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Ultraviolet Germicidal Irradiation Development Method for Transportation Disinfection Modelling

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Abstract

How do you continuously sanitise a coach/bus? Travelling on a coach during the COVID 19 pandemic was risky, and still is in some regions. There are many means of viral transfer: fomites, which is via contact after touching an infected surface; through direct droplet ballistics after a cough, and finally through aerosolization of the sputum into the air. Clean hands and masks reduce the former two. Mitigating viral load aerosol accumulation within the bus is of personal, commercial and societal interest. Done correctly, the passengers are safer; the transport organisation maintains hygienic business conditions and the society sees the viral spread reduction. Ultraviolet Germicidal Irradiation (UVGI) has been in use in operating theatres and water plants for over 100 years to reduce viral and bacterial load in the air and water.

Valeo's Thermal Commercial Vehicles (TCV) product group proposed, developed and now manufactures the most powerful coach/ bus UV Purifier module available. If the module is located within direct reach of the main air conditioning inlet, disinfected air is then delivered and entrained into the vehicle HVAC air delivery system. There it is cleanly distributed to the passengers and driver.

During development two linked problems emerged:

1. Where do you put the module(s) in retrofit?

2. How do you keep the UV-C levels sufficiently high enough to kill the SARS Cov-2 virus but then low enough for continuous driver and passenger daily exposure?

Computational Fluid Dynamics (CFD) provides the insight necessary to solve them. However, although high and low UV-C limits can be defined for the latter limit problem, devising a suitably representative model presented a novel challenge to Valeo TCV. This paper deals with the introduction of the radiation and viral field modelling into Valeo's CFD toolset. Reformulating the InfraRed radiation model into essentially monochromatic UV-C band radiation, and with thoughtful design allowed us to develop a very high intensity virus killer that was also perfectly safe in the vehicle cabin.

The modules are sold worldwide. Most importantly we use them daily on our team member transportation coaches to keep our employees safe to and from work at our production facilities.

Keywords

COVID-19, viral transfer, automotive, CFD, HVAC

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1 Introduction

During the 2020 COVID-19 pandemic, improving safe transportation to work was determined a priority for Valeo TCV, which was tasked with designing a retrofit Ultraviolet (UV) Purifier to continuously sanitise the air in public buses [1], culminating in the creation of a UVGI system (Ultraviolet Germicidal Irradiation) [2]. The understanding was that the COVID-19 virus could transfer person to person by three progressively finer mechanisms: fomites, droplet ballistics and aerosolization. Other work was being done around the world at this time mapping the spread of the virus [13].

Fomites are inanimate objects with surfaces contaminated by a virus, leading to infection via contact. Virus droplet ballistics refers to the short-range projectile transfer from an infected person via short duration airborne droplets, lofting virus containing droplets through the air, subjected to gravity. Both these transfer mechanisms are made less effective by social distancing, personal / commercial cleanliness, and face coverings [3]. Through the aerosolization transfer mechanism, an infected individual will continuously contaminate an unvented enclosed space, thereby increasing viral concentration.

In the early months of COVID-19 it was aerosolization, the then-unknown virus transmission phenomenon, that was most alarming to the public, commerce and authorities; it was not mitigated by handwashing, social-distancing, and being in an enclosed space for an extended period increased the likelihood of catching the virus [3].

The primary modelling objectives during the design phase were:

- Location of the purifier in the bus,
- HVAC (Heating, Ventilation and Air-Conditioning) modal impact on the flow field,
- Flow field impact on the viral field,
- Function of purifier: UV internal irradiation and UV external radiosity.

Viral transport modelling inside the bus environment is affected by the settings of the main HVAC and the driver's cabin HVAC. These two systems and the ventilation extractor locations dictate the major flow patterns that the aerosolized virus-laden droplets ride upon. Positioning of both contaminated and susceptible target individuals also affects who is exposed to higher viral loads.

Modelling the virus in the "aerosolized state" (a homogeneous mixture) used a simple method. An arbitrary field, called the virion (the complete, infective form of a virus outside a host cell, with a core of RNA and a capsid.) [10] passive scalar field, allowed concentration to be defined at source and measured throughout the vehicle. The concentration is normalised to an arbitrary level in the occupants' mouths. This arbitrary field allows measurements and relative reductions in concentrations to be quantified [4].

There were two critical elements in the design of the UV Purifier: the most efficient positioning of it within the bus, and the effective containment of Ultraviolet-C (UV-C) irradiation within the unit. The UV-C band is 100-280 nm, and a wavelength of 254 nm was used in this model. CFD modelling included radiation effects and viral field-modelling to evaluate both the UV-C containment and UV Purifier position. Both these modelling techniques were new to Valeo Thermal Systems.

Multiple modal settings were run in the model, including both main cabin and driver's cabin HVAC modes, occupant locations within the bus, and seating location of a variety of infected occupants. The HVAC modes and passenger positions which resulted in the best scenario for mitigating viral spread were determined.

2 Methodology

The fluid volume of the total internal space in a Mercedes Citaro City Bus [5] was generated from analysing its dimensions. Figure 1 shows the general bus dimensions, the layout of the seats and the driver's cabin area. Figure 2 displays the CFD model of the bus domain, and was used to assess occupant location, viral spread and viral concentration reduction across the various HVAC configurations.

The main HVAC and the driver's cabin HVAC systems were simplified to inlet and outlet boundary conditions, representing the fresh and recirculated air in the vehicle. The main HVAC was configured to recirculate the total internal cabin air, thus increasing or decreasing the viral concentration accordingly. Mannequin dummy geometry of a basic driver and several passengers were constructed

and positioned in a variety of seat positions. Transparent physical partitions segregated the driver cabin area from the main cabin. The main HVAC distributes flow via ducting to the front and rear. The ventilation extractors at the rear of the bus allow the normal extraction of stale air out of the vehicle. The fresh air flow feed is from the driver's cabin HVAC at the front of the vehicle.

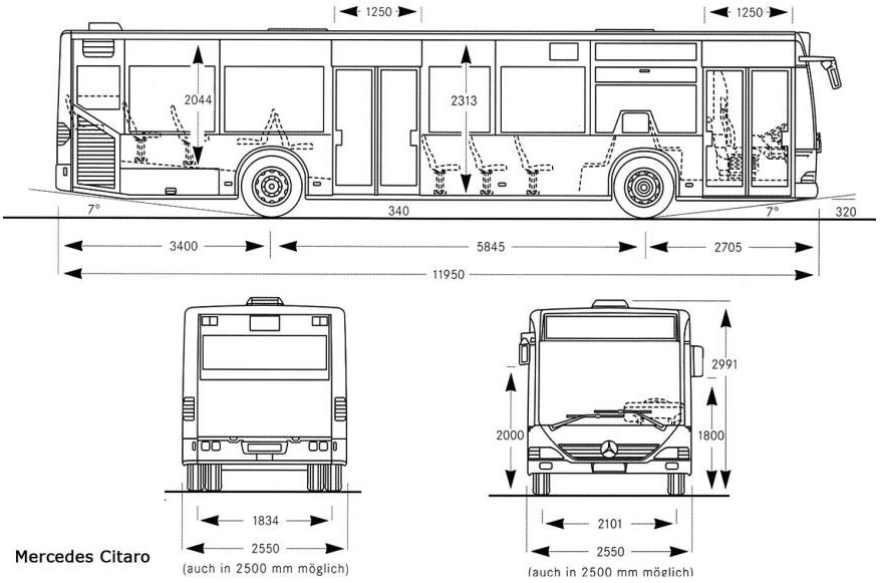

Figure 1. Mercedes Citaro Schematic, a typical bus environment.

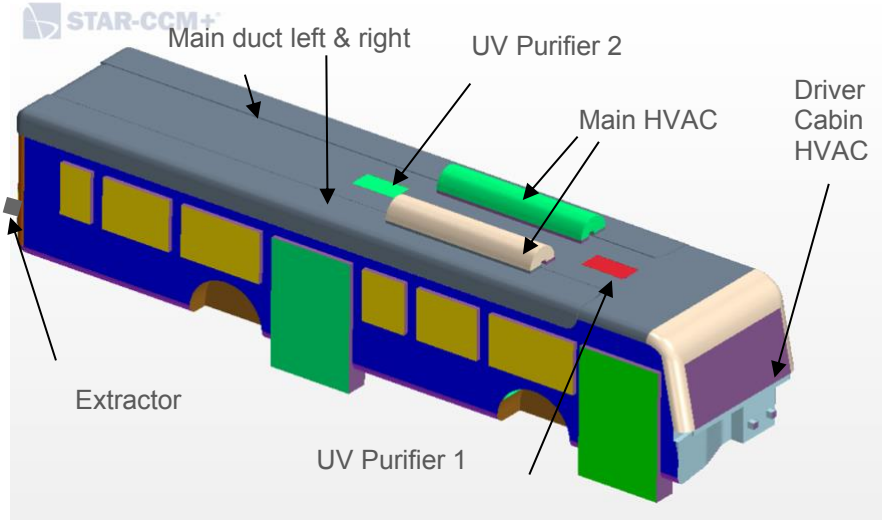

Figure 2. Typical bus for understanding covid virus concentration distribution.

