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Ultraviolet (UV) and other Disinfection Devices for Public Transit in Response to COVID-19

FINAL REPORT
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16. Abstract

This project was designed as a rapid effort to evaluate ultraviolet (UV) disinfection technologies with a specific emphasis on UVC (ultraviolet germicidal wavelength) efficacy and practicality for surface disinfection of bus interiors. With more than 3,700 vehicles in NJ TRANSIT's fleet, the deployment of any new technology must be carefully weighed against alternatives to ensure it achieves the desired results. The study LiDAR surveyed six vehicle types and developed virtual environment 3-D models for a NABI 40-ft bus and a mini-bus used for paratransit. Using the operational constraints, these models were used to run simulations to determine UVC source placement. The model showed for the 40-ft bus that 65.61% and for the mini-bus that 70.88% of visible surfaces would receive a direct line of sight dosage. Field testing was then conducted using UVC sources and a spectrometer. All but three (3) mini-bus and six (6) measured NABI locations received dosages in excess of the established threshold required to achieve a 10.6 mJ/cm2 kill dosage. However, even these locations still received some level of irradiation. This confirmed the simulation results and implies that the true percentage of the bus receiving a kill dosage is much higher than the model prediction, which could not predict reflected light. However, any gap in coverage of a critical or high touch surfaces like a wheelchair seatbelt raises overall efficacy concerns for UVC disinfection of surfaces. Although UVC for disinfection is highly effective there are a number pragmatic considerations too. In comparison to chemical disinfection via spray and air-dry procedures, using a portable UVC source does not appear to save labor time or cost. Ultimately, in comparison to the simplicity and speed of spraying an EPA List N approved chemical disinfectant, the time and logistics of UVC may not be practical for fleet wide deployment. The research team also reviewed available literature concerning HVAC systems and their ability to remove virus particles from the air. If performance permits, the HVAC should be upgraded to MERV 13 or better filter, or the highest compatible filter, at a minimum MERV 8. For in-duct ion and photocatalytic oxidation systems, the research team has health and efficacy concerns. Similarly, due to the rapid air exchanges within the bus HVAC system, the low UVC exposure time of air in-duct UVC devices, it is unclear if they achieve the full kill dosage required. However, repeated in-duct UVC exposure may result in a net cumulative dosage that weakens or possibly kills some unknown percentage of virus.

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Glossary of Terms

Ionization	An electrically charged atom or molecule created through the atom gaining or losing electrons acquiring a negative or positive charge.
LiDAR	Laser scanner used to measure the reflections of surfaces with laser light to make a digital 3D representative model.
mJ/cm2	(Milli Joule per centimeter squared) Unit commonly used to describe total energy emitted by an ultraviolet light source. Also used to describe total dosage delivered.
Photocatalytic	A material absorbing light which brings it to a higher energy level which combines with a reacting substance in order to make a chemical reaction.
Point cloud	Set of data points in space produced by a LiDAR 3D scanner which measure points on the external surfaces around them.
Reactive oxygen species (ROS)	Chemical species which are chemically reactive containing oxygen.
Spectrometer	Scientific instrument used to measure properties of light, specifically for this project, wavelength and intensity.
UVC	Germicidal portion of the ultraviolet spectrum found within the 200 to 280 nm range, also referred to as germicidal UV.
uW/cm2	(Micro Watt per centimeter squared) Unit used to describe the intensity of a UV light source at a certain distance. Essentially the rate at which the energy is being delivered (1 Joules = Watt/s).

2 ABSTRACT

This project was designed as a rapid 25-day effort to evaluate ultraviolet (UV) disinfection technologies with a specific emphasis on UVC (germicidal ultraviolet wavelength) efficacy and practicality for surface disinfection of bus interiors. With more than 3,700 vehicles in NJ TRANSIT's fleet, the deployment of any new technology must be carefully weighed to ensure it achieves the desired results and if it can be scaled up for such a large fleet. Although very little information currently exists for UVC efficacy against SARS-CoV-2 (COVID-19) there is a wealth of information for SARS-CoV-1. As new data becomes available it's likely the kill-curve recommendation will change; current data suggested ranges from 0.56 mJ/cm2 to 37 mJ/cm2.[1] At this time, after reviewing the literature, the research team recommends a conservative but reasonable estimate of 10.6 mJ/cm2 to achieve a 1-log (90% reduction) kill rate. While working with NJ TRANSIT several operational constraints were also established. For example, an acceptable maximum UVC operational time of 7 minutes, which directly relates to turnaround time while the buses are readied for the next day. Each of the 16 garages house on average 200 buses with a turnaround of only a few hours to refuel, clean, and perform daily service before the buses return to the road. Seven minutes effectively means an equivalent of 24hrs of UVC lamp on-time would be required per garage every night. This has implications on equipment needs for simultaneous disinfection, storage of UVC equipment, power draw, dedicated staffing, and other impacts on nightly service and garage operations. The study also LiDAR surveyed six vehicle types and developed virtual environment models for a NABI 40-ft bus and a mini-bus used for paratransit. Remnant surfaces that would likely never receive contact or even UVC light were removed from the model to provide a more realistic visible/touchable surface analysis. For example, the side of the seat that touches the bus shell, or where the back of the seat in the last row is leaning against the bus shell, was eliminated. Using the operational constraints, the model was used to run simulations to determine UVC source placement and estimated surface percentage receiving a kill dosage. The model showed for the 40-ft bus that 65.61% and for the mini-bus that 70.88% of visible surfaces would receive a direct line of sight dosage. Field testing was then conducted based on the models optimized locations on the 40-ft and mini-bus using UVC sources, UVC meter, and spectrometer. The results of the model were common reviewed and refined to prioritize high touch surfaces like seats. Shadowed areas, which could still receive some "indirect" light such as reflected dosage, were field measured. All except three (3) test mini-bus locations (back of the last row of seats, back of wheelchair seatbelt, and the strap storage bag) received dosages in excess of the established 25 uW/cm2 threshold required to achieve a 10.6 mJ/cm2 kill dosage in less than seven minutes. All measured NABI locations received dosages except six (6) test locations. However, even these locations still received some level of irradiation. This confirmed the simulation results and implies that the true percentage of the bus receiving a kill dosage is much higher than the

