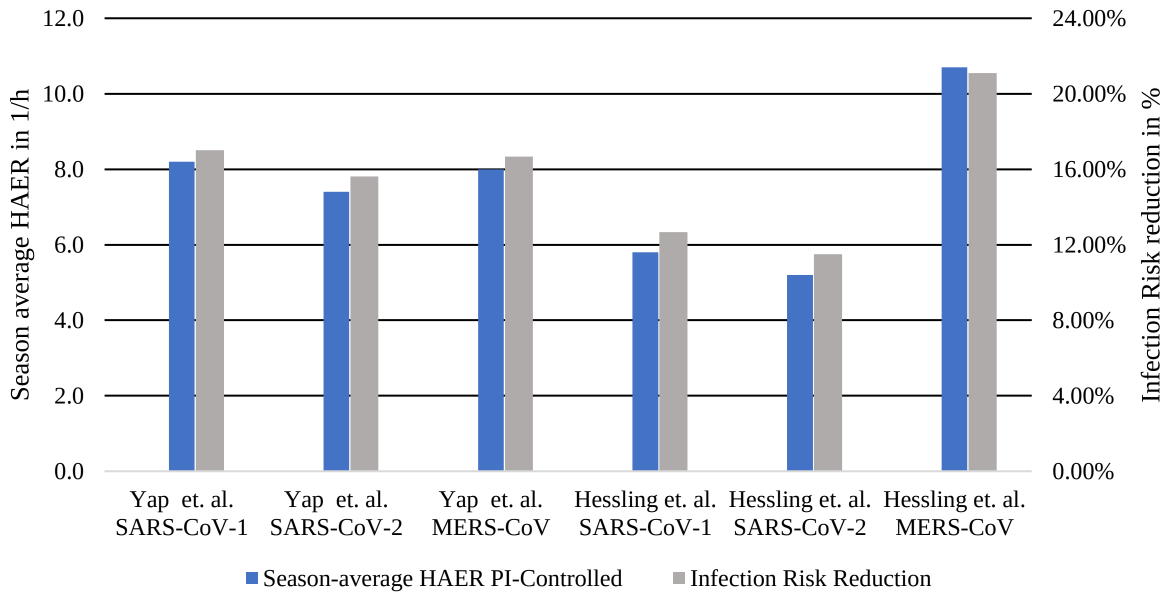

Figure 7 HAER and infection risk reduction calculated with models by Yap et. al. *[9]* and Hessling et. al. *[10]* for SARS-CoV-1 and SARS-CoV-2 in Stuttgart; ACH = 40; T_i : PI-controlled

The resulting HAER and risk reduction differ due to the different models. Assuming that the response of the microorganisms to thermal shocks is comparable due to their similarity, the HAER is between 6.0-9.2 1/h with CI=95%. The resulting risk reduction with CI=95% is between 12.1% and 18.5%.

4 Discussion & Conclusion

This study showed that infection risk reduction is possible by using the heating energy required for the cabin. By using thermal inactivation, approx. 13% of the energy required to heat the vehicle can be saved compared to increasing the air exchange rate with fresh air to achieve comparable infections risks. Compared to a HEPA Filter, the energy saving is significantly lower and <1%. However, thermal inactivation offers the advantage that the filters do not need to be replaced. The costs for regular filter replacement and maintenance should be considered in future studies. In contrast HEPA-filters offer constant air cleaning performance while the thermal inactivation system reacts sensitively to boundary conditions as location and temperature, inactivation characteristics of the pathogen and system parameters such as inactivation temperature. The suitability of such a system for different climatic regions must be demonstrated by further simulation studies. So far, the effectiveness has been demonstrated in regions with cold to temperate climates. Furthermore, the characteristics and modeling of the thermal inactivation of pathogens have a major influence on the applicability of thermal inactivation. It is advisable to obtain a more precise basis for modeling through further measurements, especially with short thermal exposure times, as models and experimental results currently available in the literature show deviations which could be based on different experimental setups.

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References

[1] Y. Shen, C. Li, H. Dong, Z. Wang, L. Martinez, Z. Sun, A. Handel, Z. Chen, E. Chen, M.H. Ebell, F. Wang, B. Yi, H. Wang, X. Wang, A. Wang, B. Chen, Y. Qi, L. Liang, Y. Li, F. Ling, J. Chen, G. Xu, Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China, JAMA internal medicine 180 (2020) 1665–1671. https://doi.org/10.1001/jamainternmed.2020.5225.