For a bus, the fundamental HVAC energy/thermal power balance with respect to cold weather is correlated with using a large amount of recirculated air to maintain passenger comfort. In comparison in a car, the waste thermal energy from the internal combustion engine is more than enough to allow fresh air alone to be used to heat the car's cabin. The heat is then wasted when flushed out of the rear extractors into the street. On a bus in the same cold weather conditions, even with a larger engine than the car, the much larger surface area/volume of the whole bus cabin means the thermal load required to maintain cabin comfort is an order of magnitude larger than the car. The airflow and thermal implications for the bus in that cold environment result in recirculation mode being required to properly maintain the thermal comfort of the occupants.

In cold climates, the bus operator has to choose between maintaining passengers' thermal comfort by recirculating the air (with potentially accumulating viral load) or chilling the passengers with poor thermally conditioned air (while having virus-free fresh air). Buses, due to their large surface area and volume, require mostly recirculated air from a thermal load point of view, thus leading to a dilemma when considering virus accumulation in the cabin. Valeo's UVPurifier counters this thermal conundrum.

In a warm temperate climate open windows and ventilation naturally lowers the viral concentration. But in a hot humid environment the HVAC settings need to be in recirculation mode due to the large thermal loads.

Table 1. Modal settings investigated: MODE A with All ON is represented in this paper. Other modes (B to H) indicate many different configurations to help understand the virion concentrations.

		Air Distribution				
MODE	Quick Name	Driver Cabin Fresh Air	Main HVAC Recirc Air	UVP1 Recirc Air	UVP2 Recirc Air	Notes
A	All ON	ON	ON	ON	ON	Check UVP works at bus configuration
B	UVP OFF	ON	ON	OFF	OFF	How bad is it when the UVP is off?
C	Panel OFF	OFF	ON	ON	ON	No fresh air in system
D	Main AC OFF	ON	OFF	ON	ON	Ventilation from driver panel
E	UVP Only	OFF	OFF	ON	ON	UVP alone
F	All OFF	OFF	OFF	OFF	OFF	No AC systems operating. Parked bus.
G	Main AC Only	OFF	ON	OFF	OFF	Main AC homogenised virus throughout cabin.
H	Panel Only	ON	OFF	OFF	OFF	Front Panel fresh air clearing the bus.

The HVAC settings dictate the comfort of passengers and driver in terms of thermal, humidity and visibility conditions. The driver must be kept in thermal comfort throughout the workday for safety and good working conditions. The HVAC mode configurations in Table 1 show the possible combinations which may increase and decrease the viral load accumulations in the bus.

Eight HVAC mode settings (A to H) were simulated, primarily to understand their interaction; however, only Mode A is the focus of this paper. The other modes tend to increase the viral concentrations within the bus. Turning off fresh air flow or the UVPurifier units would result in increased accumulation of the virus.

2.1 Bus mesh settings and physics

The mesh used in the model was polyhedral: 25 mm nominal, and 5 mm minimal size. The model was run as a steady state to converge to the asymptotic worst-case concentrations. The simple K-epsilon 2-layer turbulence model was used to capture the boundary layer effects in the ducts and walls. This was run with multiple passive scalar fields.

Boundary conditions were set to the following values:

- Main HVAC at 1.419kg/s per side, recirculation,
- UV Purifiers at 0.66kg/s each, recirculation,
- Driver's cabin HVAC at 0.05kg/s, fresh air,
- Driver and Passenger 7: breath flow rates at 0.0025kg/s continuous,
- Driver and Passenger 7: exhale contaminated air at 1 Mvirion/breath,
- Extractors are set to pressure outlets.

The virus was modelled as a simple passive scalar quantity, which represents a concentration cloud. This is the only transmission method that can be modelled in the bus, as it can be influenced by a factor other than a change in personal habits. The fomite / contact transmission is a direct mechanical transfer that is mitigated at a personal cleanliness level. The droplet ballistics approach from person to person again is mainly a personal cleanliness issue related to personal etiquette while coughing, sneezing, and social distancing.

Continuous background cleaning of air with the UVPurifier, has no effect on any active coughing and sneezing within the bus. The passive scalar modelling is used to understand the contamination or viral concentration between asymptomatic carriers [6] [7] and un-masked passengers. This evaluates the unconstrained transmission between maskless and non-infected individuals in the bus.

The virion field modelling required the development of a passive scalar "sink" function. This represents the reduction in virion field passing through each UVPurifier (UVP1 and UPV2). A simple model was set up to reduce the virion concentration to the design intent.

The UVPurifier sink was calibrated to remove ~99.5% of the virions passing through it, deactivating the RNA.

- -7000 kg/m^{3}s for the sink,
- -5000 kg/m^{3}s for the sink derivative,
- 700 mm length.

2.2 Passive scalar – Aerosolization

The aim was to find a simple, logical modelling method to represent the aerosolized viral field. The simple passive scalar field method (software STAR-CCM+ V 12.06.007) was used to assess the concentration of the virus from a source occupant transmitting throughout the vehicle cabin. Passive scalar fields by definition do not interact with gravity, nor with each other. Simulation times are fast for the steady state limit cases. The passive scalar method assumes the two convective mechanisms to transport the virus are:

- advection - bodily movement following the flow,
- diffusion - molecular diffusion throughout the flow; turbulent Schmidt number = 0.9, molecular diffusivity = Schmidt number = Viscous diffusion rate / molecular diffusion rate = 0.9 mu/(rho*D).

The passive scalar field provided an objective method to see concentration reductions or enhancements. Selection of a suitable incoming level to represent the contaminating virion field was required [10]. Choosing an arbitrary concentration of 1 Mvirion/breath was the scalar starting point used in the infected individual's exhalation. These 1 million virions per breath, as a concentration form, would then disperse and diffuse according to the flow fields imposed by the vehicle HVAC systems. The decay in virus concentration with distance from the source was apparent in early results. The selection of the fixed 1 Mvirion/breath gives a good basic metric for comparison purposes. Reductions in the concentration level down from the 1 Mvirion/breath was the main point of interest.

3 Results

Introducing the cabin results section, there are several steps to the analysis, two methods are used; main field streamlines showing the flow structures and then the virion cloud fields. The contaminated driver and passenger 7 are highlighted to show what happens to the flow and virions emanating from them. The flows and virion cloud travel both fore and aft at the same time, due to implications from advection and diffusion of the fields.

3.1 Flow field in the main cabin with velocity projected on streamlines from main HVAC

Figure 3 shows the main air flow structures in the All -ON (Mode A) system setting. The streamlines set up the main flow structures in the vehicle, listed below:

- General plug flow from front to rear, due to the fresh air flow from the drivers' vent outlets. The implications became evident when analysing the viral concentrations.
- The recirculation of the main HVAC system flows back into its intake, bringing virus-cleaned air from the two UV Purifiers in the central ceiling area, then flows into the left and right distribution ducts, running from front to back of the vehicle.
- A curtain-flow down the windows next to the passengers (see green streamlines down the windows). This downdraft creates two counter rotating main vortices down the centre of the bus (the blue swirling streamlines).
- Some flow leaves the bus via the rear vehicle extractors, and some goes forwards from the rear to the rear inlet of rear UV Purifier (UVP 2), where the air is sterilised (green contraction streamlines in the central upper region).
- From the forward ducts some air flow goes rearwards to the front UV Purifier (UVP 1) inlet where it is sterilised (green contraction streamlines in the central forward upper region).
- The main HVAC "central return" location forces the air to travel throughout the cabin, stirring and mixing the whole cabin air volume continuously. The passenger region of the cabin has no safe place where only fresh air passes through.
- This is a fundamental consequence of not being able to use fresh air from the thermal comfort energy balance point of view in the bus environment.

- A contrary example: Aircraft ventilation has a similar vertical curtain-flow with minimal flow transfer forward or rearward from one passenger row to the next. The flow return exits the cabin beneath the seat from where it originated.