model prediction. This includes reflections onto critical high-touch areas such as armrests, backs of seatbelts, tops of handrails near the ceiling, and the back of some seats. However, any gap in coverage of a critical or high touch surfaces like a seatbelt raises overall efficacy concerns for UVC disinfection of surfaces. Although UVC for disinfection is highly effective there are a number pragmatic considerations too. In comparison to chemical disinfection via spray and air-dry procedures, using a portable UVC source does not appear to save labor time or cost. Nevertheless, portable UVC can still be invaluable to supplement chemical disinfection for particular applications. For example, UVC disinfection might be used to further minimize risk as a redundant safety procedure; such as when its known that a bodily fluid was discharged (i.e. blood, vomit) or if an employee is confirmed COVID-19 positive. Ultimately, in comparison to the simplicity and speed of spraying an EPA List N approved chemical disinfectant, the time and logistics of UVC may not be practical for fleet wide deployment for surface disinfection but it can still be a valuable tool. The research team was also asked to review available literature concerning HVAC disinfection devices for air treatment. Increased ventilation and better filtration are commonly cited as recommendations. If system performance permits, the HVAC should be upgraded to MERV 13 or better filter, or the highest compatible filter, at a minimum MERV 8, preferably with antimicrobial. At this time, in reference to in-duct ion and photocatalytic oxidation systems, the research team has health and efficacy concerns. Similarly, due to low UVC exposure time the in-duct UVC devices it is unclear if they achieve the full kill dosage required. However, due to the rapid air exchanges within the bus HVAC system, repeated in-duct UVC exposure may result in a net cumulative dosage that weakens or possibly kills some unknown percentage of virus. This approach may lower the overall risk exposure without the same health concerns. However, it’s more than likely that the HVAC cannot be upgraded to MERV 13 or better either due to filter availability, lack of pressure testing data, or overall HVAC system inability; therefore, it’s highly-recommended to further investigate and incorporate an in-duct system such as in-duct UVC system along with at a minimum MERV 8 filter.

3 DESCRIPTION OF THE PROBLEM

Due to the COVID-19 pandemic, extra measures are being taken in the regular disinfection of public spaces, including all forms of public transportation. The supplementation of ultraviolet (UV) disinfection devices to current cleaning practices used on public transit vehicles, stations, and facilities has the potential to reduce the spread of COVID-19, restore the general public's confidence in using public transportation, and expedite restart and recovery.

This effort was conducted by Rutgers University's Center for Advanced Infrastructure and Transportation (CAIT) in partnership with the Environmental and Occupational Health Sciences Institute (EOHSI) in response to NJ TRANSIT's request for assistance in the investigation of the applicability and feasibility of disinfection devices for use on their public transit vehicles. The ability to kill or disable viruses is of keen importance during the COVID-19 pandemic as well as for the recovery periods that follow to make customers more confident in their use of public transit, particularly vulnerable transit customers such as seniors or customers with disabilities.

Recent studies have shown that rider confidence is down drastically when it comes to using public transportation. Surveys as recently as April 2020 have consistently shown that between 48% and 54% of riders were found to be averse to taking public transportation.[2,3] "More than 20% of respondents who regularly used buses, subways or trains now said they no longer would, and another 28% said they likely would use public transportation less often."

In response to the COVID-19 pandemic, NJ TRANSIT has enhanced its cleaning procedures to disinfect its vehicles every 24 hours, and at major stations and terminals on each shift throughout the day in an effort to help control the spread of coronavirus. In coordination with this enhanced cleaning regime, the use of UVC disinfection during these cleaning times shows potential to help reduce the spread of COVID-19 and restore rider confidence.

Ultraviolet light in the germicidal range (200-280 nm light) known as "UVC" has proven to be effective at disinfecting water and surfaces, and may help reduce the risk of infection due to the COVID-19 virus. UVC light energy is not the same as the UVA and UVB light wavelengths found in exposure to sunlight.

As per NJ TRANSIT's request, the purpose of this study is to test and provide validation support for a pilot UVC deployment. The research team was tasked to perform a LiDAR survey of representative bus vehicles and model the placement of UVC light sources to quantify the surface areas that would receive UVC disinfection exposure. The team was also to perform field validation tests using a spectrometer to measure the intensity of exposure throughout the bus based on the recommended locations from the LiDAR survey. Lastly, the team was to review potential air disinfection technologies within the context of published materials.

4 APPROACH

This project was designed as a rapid 25-day effort to evaluate UVC disinfection technologies with a specific emphasis on UVC efficacy and practicality for surface disinfection of bus interiors. With over 3,700 vehicles in NJ TRANSITs bus fleet the deployment of any new technology must be carefully weighed to ensure it achieves the desired results and if it can be scaled up for such a large fleet. The research approach focused on fast turnaround of results for NJ TRANSIT. For this reason, certain assumptions, operational parameters, and simplified testing processes were established to expedite results. A more robust testing schema is recommended to expand on these initial findings.