[2] C.A. Faulkner, J.E. Castellini, W. Zuo, D.M. Lorenzetti, M.D. Sohn, Investigation of HVAC operation strategies for office buildings during COVID-19 pandemic, Building and Environment 207 (2022) 108519. https://doi.org/10.1016/j.buildenv.2021.108519.

[3] M. Zaatari, A. Novoselac, J. Siegel, The relationship between filter pressure drop, indoor air quality, and energy consumption in rooftop HVAC units, Building and Environment 73 (2014) 151–161. https://doi.org/10.1016/j.buildenv.2013.12.010.

[4] G. Berry, A. Parsons, M. Morgan, J. Rickert, H. Cho, A review of methods to reduce the probability of the airborne spread of COVID-19 in ventilation systems and enclosed spaces, Environmental research 203 (2022) 111765. https://doi.org/10.1016/j.envres.2021.111765.

[5] M. Slavikova, J. Strukova, B. Klempa, F. Simancik, S. Pastorekova, V. Zelnik, J. Kopacek, Heat inactivation by high temperature as an approach to combat infections caused by airborne pathogens, Acta Virol. 67 (2023). https://doi.org/10.3389/av.2023.11640.

[6] Henrik Alexander Grübbel, Werner Kraft, Frank Rinderknecht, Simulative investigation of the thermal inactivation of SARS-CoV-2 in the cabin air of a people mover, in: International Society for Indoor Air Quality (Ed.), 18th International Conference on Indoor Air Quality and Climate: INDOOR AIR 2024, 2024.

[7] DLR, U-SHIFT: On-the-Road Modular Vehicle Concept, 2023, https://verkehrsforschung.dlr.de/en/projects/u-shift.

[8] B. Torregrosa-Jaime, F. Bjurling, J.M. Corberán, F. Di Sciullo, J. Payá, Transient thermal model of a vehicle's cabin validated under variable ambient conditions, Applied Thermal Engineering 75 (2015) 45–53. https://doi.org/10.1016/j.applthermaleng.2014.05.074.

[9] T.F. Yap, Z. Liu, R.A. Shveda, D.J. Preston, A predictive model of the temperature-dependent inactivation of coronaviruses, Applied physics letters 117 (2020) 60601. https://doi.org/10.1063/5.0020782.

[10] M. Hessling, K. Hoenes, C. Lingenfelder, Selection of parameters for thermal coronavirus inactivation - a data-based recommendation, GMS hygiene and infection control 15 (2020) Doc16. https://doi.org/10.3205/dgkh000351.

[11] D. Müller, K. Rewitz, D. Derwein, T.M. Burgholz, M. Schweiker, J. Bardey, P. Tappler, Abschätzung des Infektionsrisikos durch aerosolgebundene Viren in belüfteten Räumen; 2. überarbeitete und korrigierte Auflage. https://doi.org/10.18154/RWTH-2021-02417.

[12] VDV, VDV-Schrift 236: Klimatisierung von Linienbussen, 2018.

[13] RAL Deutsches Institut für Gütersicherung und Kennzeichnung e.V., Gütesicherung RAL-GZ 791 Buskomfort, Bonn, 2023.

[14] N. Shinohara, K. Tatsu, N. Kagi, H. Kim, J. Sakaguchi, I. Ogura, Y. Murashima, H. Sakurai, W. Naito, Air exchange rates and advection-diffusion of CO2 and aerosols in a route bus for evaluation of infection risk, Indoor air 32 (2022) e13019. https://doi.org/10.1111/ina.13019.

[15] Peter Schild, Mads Mysen, Recommendations on Specific Fan Power and Fan System Efficiency: Technical Note AIVC 65, Sint-Stevens-Woluwe, 2009.

Presenter Biography

Henrik Grübbel studied in Stuttgart and Linköping. He holds a B.Sc. and M.Sc. in aerospace engineering from the University of Stuttgart. Since 2021 he is a research associate and PhD candidate at the Institute of Vehicle Concepts at the German Aerospace Center (DLR). His research work is about the development of thermal storages with metallic phase change materials for the use in battery-electric vehicles. Currently he focuses on the investigation of the thermal inactivation of airborne pathogens in cabins of battery-electric public transport vehicles.