3.2 Flow field in the driver's cabin with driver virion field projected onto velocity streamlines

Figure 4 shows the local virion field from the driver's mouth mapped onto streamlines into the main cabin. The streamlines are ingested by the front UVP 1, which heavily irradiates and then exhausts the flow towards the inlet of the main cabin HVAC.

The driver virion field reduces in concentration rapidly as a result of advection and diffusion, falling from the initial assumption of 1 Mvirion/breath, to ~1.7kvirion/breath in the driver's cabin. Then the concentration subsequently falls to ~10 virion/breath after ingestion into UVP 1, which is seen exiting the unit.

These two reductions in concentration are considered the "social distancing effect" and the "Virus Killer effect". More intricate modelling of these effects, with regard to droplet ballistics was later performed [8]. It must be noted that streamlines alone would be suitable for tracing a non-diffusive or purely advective field. However, the molecular diffusion ensures the virions, or their sub microscopic, aerosolized containment droplets diffuse laterally away from the streamlines as the cloud spreads.

3.3 Driver's virion passive scalar field in the main cabin

Figure 5 shows the cabin with six carefully chosen concentration scales of the driver virion passive scalar field concentration. The concentration falls due to a distance square law as the field spreads out; the symmetry condition of walls, and the removal of the virus in the UVPurifiers.

Figure 5.a and b. demonstrate the social distancing effect. The driver's mouth is at 1 Mvirion/breath, and very quickly falls to ~10,000 virion/breath within ~0.5m radius of the mouth. The concentration field falls to 2,500 virion/breath within about ~1m radius of the mouth. The rate of decay then flattens out dramatically through the rest of the bus, as seen in figures 5c, 5d, 5e and 5f. This "flat" concentration from 1,300 to 980 virion/breath is stemming from both the drivers' fresh air and the re-entrainment of the sanitised air from the UVPurifier.

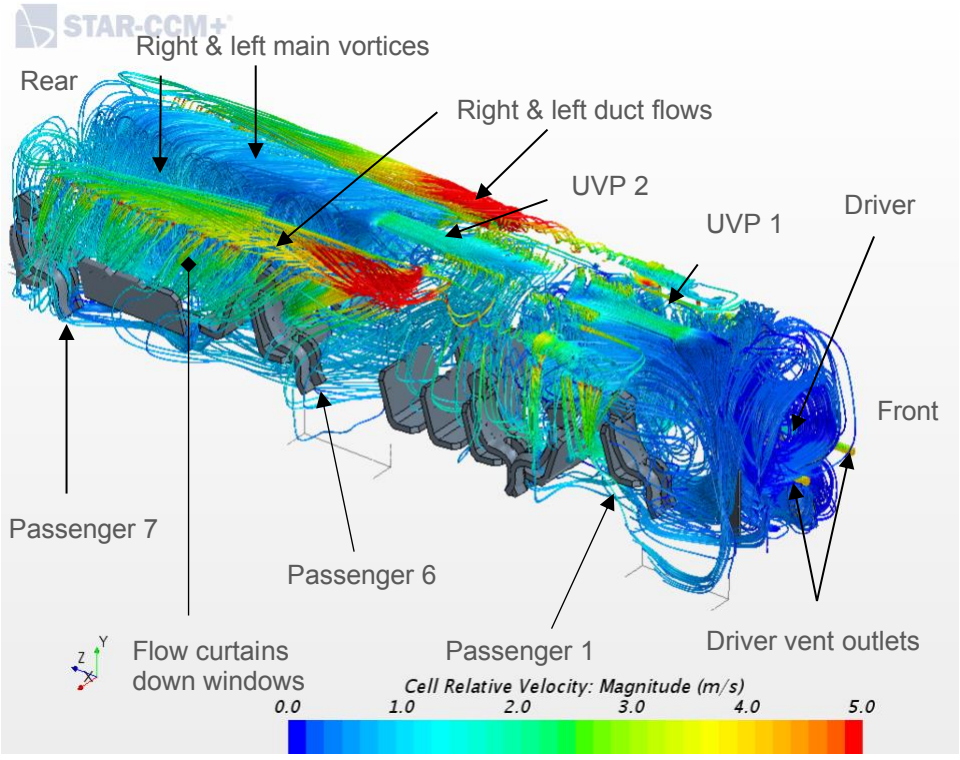

Figure 3. Velocity streamlines through cabin from Main HVAC, ducting, Driver Cabin HVAC and UVP 1+2.

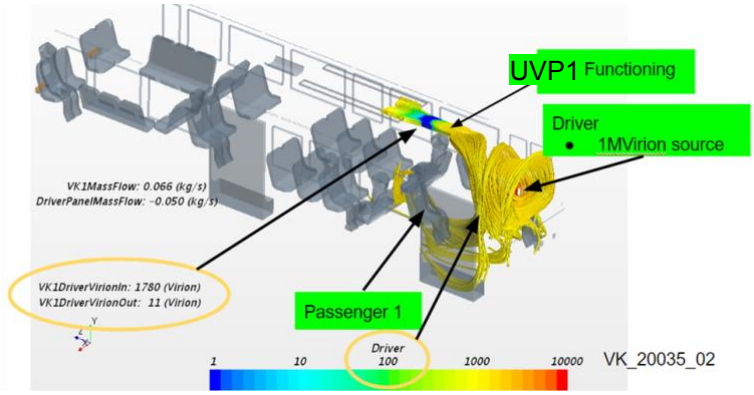

Figure 4. Streamlines showing virion dispersion field as passive scalar from driver through UV Purifier (UVP 1).

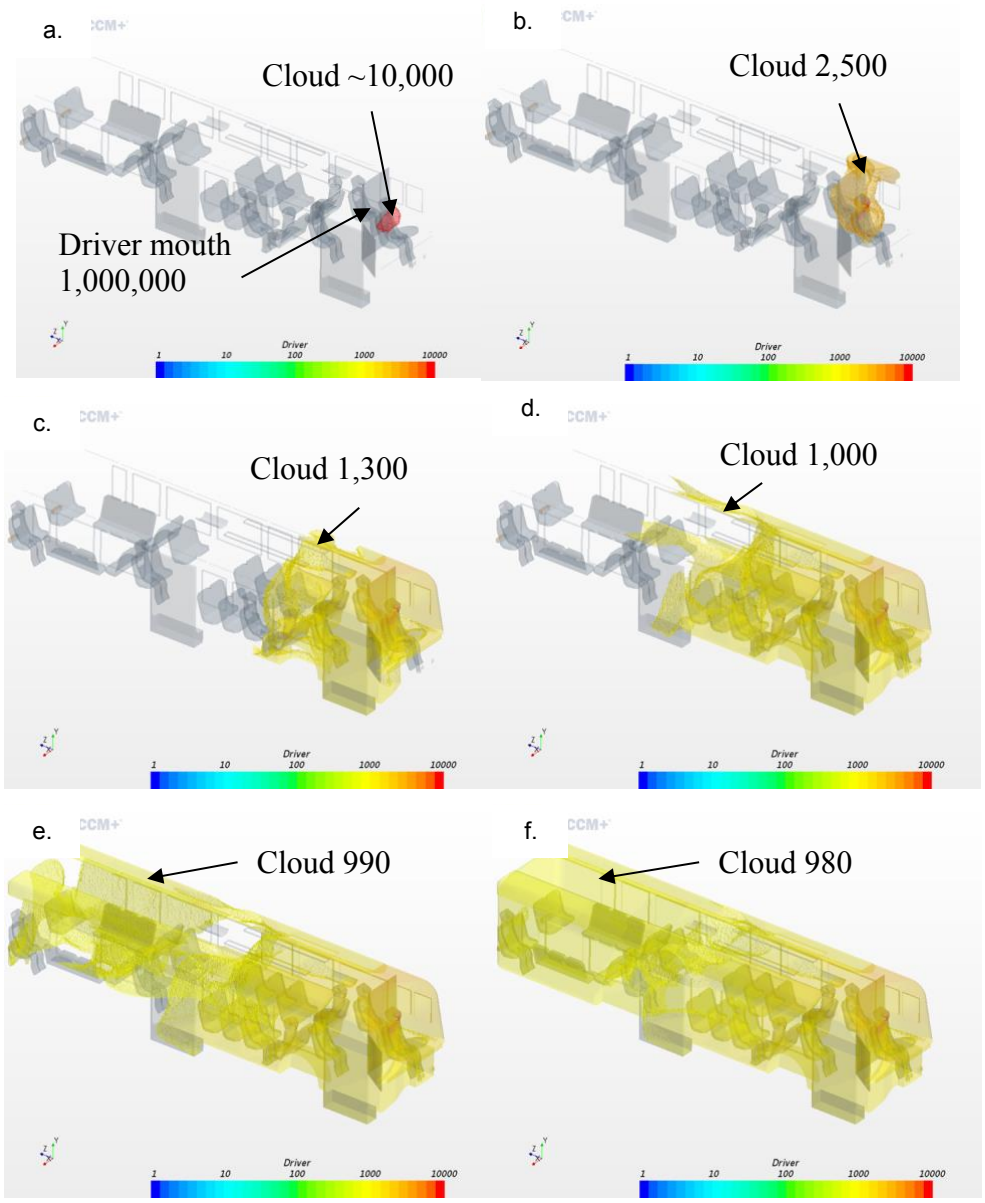

Figure 5. Driver virion passive scalar field concentration fronts. UVP 1 and UVP 2, main cabin HVAC and driver's cabin HVAC activated, showing reduced overall concentration. Contours chosen to show specific shallow front to rear gradient distribution, with figures a-f showing decreasing viral concentration.