For example, Mercury UVC bulbs are readily available from many manufacturers and are used in a variety of different UVC devices. These devices have differing number of total bulbs, bulb length, intensity, power requirements, size, weight, timers, motion sensors, intensity sensors, and other features. However, the intent was not to identify a specific vendor for deployment but instead provide guidance on the overall ability of UVC to provide the irradiance, or more specifically energy over a time duration required to disinfect. A variety of devices were identified as reference to ensure that indeed a commercially available product exists that matches the operational parameters required. Therefore, a representative UVC source was used for this project even though a number of devices were identified that could be used with differing durations and placements.

The research approach of this project addresses:

- **Literature search and best practices**
- **UVC disinfection of surfaces**
    - LiDAR assisted Bus Sanitization Modeling: Perform LiDAR survey inside bus, build BIM model of bus, model UVC source locations to determine line of sight coverage
        - Testing efficacy of the UVC disinfection: UVC intensity measured spectrophotometrically and with a UVC meter, ensuring that a high enough UVC light intensity is achieved at all spaces to be disinfected.
    - UV light bleed - validate exterior safety measures, measure any exterior UVA, UVB, and UVC penetration through windows
    - Identify commercially available UVC devices and collect general information on
    - Preliminary cable management and power
- **HVAC and airflow for air disinfection**
    - Review best practices and any vendor/agency recommendations for HVAC filtration and UVC treatment in HVAC. Review ion generation technology within the context of published materials.

5 FINDINGS

5.1 Best Practices and Literature Review

Disinfectants and biocidal agents employ non-specific methods for either inactivating or membrane disruption of microbial pathogens (i.e. bacteria, fungi or viruses) often found in droplets that can lead to epidemics or pandemics. Non- “chemical” disinfection techniques include, for example, ultraviolet germicidal irradiation (UVGI), photocatalytic oxidation (PCO), or plasma ion generation. The disinfection efficacy is driven by physicochemical characteristics of the agent, as well as the cell morphology, and physiological status of the microorganism. Membrane disruption, macromolecular modification, and metabolic inhibition create downstream effects that render the pathogen neutralized, either directly resulting in cell death or by initiation of self-destructive processes.

5.1.1 Ultraviolet Background and Kill Dosage

Ultraviolet (UV) light to disinfect is widely used in clinical, water treatment, and other settings. UV is found in the 100-400 nm wavelength with UV-A, UV-B, and UV-C being subsets. UVC is well established as germicidal in the 200-280 nm wavelengths where 254 nm is commonly cited as the germicidal wavelength as it’s generated from readily available Mercury UVC bulbs. In addition to Mercury UVC there are also LED and pulsed Xenon (sometimes referred to as PX-UV) lamps. Mercury bulbs are “on” with a constant wave UVC intensity; while pulsed Xenon flashes “on/off” at a higher intensity every few seconds. LED UVs don’t contain Mercury and have longer lifecycles. However, they are much less common than Mercury bulbs. Due to the different mechanism and sources, the amount and duration of disinfecting energy is different as are the specific wavelengths produced. Regardless of the source, UVC light within the 200-280 nm range has been shown to inactivate viruses by altering the DNA of the virus, thus rendering it unable to reproduce and spread amongst humans.

While UVC light may be effective at killing bacteria and viruses, it also poses a health risk to humans. Light within this spectrum can cause damage to the outer epidermal layer as well as well as the outer layer of the cornea. The 222 nm wavelength referred to as Far-UVC is more recently cited as claiming to reduce human exposure risk while still providing germinal benefits. Wavelengths of UVC light in the 222 nm are said to be safer on the skin and corneal tissue than other more commonly found UVC light sources which generally operate around the 254 nm range, although there have been inconsistent studies confirming these claims.[4],[5]

At the lowest end of the ultraviolet spectrum, the 100- 200 nm range, UVC light begins to produce ozone as a bi-product by reacting with the air. Ozone has the potential to be used as an additional disinfecting measure, but comes with its own health risks including irritating nasal passages, nausea, and with longer exposures, lung inflammation.[6] Therefore, the UVC in the 254 nm wavelength was selected for the purposes of this project since it is well established for disinfection and its health exposure complications are known and manageable.

Very little information currently exists for UVC efficacy to disinfect SARS-CoV-2 (COVID-19) however there is a wealth of information for SARS-CoV-1. As new data becomes available it's likely the kill-curve recommendation will change; current data suggested ranges from 0.56 mJ/cm2 to 37 mJ/cm2 [1] and even higher. After reviewing several journal articles, the recently published May 2020 paper titled Ultraviolet irradiation doses for coronavirus inactivation – review and analysis of coronavirus photoinactivation studies provides an excellent summary. "Coronavirus inactivation experiments with ultraviolet light performed in the past were evaluated to determine the UV radiation and dose required for a 90% virus reduction. This analysis is based on the fact that all coronaviruses have a similar structure and similar RNA strand length. The available data reveals large variations, which are apparently not caused by the coronaviruses but by the experimental conditions selected. If these are excluded as far as possible, it appears that coronaviruses are very UV sensitive. The upper limit determined for the log-reduction dose (90% reduction) is approximately 10.6 mJ/cm2 (median), while the true value is probably only 3.7 mJ/cm2 (median)." [1]

The paper goes onto discuss the results of 34 published studies for many different coronaviruses, including SARS-CoV-1, MERS, and others but not SARS-CoV-2. It also discusses the methodology to and the elimination of outliers and results from higher-absorption media suggesting that "the total median log reduction dose would be 3.7 mJ/cm2 (average 5.8±5.5 mJ/cm2)."[1]

For the purposes of this feasibility study the research team used 10.6 mJ/cm2, which conservatively will result in a 1-log (90% reduction) kill rate. Please note that according to a July 7, 2020 press release, US Environmental Protection Agency (EPA) has partnered with Los Angeles Metropolitan Transportation Authority to evaluate a number of new technologies, including UVC and air filtration for public transit systems to address COVID-19.[7] When the recommendation from EPA to achieve a kill dosage is finalized at some later date, if it's closer to 3.7 mJ/cm2 then the 10.6 mJ/cm2 would likely result in a 2-log (99% reduction) or better.