3.4 Flow field in the main cabin stemming from Passenger 7

The passive scalar method allows us to contiguously model multiple virion fields, each delimited by name and concentration strength. The source strength and sink locations can also be configured per field. This enables the modelling of multiple infected individuals at the same time, tracking their appropriate variant field and assessing many potential target occupants.

In Figure 6, the passive scalar field emitted from the mouth of passenger 7 sitting in the rear right of the vehicle, is mapped on flow streamlines. The passenger 7 virion field disperses a little differently to that of the driver. There is a small increase in the concentration in comparison with the driver field, even though the passenger 7 source was still set to the same starting point of 1 Mvirion/breath concentration. There are two main rear to front contra-rotating vortices swirling the virion field forward in the bus along the main flow structures from passenger 7, which subsequently are ingested by UVP 2. In this unit the viral concentration drops from about ~2600 to ~150 virion/breath. The concentration in the cabin was ~2600 virion/breath for the passenger 7 field, compared to the driver variant of ~1700 virion/breath at the UVP1 inlet. See Figure 4 and Figure 6.

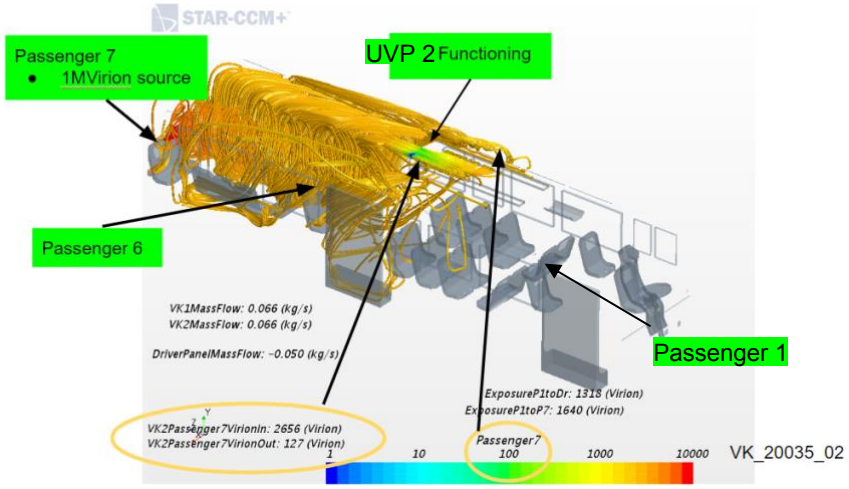

Figure 6. Streamlines showing virion dispersion field as passive scalar from passenger 7 through UVP2.

3.5 Passenger 1 exposure to Driver field or Passenger 7 field

Passenger 1 experiences a field of ~1600 virion/breath from passenger 7 source, compared to a level of ~1300 virion/breath from the driver. The driver is seated much closer to passenger 1 than to passenger 7, but passenger 7 is more likely to infect passenger 1, than the driver is. Both concentrations are much lower than the 1 Mvirion/breath initial setting. The fresh air field flowing from the driver's cabin improves the ventilation going rearward, and reducing the concentration from front to back. The main cabin flow structures increase the Passenger 7 field as it is drawn forward on the main vortices.

3.6 Passenger 7 virion passive scalar field in main cabin

In Figure 7 there are similar structures for the passenger 7 virion field but conversely moving in the forward direction from the rear of the vehicle, compared to those seen in Figure 5. Passenger 7 has a local intense concentration in Figure 7a, about 10,000 virion/breath projected forward within the core of the main right-hand vortex travelling from the rear. Figure 7b to Figure 7f show the concentration levelling out as the plume disperses forward and laterally in the bus. The gradient goes from 2,800 to 1,400 virion/breath. Compare Figure 5 and Figure 7 to see the two opposite effects of the driver's variant compared to the passenger 7 variant in diffusing and advecting through the cabin in opposing directions.

As previously mentioned, the passenger 7 field is somewhat stronger pushing forwards compared to the driver's field going rearward. The latter has the fresh air component from the driver 's cabin HVAC to reduce the concentration to a lower level. This is an example of the fresh air decreasing the viral concentration.

Figure 8 is a histogram of the cloud concentrations from front to rear for the driver, and from rear to front from passenger 7. Both start at 10,000 virion/breath near the occupant creating the field, and then decrease relatively quickly to a flatter gradient through the bus.

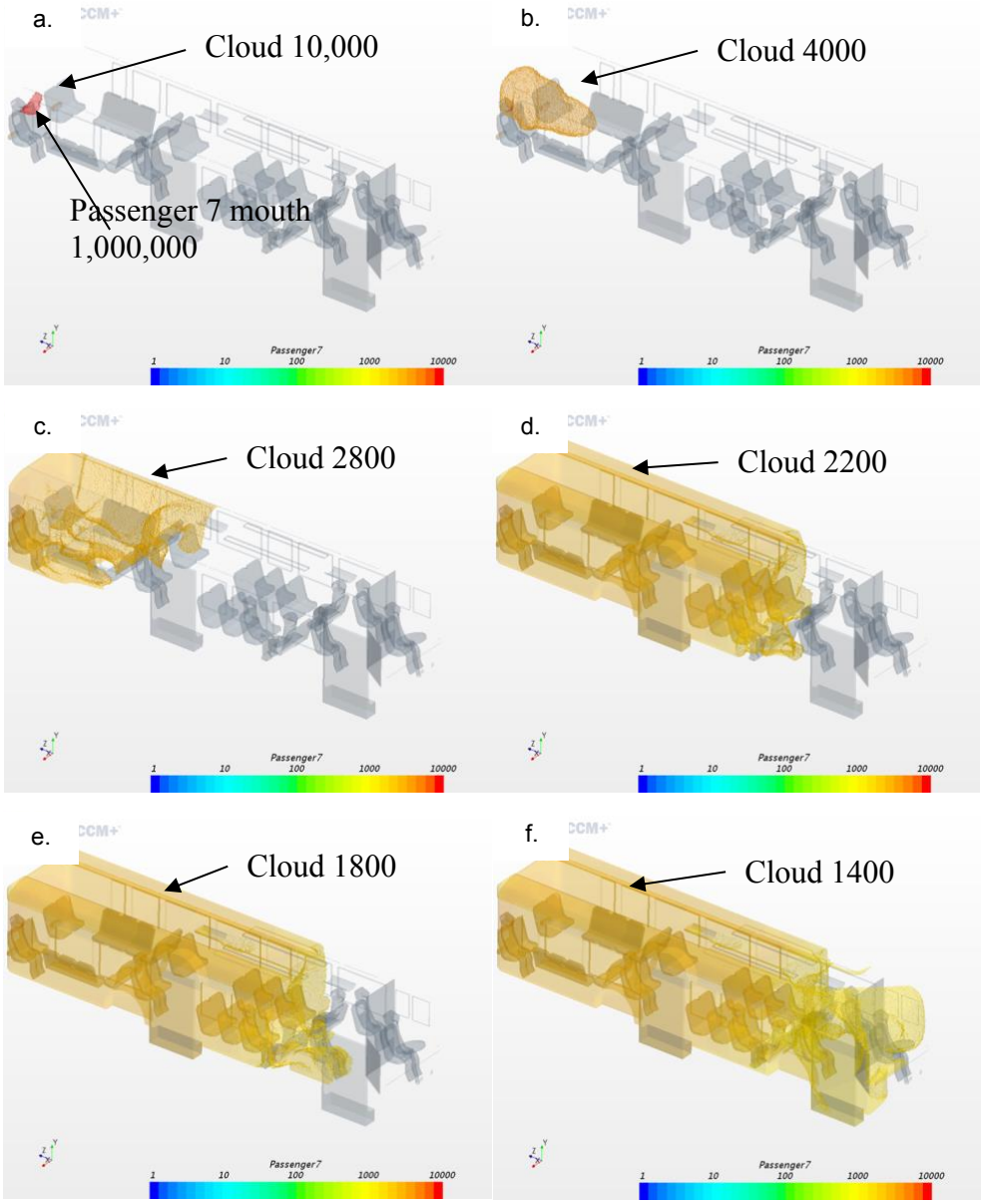

Figure 7. Passenger 7 virion passive scalar field concentration fronts. UVPurifiers 1 and 2 (UVP 1 + 2), main HVAC and driver fresh air activated, showing reduced overall concentration. Contours chosen to show specific rear to front gradient distribution.

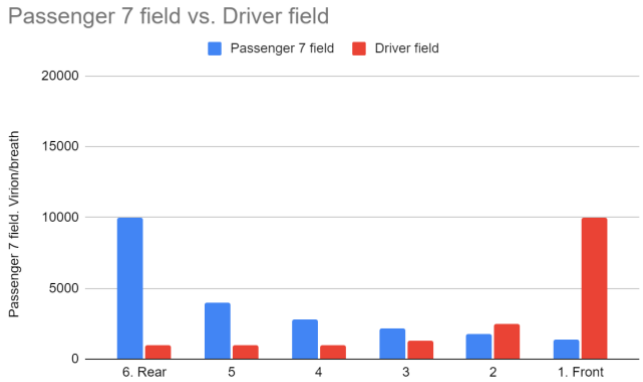

Figure 8. Passenger 7 viral concentration compared to driver viral concentration comparison from front to rear of bus.

4 Modelling of UV-C irradiation

The UVPurifier's intended action was demonstrated in the bus modelling. Subsequently the UV light within the UVPurifer was modelled to ensure that the light field strength is sufficiently intense to damage the virus RNA, but still be safe enough in the vehicle for the driver and passengers' eyes and skin.

Figure 9 shows the UV Purifier unit containing inlet / outlet fans behind structural grills, power electronics, transformer, cover, base and efficient inlet / outlet light traps. The traps allow easy air flow but are essential in blocking the UV-C radiation from escaping the unit. The design of the unit, lights, light traps and fan system dictates its effectiveness. A model of the UV-C light field physics was created to simulate the irradiation of components.

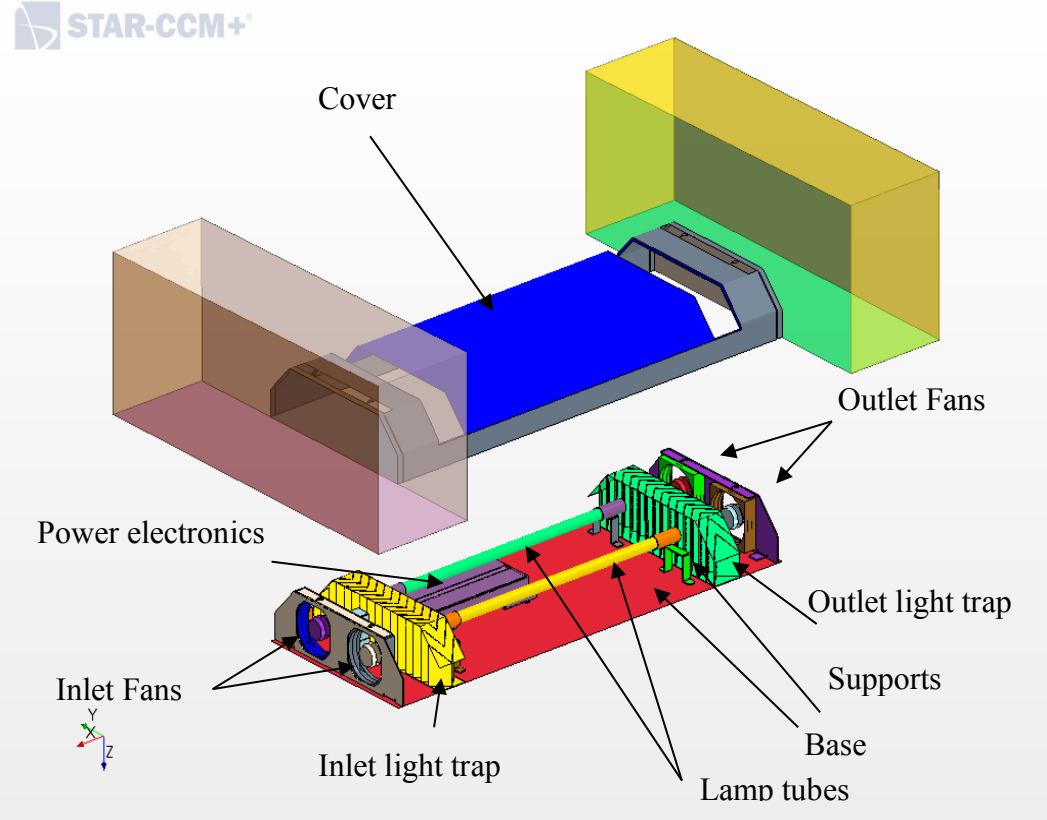

Figure 9. UV Purifier structure.

A multiband thermal radiation surface-to-surface technique was used to successfully model the main elements of the irradiation system. The model used a patch mesh discretizing the reflecting surfaces. The cell size is similar to the surface of the volume mesh. Figure 10 shows the patch mesh. The patch surface emissivity (absorptivity) represents the material radiation reflective properties. The radiation cascade, radiant exitance, irradiation, radiosity, radiant exposure and emissivity fields were set or calculated.

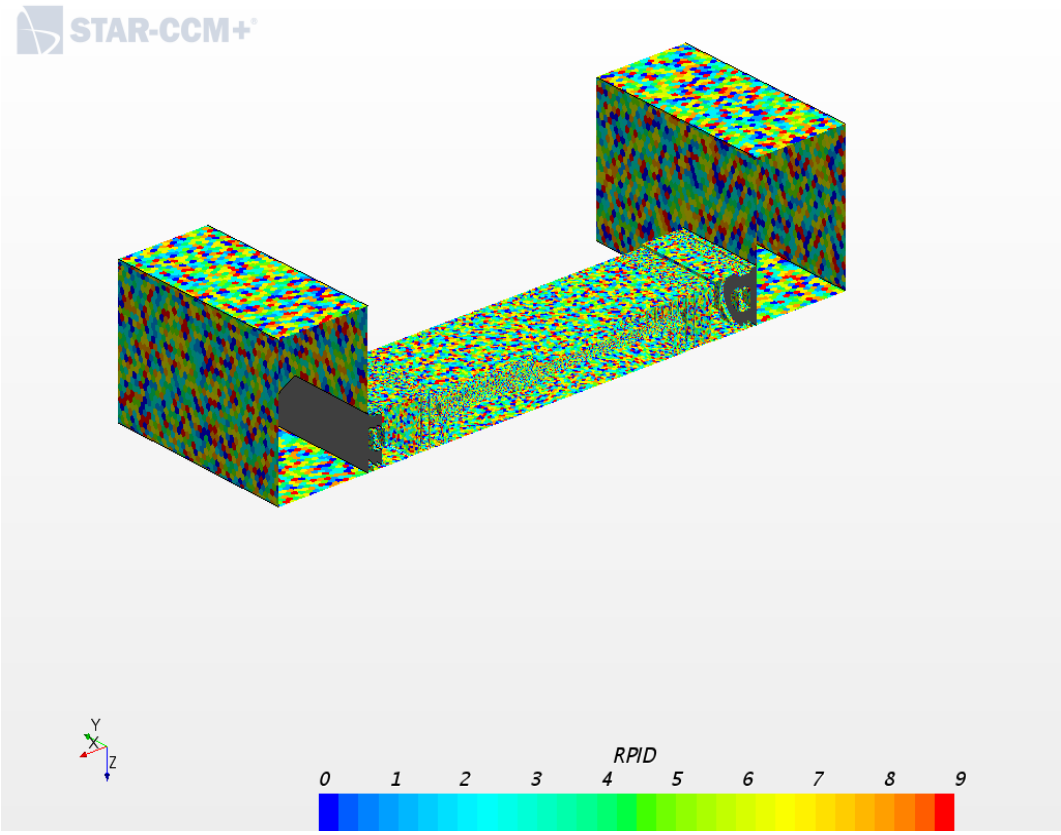

Figure 10. Radiation surface patch mesh.