5.1.2 What are Transit Agencies Doing

NJ TRANSIT has increased cleaning efforts in order to better combat the spread of SARS-CoV-2 (COVID-19) through daily disinfection of their bus fleet using foggers containing known antiviral pesticide solutions. In response to the COVID-19 pandemic, NJ TRANSIT has enhanced its cleaning procedures to disinfect its vehicles every 24 hours, and at major stations and terminals on each shift throughout the day in an effort to help control the spread of coronavirus. In coordination with this enhanced cleaning regime, the additional use of UVC disinfection during these cleaning times shows potential to help reduce the spread of COVID-19 and restore rider confidence.

Transit agencies throughout the US and worldwide have also begun to use new technologies such as UVC light to help disinfect their vehicles in an effort to reduce the spread of COVID-19. Internationally, the public transportation firm **Yanggao** in Shanghai, China is using UVC disinfection lights inside bus interiors as well as UVC lighted cleaning bays to illuminate each bus from the outside as well. Transit authorities within the U.S. such as New York's Metropolitan Transportation Authority (**MTA**) have also begun to explore the usage of UVC. A pilot study using a pulsed xenon UVC system manufactured by Puro UV Disinfection Lighting onboard their subway is currently underway with plans to eventually expand the use of UVC disinfection to their entire fleet of vehicles.

The Southeastern Pennsylvania Transportation Authority (**SEPTA**) has currently increased their sanitizing efforts of both their rail vehicles as well as buses to at least twice per day utilizing backpack sprayers with disinfecting pesticides, and an additional deep cleaning of each vehicle every 14 days.[8]

Dallas Area Rapid Transit (**DART**) has recently adopted an increased daily cleaning regime using hydrogen peroxide foggers as well. Long before the COVID-19 outbreak, DART also equipped over 70% of their buses with SanUVAire Breathe Safe Germicidal UV Systems which utilize UVC disinfection within the HVAC units to help kill viruses as air is recirculated throughout the bus. [9]

Without conducting a full survey of Transit agencies it's impossible to know exactly what each agency is doing to address COVID-19. However, for reference purposes the research team scanned media reports and agency websites to capture a sample of activities that major transit agencies are deploying or researching; these include:

1. **New York City Transit Authority**
    a) EPA-registered antimicrobial products
    b) Ultraviolet light (UV)
    c) Ozone
    d) Steam
    e) Electrostatic sprayers
    f) Foggers

2. **Washington Metropolitan Area Transit Authority**
    a) Frequent cleaning of buses, trains and high-touch surfaces
    b) Rear-door boarding
    c) Supply conservation

d) Mask/face-covering requirement
e) Additional buses to provide more capacity/service

3. Chicago Transit Authority
a) Rear-door boarding
b) Ridership limits
c) Electrostatic sprayers
d) Preventative surface coatings
e) UVC Lighting

4. Massachusetts Bay Transportation Authority
a) Daily disinfecting with focus on high-touch points
b) Fogging
c) Electrostatic sprayers

5. Bay Area Rapid Transit District
a) Hospital-grade disinfectant in stations and on trains
b) Longer trains to help promote social distancing
c) Personal hand straps
d) UVC lighting

6. Port Authority of New York and New Jersey
a) Required face masks/coverings
b) Disinfect high touch areas 3 times per day
c) Electrostatic sprayers
d) Deploying hand sanitizer stations
e) Increased train schedule

7. Southeastern Pennsylvania Transportation Authority
a) Rear-door boarding
b) Ridership limitations
c) Increased cleaning/disinfecting
d) Operator shields
e) Markers for social distancing

8. Metropolitan Atlanta Rapid Transit Authority
a) Electrostatic sprayers
b) Traditional cleaning
c) Increased frequency of cleaning

9. Los Angeles County Metropolitan Transportation Authority
a) Disinfect high-touch surface 3 times per day
b) EPA-approved disinfectants
c) UVC lighting

d) Air filtration systems,

10. Miami-Dade Transit

a) Increased disinfection frequency
b) Sprayers
c) Installing hand sanitizer units aboard buses
d) Additional busses

11. Port Authority Transit Corporation

a) Enhanced cleaning and sanitization of High-touch areas
b) Awareness campaign promoting hygiene
c) Participating in workshops to share information and best practices

12. Staten Island Rapid Transit Operating Authority

a) Changed schedule to match Staten Island Ferry
b) Staten Island Ferry requires masks and is using markers to promote social distancing

13. Maryland Transit Administration

a) Face mask requirement
b) Increased frequency of disinfecting high-touch surfaces

14. Greater Cleveland Regional Transit Authority

a) UVC lighting to clean high traffic areas
b) cleaning all touchable surfaces with a cleaning agent recommended by the Centers for Disease Control (CDC).

As of the time this report was prepared, the only recommended disinfection for transit vehicles by the Center for Disease Control and Prevention (CDC) is through pesticides found on the United States Environmental Protection Agency's (EPA) "List N" disinfectants, containing primarily hydrogen peroxide, quaternary ammonium, and chlorine-based products. There are currently no EPA or CDC recommended guidelines for the use of UVC light towards the disinfection of transit vehicles (viruses in general).