The simulation modelled the attenuation of the peak UV-C light through the light traps and dropped in intensity by 5-6 orders of magnitude. The reduction from peak irradiation levels of ~100mW/cm^2 to ~0.001 mW/cm^2 enabled the UVPurifer to be medically certified [11]. An exposure time of a few seconds in the UVPurifier with 100mW/cm^2 peak irradiation damages the viral RNA, whereas skin or eye exposure to 0.001mW/cm^2 for 8 hours per day is within acceptable limits [11].

Integration of this irradiation over time provided the radiant exposure values, and calculations were used to establish suitable targets for the radiant exposures to the UV-C light for the occupants. From the literature [12], the internal irradiation target was set to be >90 J/m^2 radiant exposure in order to disable virus RNA, whereas the external radiosity target has been selected as <0.0002mW/cm^2 for 8hrs skin exposure [12] as not to over-expose occupant DNA.

Modelling the UV light field involved choosing suitable source strength(s), size, distribution and configuring for the radiant exitance from the UV lamp tubes, as displayed in Figure 11. The diffuse radial and longitudinal radiant exitance fields from the two lamps disperse into the long reflecting cavity of the UVPurifier. The multiple sources, multiple reflections, re-reflections, absorption and re-absorptions sets up the UV radiation field in the cavity to damage the RNA of the virus as it transits through.

Figure 12, shows various components in the unit were selected for their emissivity / absorption properties to give suitable boundary conditions which would both enhance the field and attenuate the field in the respective directions required. Many variations on the internal geometry, the traps and lamp positions/ configurations were assessed. The emissivity settings here are just one example. Figure 13 shows the boundary irradiation field, which is essentially the integrated irradiation on surfaces from the source and all reflected amounts inside the unit. It is the resultant field cascaded onto the surfaces, i.e., the surface and the air/media become irradiated, and consequently damaging the viral RNA with appropriately high energy UV-C photons. For example, see the irradiation onto the power electronics.

The boundary radiosity field in Figure 14 is the re-radiated integrated emission from the internal surfaces. For example, the radiation flux emanating from the traps is the trap radiosity. The definition of emissivity is the ratio of the boundary radiosity to the boundary irradiation. The resultant field shows that careful material property and geometry selection gives an efficient UV-C irradiation field along with an appropriately low pressure drop flow field, allowing air flow to pass through easily, maintaining and containing the intense irradiation of the viral RNA as it transits through the UVPurifier.

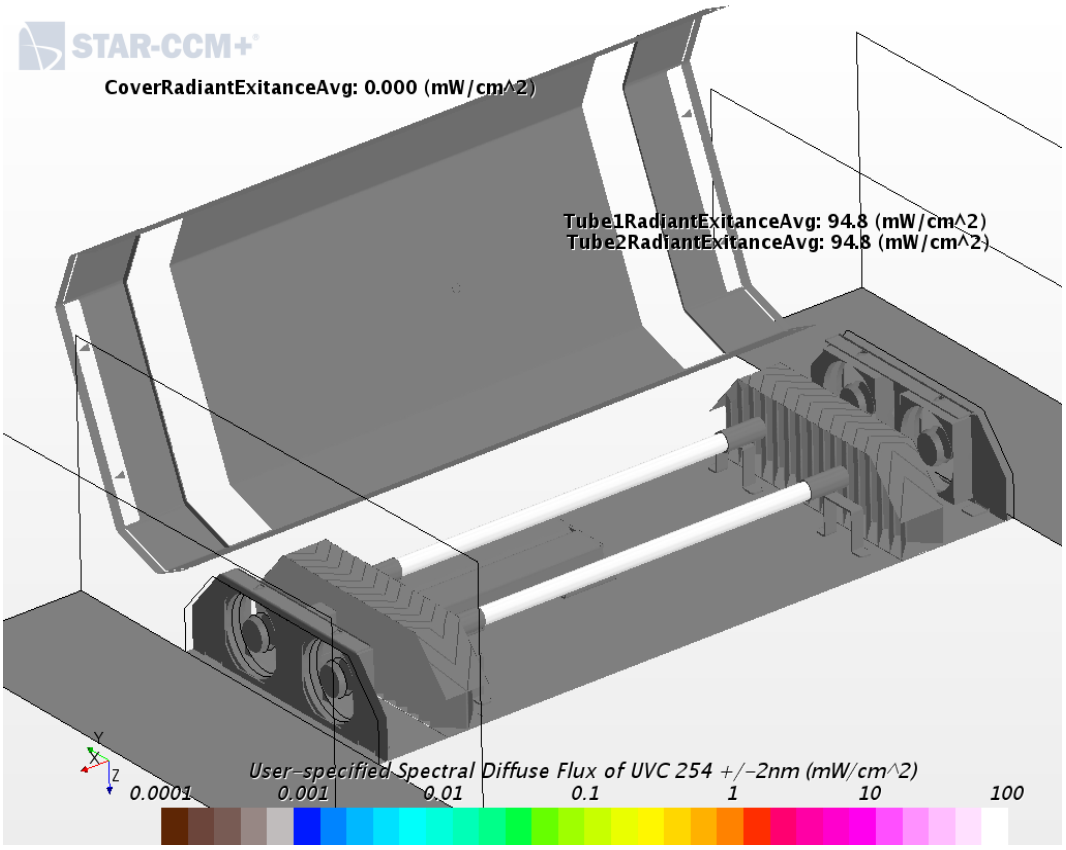

Figure 11. Radiant Exitance (radiation flux leaving a source) from UV lamps.

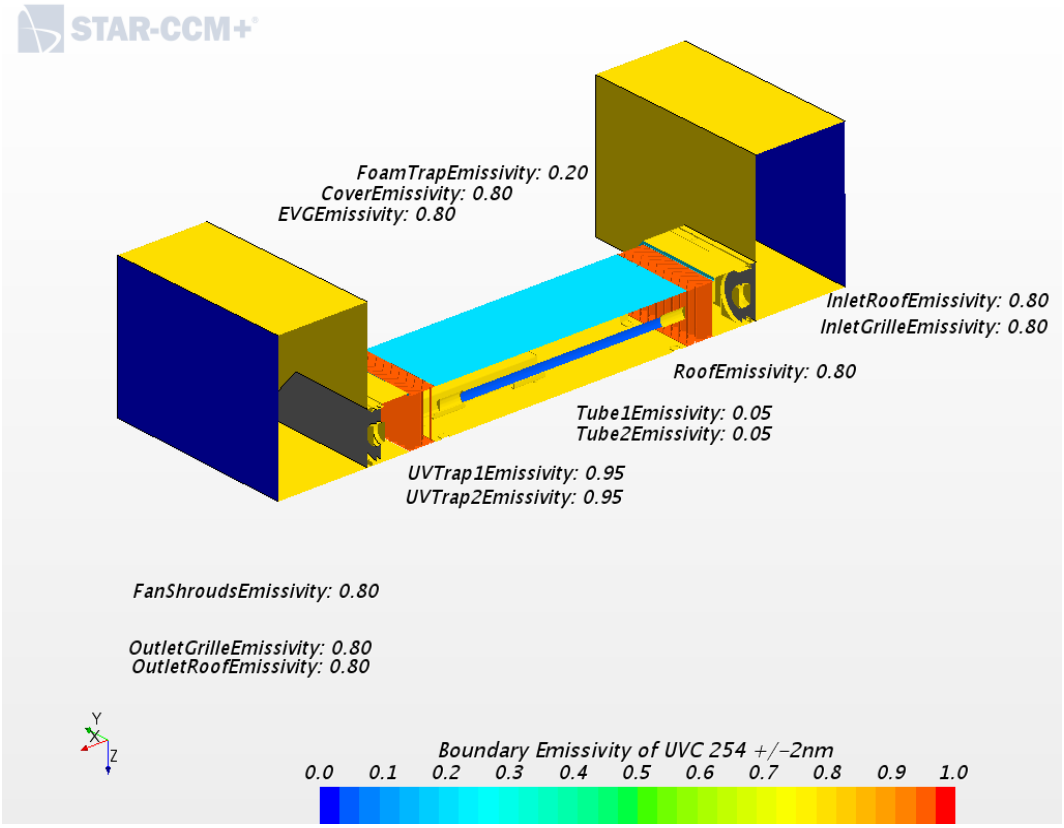

Figure 12. Boundary emissivity (reflect 0 to absorb 1.0).