The American Public Transportation Association (**APTA**) is currently **recommending that all transit agencies perform their own research when it comes to the use of UVC light for disinfection** of their vehicles as there are currently **no consolidated list of UVC products suitable for use by transit agencies nor are there any established standards**. [10]

5.1.3 *Other than List N disinfectants*

EPA List N includes surface disinfectants registered with EPA but does not include devices such as UVC for surface or air treatment, ion generators, ionizer/electrolytic, and ozonation devices. The EPA doesn't routinely review efficacy of UV disinfection devices nor other pesticidal devices. Although the devices are not regulated, the manufacturers cannot make false and misleading claims. Therefore, manufacturers are required to have scientific data to support their claims. EPA "therefore cannot confirm whether, or under what circumstances, such products might be effective against the spread of COVID-19." [11]

5.1.4 *Health and safety guidance*

The recommended maximum UVC exposure time given by the National Institute for Occupational Safety and Health (NIOSH) is no more than one minute at 50 uW/cm2 (which calculates to do not exceed 3 mJ/cm2 per 1-minute of exposure) total irradiance incident on unprotected skin or eyes.[12],[13] Occupational Safety and Health Administration (OSHA) does not have an established UV level of exposure limit. According to the 2004 International Commission on Non-Ionizing Radiation Protection (ICNIRP) report the amount of 254 nm wavelength should not exceed 6 mJ/cm2 per 8-hour exposure.[14] <u>This is quite low and would be exceeded rapidly while working unprotected in proximity to any of the commonly available devices.</u> Therefore, precautions such as PPE, protocols to avoid exposure, employee training, motion sensors to shut off devices, or a combination of these measures must be used to ensure worker exposure is less than the one minute recommended by NIOSH.

While UVC light is absorbed (i.e. filtered out) by most conventional glass and plastic, there are some additional concerns regarding pulsed Xenon lamps. The pulsed Xenon flashes and produces a wavelength in the visual spectrum that readily passes through the windows, which can be a visual distraction and a potential hazard for drivers and workers in the bus garage/depot environment.

As with any common fluorescent and compact fluorescent lights (CFLs), the bulbs contain harmful Mercury. Generally, these bulbs are safe from Mercury contact exposure when intact, but do pose a safety risk when broken. Procedures and guidelines for disposal and handling of broken UVC bulbs is comparable to similar size standard fluorescents. Precautions should be taken while handling to avoid bulb breakage. Loose dangling power cords or safety chains, coiling of power cords, bumping, dropping, etc. can all result in broken bulbs and Mercury exposure. Unlike standard fluorescents, UVC bulbs use quartz glass which allow the UVC wavelength to pass through the glass; this type of glass has the same potential hazard of any broken glass. Efforts to minimize dispersal, generating dust, and spreading of the Mercury vapor should be taken, turn off blowers, avoid using vacuum cleaners, use stiff paper to scoop up debris, use duct tape to pick up small bits, use a damp cloth, and properly dispose of waste in a plastic bag or closed container. EPA has developed cleanup and disposal guidance to minimize health risk exposure, these have been included in the appendix of this report.

- “DO NOT VACUUM. Vacuuming is not recommended unless broken glass remains after all other cleanup steps have been taken. Vacuuming could spread mercury-containing powder or mercury vapor.
- Be thorough in collecting broken glass and visible powder.
- Place cleanup materials in a sealable container.”[15]

It is recommended to institute a training program for employees using UVC for disinfection. Topics can include but not be limited to: exposure risk associated with UVC lights and Mercury from broken bulbs, proper PPE during use, emphasis on proper eye protection even when risk exposure is minimal, notification of other employees of UV in use, cleanup of broken bulbs, handling, placement, storage, potential damage to materials from overexposure to UV, use of safety chain or cable to avoid accidental dropping, among others.

Beyond UV, the CDC has COVID-19 guidance available for users of transit and transit operators, for quick reference this information has been included in the Appendix of this report.

5.2 UVC Disinfection of Surfaces

UVC has been used for more than 40 years to disinfect drinking water, waste water, air, and surfaces, and all bacteria and viruses tested to date respond to UV disinfection. UVC disinfection systems are already being used in some hospitals globally and have been shown to reduce infection rates at hospitals as much as 30% when added to regular cleaning.[16] In addition to UVC lamps and robotic systems being used in select hospitals, some international transit agencies have also begun deploying UVC systems in an effort to reduce the spread of coronavirus. The public transportation firm Yanggao in Shanghai, China is currently using UVC disinfection lights inside bus interiors as well as UVC lighted cleaning bays to illuminate each bus from the outside as well. Transit authorities within the U.S. such as New York's Metropolitan Transportation Authority (MTA) have begun to explore the usage of UVC disinfection as well through the trial use of UVC lamps within their subway vehicles.

Deploying UV disinfection systems across NJ TRANSIT's significant assets is a sizable undertaking with a daily weekday ridership of nearly 1M riders. Broadly speaking, NJ TRANSIT assets include: 166 rail stations, 62 light rail stations, 30 bus terminals, and more than 16,000 bus stops; 1,081 commuter railcars and 71 light railcars; and 3,707 buses (owned and leased).

Given the time sensitive nature of this project the research team implemented a rapid and practical approach to this study with respect to the technologies available. UVC disinfection has been shown to be very effective in the past. However, there are some practical considerations that were made:

- Time and distance - Light dissipates with distance, therefore the further a UV bulb is from a surface the less effective it will be at disinfecting. Alternatively, a UVC bulb will require more time to achieve the same disinfection as one that is closer. Therefore, bulb intensity, time, and distance are all major factors.
- Light travels in a straight line – Surfaces that are shadowed or not in the line of sight of the UV bulb will not receive full intensity disinfection, though there might be some level of UV penetration into shadowed areas. Therefore, the straightest line to the surface being disinfected is a major factor.
- Prioritize disinfection of horizontal surfaces - Horizontal surfaces tend to be: a) high touch areas and b) a larger percentage of settlement zones. Therefore, any technology that can show a preference for horizontal surfaces will likely be more effective at eliminating COVID-19 virus.

While working with NJ TRANSIT, several operational constraints were established. For example, an acceptable UV operational time of 7 minutes; which directly relates to turnaround time while the buses are readied for the next day. Each of the 16 garages house on average 200 buses with a turnaround of only a few hours to refuel and perform daily service before the buses return to the road. This effectively means that an equivalent of 24hrs of UV lamp on-time would be required per garage every night. This has implication on equipment needs for simultaneous disinfection, storage of UV equipment, power draw, dedicated staffing, and other impacts on nightly service and garage operations.

[200 buses * 7 minutes per bus / 60 minutes per hour = 23.3 hrs disinfection per garage]

These items have been addressed in detail in the following sections. However, the overarching goal of this task was to provide NJ TRANSIT with rapid results on recommended UVC light positions and corresponding intensity of light delivered over interior surfaces based on a continuous Mercury UV light source already purchased by NJ TRANSIT.

5.2.1 LiDAR Model

5.2.1.1 LiDAR scan and coverage modeling

The laser scanning and 3D modeling task in this project included the scanning of 4 buses (NABI 40-foot transit bus, cut-away style paratransit mini-bus, MCI 45-foot cruiser bus, New Flyer 60-foot articulated bus), a minivan, and a sedan; and 3D modeled a NABI bus and mini-bus. The laser scan equipment used in this project is a Faro Focus 3D scanner. In order to capture the detailed dimension and texture of each bus, multiple color scans were conducted on each bus. Depending on the size of a bus, multiple scans from different positions were conducted and then later registered together to provide complete 3D data of the bus interior and exterior. The scan process usually starts inside the bus, from the last row of seats to the front of the bus, and then moves outside to scan around the whole exterior. Some examples of bus scanning activities are shown in Figure 1 and Figure 2.

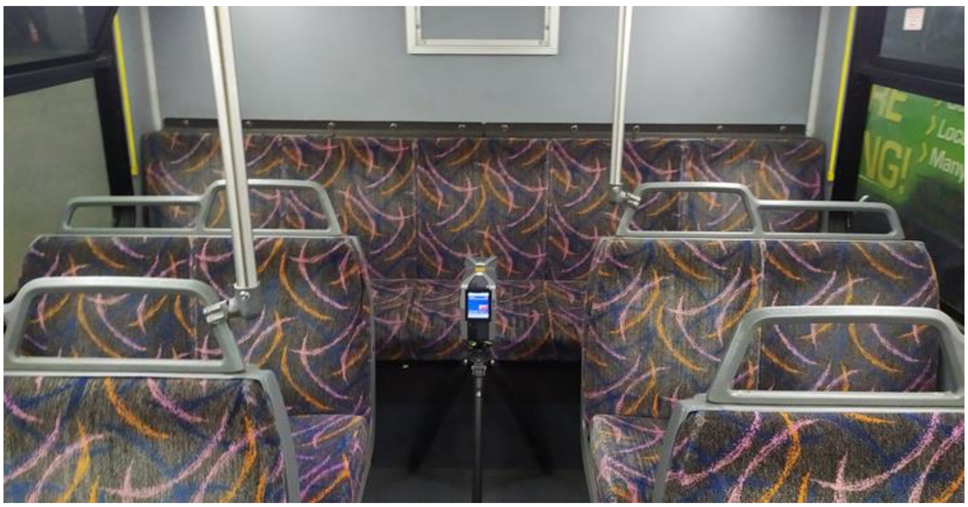

Figure 1 Scanning the interior of a bus

Figure 2 Scanning the exterior of a bus

5.2.1.2 Scan Data Post Processing

After data collection, each of the individual scans were registered together by using real time, on-site registration, automatic object recognition, scan registration, and positioning functions. After the data registration, the point cloud of the bus and associated features was generated. Then this point cloud was cut and colorized to generate a better visual representation. The registered and processed point cloud result is shown in Figure 3.

Figure 3 Exterior view of bus point cloud

5.2.1.3 3D Modeling

After the registration and cleaning process, the bus point cloud was exported to Autodesk Recap file, which is a compatible format of Autodesk Revit. The Recap file was imported into Revit, and a bus model was built by tracing the dimension of point cloud. When finished, the newly built models can be exported into the suitable format for the subsequent analysis. The final models are shown in Figure 4 and Figure 5.