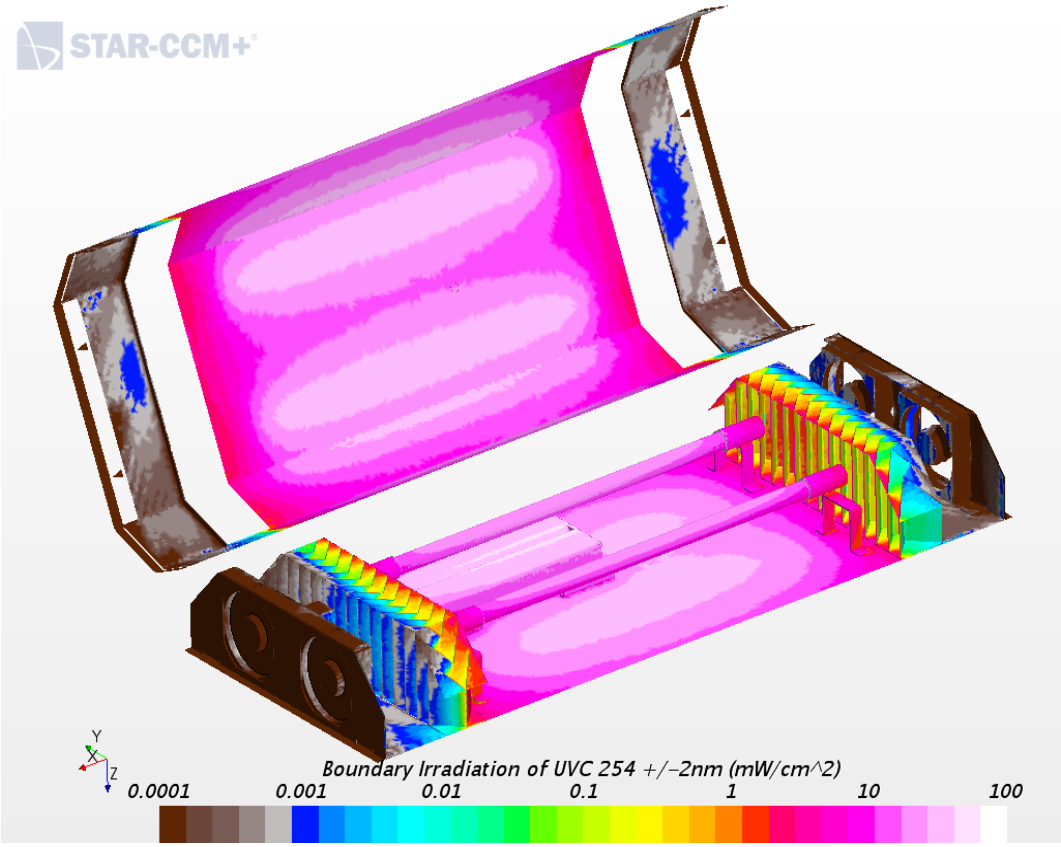

Figure 13. Boundary Irradiation field.

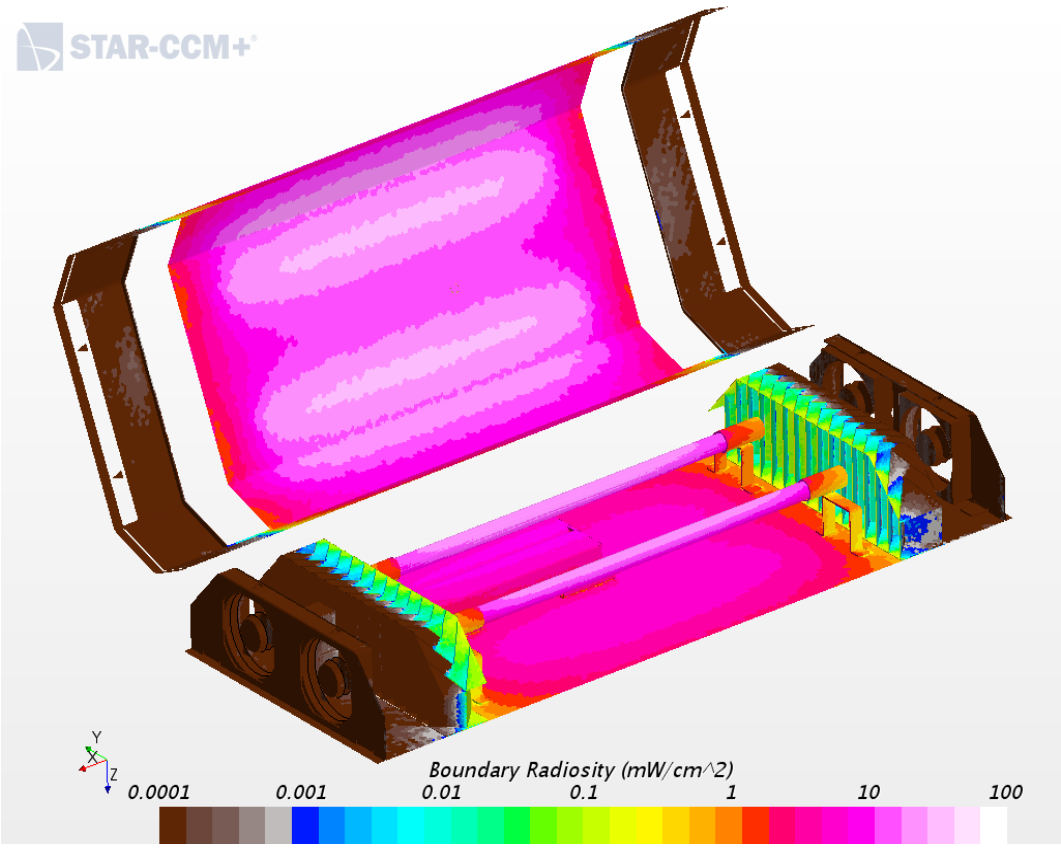

Figure 14. Boundary Radiosity field.

Figure 15 shows the surface average irradiation and radiosity from reflective surfaces / locations across the airflow and longitudinally through the UVPurifier. Significantly lower levels of UV-C light radiosity emit from the inlet and outlet regions into the cabin, compared to the internal cavity irradiation zone.

The top hat shape shows step changes in level spanning many orders of magnitude of the average irradiation strength onto each segregated surface, relative to the radiosity from those same surfaces. There are large radiation scale extremes seen, with intense radiation from ~10mW/cm2 attenuating down to ~0.0001mW/cm2 from inside to outside the light traps.

The design created a very intense irradiation field internally to give great radiant exposure to the virus during flow transiting through the unit, and safely reducing the radiosity field externally to a suitable safe exposure level for the driver's and passengers' eyes during their daily long-term exposure profile.

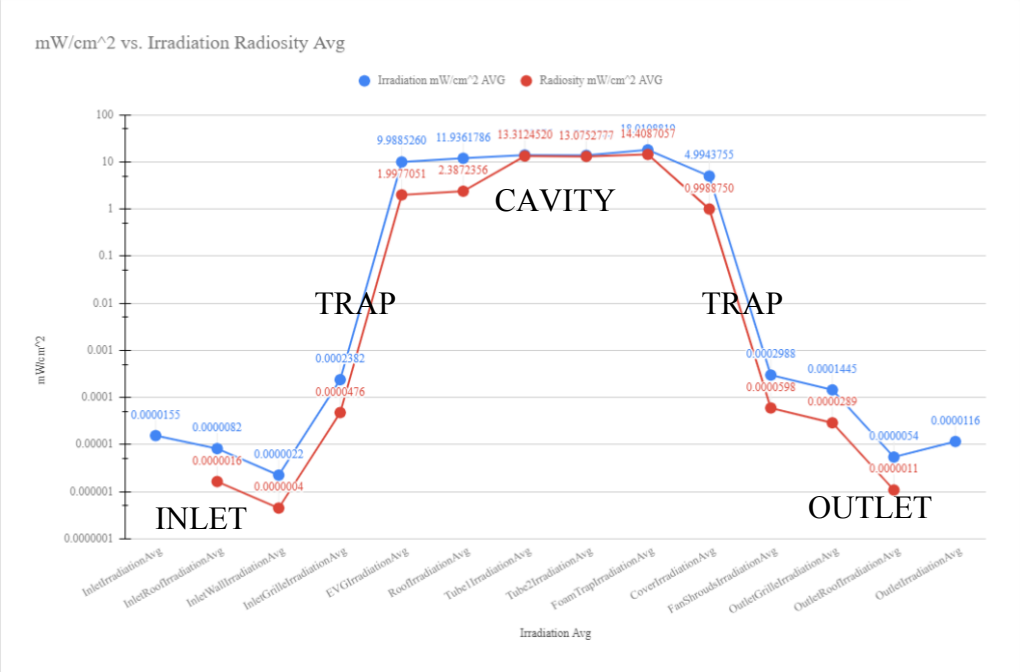

Figure 15. Boundary Irradiation & Radiosity average in UVPurifier from inlet to outlet.