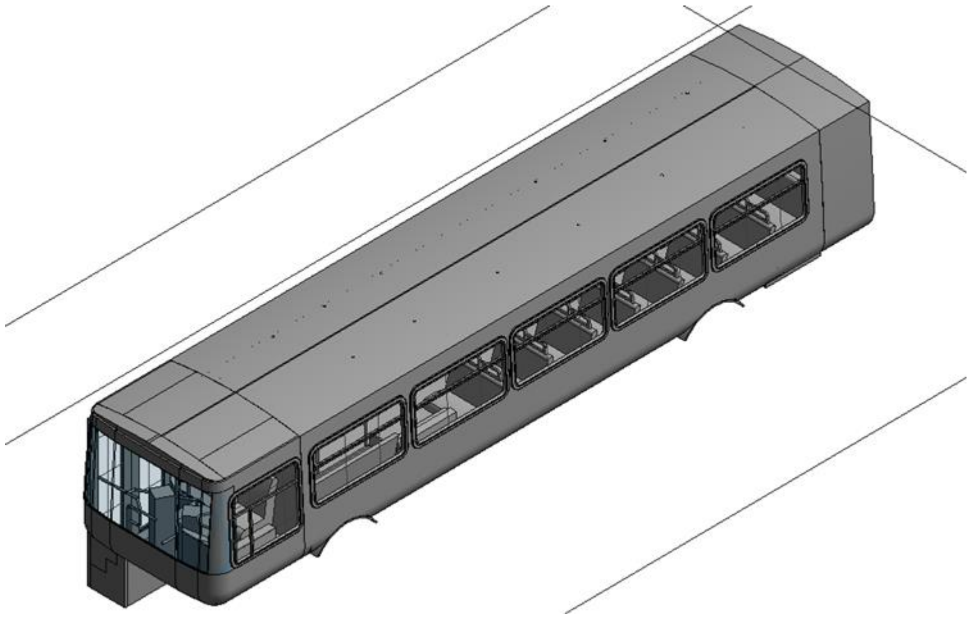

Figure 4 Model of NABI bus

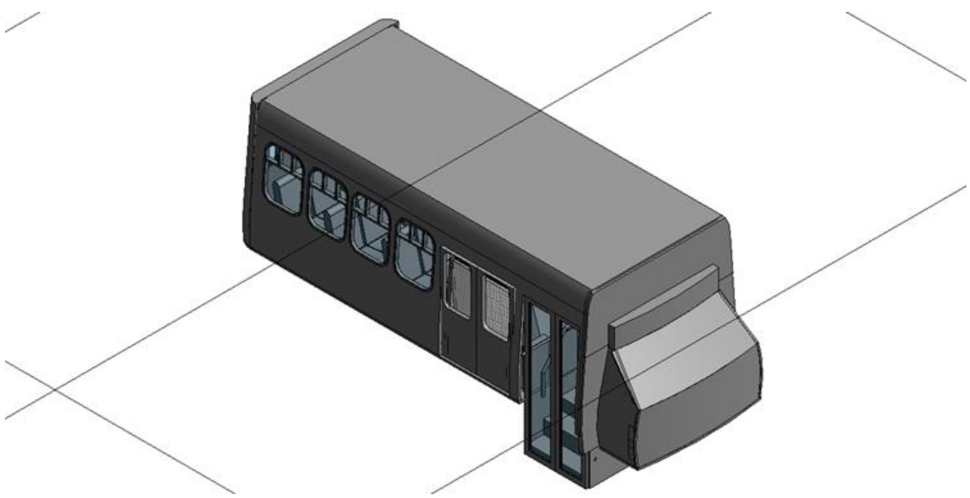

Figure 5 Model of mini-bus

5.2.2 UVC Source Direct Line of Sight Coverage Analysis

The following section describes two parallel efforts to identify the optimum UVC source placements and quantify the total line of sight coverage using the previously developed models from the LiDAR scans.

5.2.2.1 Point cloud-based approach

The point cloud-based approach is described in the Figure 6.

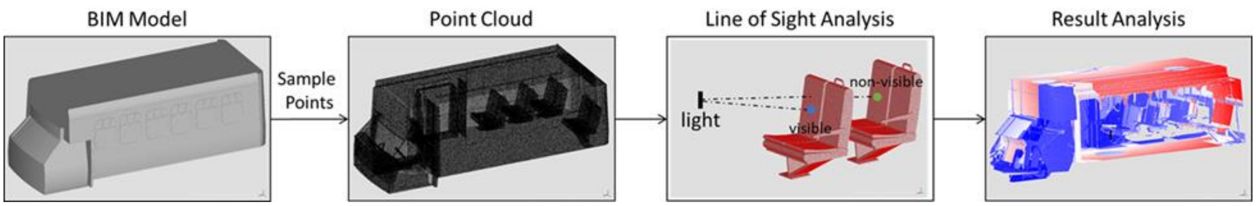

Figure 6 Line of sight analysis (point cloud-based approach)

The method can be further divided into three steps:

- Step 1: Point cloud generation. Based on the previous built 3D bus model, sample points from the mesh model in a way to make sure that the points are evenly distributed on the bus surface.
- Step 2: Line of sight analysis. Given the light position, construct the lines of sight between the light and all the points. Visible points are determined if the lines of sight are not occluded by the 3D bus model. The line of sight analysis function is implemented through the Python script.
- Step 3: Result Analysis. Visible points have been detected in step 2. The light intensity can be calculated based on the distance between points and light. Then visualize the light intensity in color, and the red represents stronger light intensity.

$$I = \frac{k}{d^2}$$

Considering the points are evenly distributed on the surface, coverage can be calculated using the following formula:

$$coverage = \frac{N_{visible}}{N_{all}}$$

$N_{visible}$ represents the number of detected visible points, and N_{all} represents the number of all the points.

To determine how many UVC sources are needed and their specific locations, a grid search strategy was used. As the Figure 7 shows, the bus space was divided into a series of 3D blocks, and the coverage is calculated when the UVC source is placed in each block. Finally, a search was conducted to determine the best position for one UVC source light as well as multiple source combinations using this method.