Are these irradiation and radiosity field targets achievable?

The high internal irradiation target exposure level is important to achieve virion RNA deactivation. The average irradiation in the cavity is 10mW/cm^2 (or 100 W/m^2), from figure 15. The basic air transit time of air through the module is 1.0s, by design flow and residence. This means we achieve 100 W/m^2 x 1 s which gives 100J/m^2 radiation exposure. Whereas the design target exposure is > 90W/m^2 for 1 s [12].

The low external radiosity target exposure level is important to keep occupant's eyes and skin safe through each working day. From figure 15, the inlet and outlet average radiosity are ~0.00001mW/cm^2 (0.00010W/m^2). Feasibly an occupant could be exposed 8hrs a day. 8 hrs (8*60*60 = 28,800s) the worst external exposure time. The target should be less than 0.0002mW/cm^2 for 8 hrs, which works out to be <0.00010W/m^2 x 28,800 s = 2.88J/m^2 as daily exposure limit.

The virus is irradiated within an exposure time of approximately one second, breaking the RNA. This needs to align with the transit time through the UVPurifier. In comparison, the external radiosity emitted from the UVPurifier inlet / outlet should safely allow 8 hours per day skin / eye exposure for occupants.

The UVPurifier model had critical aspects and generic flow design issues to overcome. The initial objectives were airflow-related for the UVPurifier to assess the pressure drop for fan selection. This was completed early in the design process using a simple CFD model of the air in the UVPurifier. It was realised that an infrared thermal radiation model could be repurposed to ultraviolet with appropriate use of the narrow band surface-to-surface model. Fluid surface geometry to represent the internal structure of the UVPurifer gave a good representation of UV-C sources, internal reflecting walls, light traps, fans and structure. The emissivity/ absorptivity settings were applied on the surfaces where the design dictated it.

5 Discussion

In the following discussion, we will address several crucial questions raised from our results concerning the effectiveness of UV purifiers. Firstly, we will examine whether the UV purifiers were positioned optimally. Following this, the impact of HVAC mode settings on the flow fields will be investigated, along with how these flow fields may influence viral transport. Lastly, we will assess the ability of the UV purifier to irradiate the virus sufficiently during its transit time and evaluate if the radiosity is minimized at the air inlet and outlet openings.

5.1 Location of UVPurifier and positioning in the bus

The UVPurifier location followed the premise that retrofit positioning just before the main HVAC inlet would indeed capture and cleanse the return. Two purifiers ensured both a front and rear return air path existed from the front and rear of the cabin respectively. The initial chosen locations functioned well.

5.2 HVAC Modal impact on flow field

In the most dispersive HVAC setting mode (A) with the driver's cabin HVAC fresh air, main HVAC recirculation and the two UVPurifiers all set on, the viral concentration field displayed multiple features:

- "social distancing" rapid drop in concentration from the mouth to about 1-2 m,
- slow decay in the base concentration away from the social distance region,
- a general good mixing of the concentration front to back,
- overall drop in concentration with both UVPurifier on and fresh air into the cabin, being recirculated and mixed by the main HVAC,
- recognition of both rearward and forward gradient concentration fields from their respective contaminated individuals shows logical gradients of concentration from the sources.

5.3 Flow field impact on viral field

Many HVAC mode configurations were run within the bus simulation to assess flow fields and dispersion of the viral concentration. Using the passive scalar method, multiple occupant source variants flowing and diffusing throughout the cabin were contiguously modelled. This gave some objective results as to what could be happening to the viral concentrations throughout the bus cabin.

Table 2 shows eight mode configurations of the HVACs and the UVPurifiers. When comparing A and F, the reduction in concentration from 1,000,000 virion/breath for A to 1318 virion/breath is much better than for F which only reduced from 1,000,000 to 989,693 virion/breath.

Table 2. Bus model modal settings run. Some representative results of the various modes. Concentration reduction from 1 Mvirion/breath from Driver to both Passenger 1 (P1) and Passenger 6 (P6).

Mode	Notes	Dr to P1 - Dr to P6
A	Check UVP works @ bus configuration	1318 - 987
B	How bad is it when the UVP is off?	3268 - 2963
C	No fresh air in system	1554 - 1097
D	Ventilation from driver panel	1460 - 1062
E	UVP alone	2680 - 1493
F	No AC systems operating. No UVP. Parked bus	989693 -790655
G	Main AC homogenised virus throughout cabin.	44172 - 43089
H	Front Panel fresh air clearing the bus.	4297 - 5018

5.4 Function of UVPurifier

The UV-C light modelling capability for Valeo TCV came to fruition in the early stages of the project. It meant capabilities and concepts of many UVPurifer designs could be assessed without high prototyping costs. Testing is not a simple process as the intensity and wavelength of UV-C lamps is known to cause keratitis of the skin and photokeratitis of the eyes [12]. Accurate modelling allowed for radiation to be deliberately directed, minimising radiosity externally from the exits of the UVPurifier whilst simultaneously maximising the irradiation of the viral RNA internally in the purifier.

6 Conclusions

The location and design of a UVPurifier system required some basic physics modelling to understand the phenomena involved. A simple passive scalar model was used to represent the virus concentration from driver and passengers who could potentially be asymptomatic. The advection and diffusion of the passive field through the bus's main HVAC and driver's cabin HVAC systems can be visualised and quantified. It helped verify the UVPurifier locations in the vehicle, confirming some flow patterns and also revealing new unexpected patterns.

The air flow patterns in the bus were dictated to a great extent by the main HVAC and driver's cabin HVAC settings. These two systems interact by setting up the flow fields which transport the viral concentrations from their potential sources to their potential targets. The concentration reductions in the scalar field from the source indicate the order of magnitude reductions that can be expected in various modes of operation in the vehicle.

Driver's cabin HVAC system assumes fresh air delivery to directly reduce the driver's daily exposure to the virus. The front HVAC can handle the driver's cabin energy differential to maintain the thermal balance for the important function of maintaining driver comfort. The driver could be working 8 hrs each day, day-in day-out, while possibly being exposed to the virus. In contrast a passenger may be on the vehicle for 15 to 30 mins.

Cabin fresh air from the front intake via the driver's HVAC system created a general plug-type flow through to the rear of the bus. It is quite important that fresh air reduces concentrations along the cabin, from front to rear. The flow that enters the front of the cabin at the driver, leaves via the extractors at the back of the bus, after traversing the flow streams throughout the vehicle.

Main HVAC assumed recirculation for energy conservation and comfort management from the originally installed pre-covid HVAC design. The main HVAC system has a very strong influence on the distribution and mixing of the virus in the cabin. It can be used to a positive extent in conjunction with front fresh air and the functioning UVPurifiers strategically located in the cabin.

Concurrently, the main HVAC system sends curtain flow down over the passengers throughout the vehicle, and then due to the main HVAC inlet being in the centre of the vehicle, it generates front to centre and also rear to centre flow patterns.

Cabin front to centre and cabin rear to centre creates swirling patterns, mixing and diffusion in the viral field, it also recirculates and potentially re-concentrates it if there is no external reduction or sinks in the cabin. This all homogenises the concentration in the cabin, whether it be good or bad. It is then further complicated by the creation of general left and right contra-rotating vortices. The pair generated from the sides into the centreline of the vehicle convects the flow back to the main HVAC inlet near the centre.

The viral concentration for a hypothetical asymptomatic driver and several passengers, showed the natural reduction of the viral concentration field with increasing distance, mostly when fresh air and the UVPurifier worked in tandem, and "social distancing" could be seen in operation. However, the vehicle HVAC settings affected the forced convection or recirculation through the cabin. The fresh air inlet, cabin circulation, UVPurifier and individual passengers' locations all led to various logical concentration fields, depending on the source and victim locations.

The choice of two intense UV lamps creating the irradiation field inside the UVPurifier was effective. The longitudinal field ensured good radiant exposure level allowing time to disable the viral RNA. The safety of the bus occupants from that intense field by careful design and implementation of the light traps at the inlet and outlet regions is ensured. This simulated a reduction in irradiation peak on the internal components from ~100 mW/cm^2 down to 0.0001 mW/cm^2, which corresponds to average irradiation ~10 mW/cm^2 down to 0.00001 mW/cm^2 on the surfaces.

7 Affiliates

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