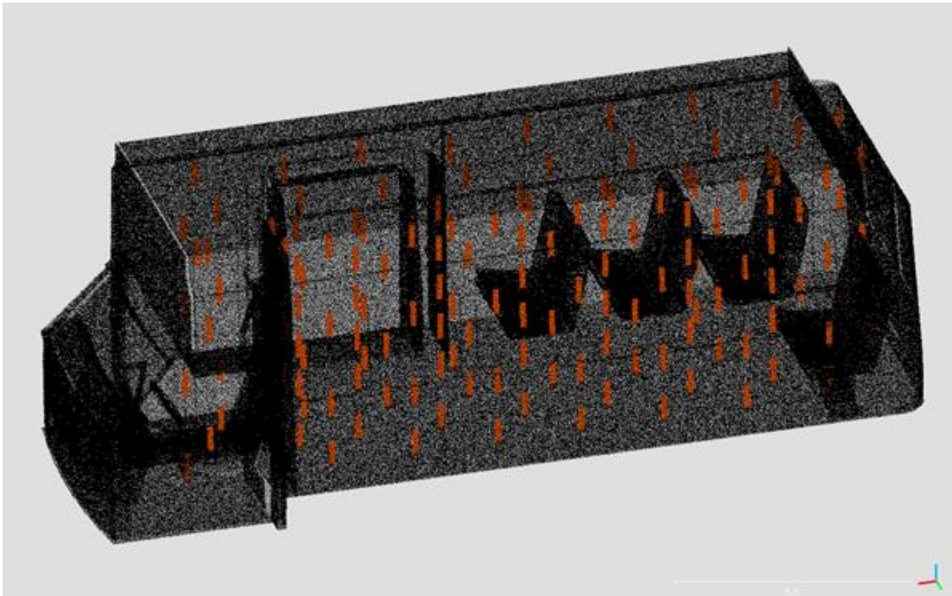

Figure 7 UVC source light position candidates

5.2.2.2 Mesh model-based approach

The mesh-based approach for line of sight analysis was conducted using Blender 2.8. The bus model was exported from BIM software and loaded into Blender as a mesh. Taken into account are several factors that may result in significant bias to the UV coverage, for instance:

- The thickness of bus shell & windows would double-calculate these areas and lead to lower UV coverage
- Large triangles on the mesh can cause over-calculated UV covered areas and produce final results incorrectly higher

Therefore, the preprocessing consists of three steps to address these issues identified above (Figure 8):

- Step 1: Objects grouping: the internal objects were divided into 4 groups: bus shell, windows, chairs, and railings. Mesh cleaning methods and line of sight analysis were applied to each group respectively.
- Step 2: Mesh cleaning was mainly applied to the objects including bus shell and windows in order to reduce these meshes to 1-layer of surfaces. These objects were

separated from the model and multiple virtual raycasts were performed from the inside of the bus. This step retains only the shined meshes (by the rays) which represent the surfaces for the bus interior.

- Step 3: The triangles on the mesh vary significantly in size. Subdividing large triangles into larger amounts of smaller ones (higher resolution) would certainly push the results closer to real results but would lower the performance of our analysis as well. Therefore, the subdividing algorithm was developed to perform subdividing method to mesh triangle adaptively. In this procedure, large triangles received more subdivision until they were divided below a certain threshold.

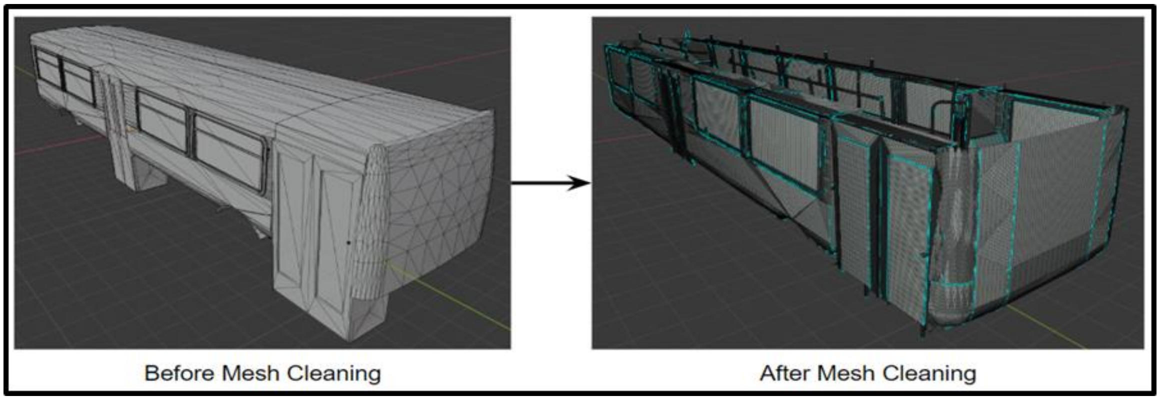

Figure 8 Blender mesh cleaning

After the mesh preprocessing was complete, the line of sight analysis was performed taking advantage of the raycasting function based on the given locations of the UV light sources. The function was applied between the points representing light sources and all triangles in the bus mesh, but only counted the triangles within the effective range of the UV disinfection (estimated at 9.6 feet). After all the visible triangles were identified, the final coverage results (total & by group) were calculated with the formula below:

$$Coverage = \frac{S_{visible}}{S_{total}}$$

$$Coverage(G) = \frac{S(G)_{visible}}{S(G)_{total}}, G \in \{bus\ shell, windows, chairs, railings$$

In order to identify the best UVC source placement, the internal space of the bus was divided into grids and different combinations of the lamp locations were tested with respect to lamp quantities (e.g. 1, 2, 3, and 4 UVC sources). (Figure 9)

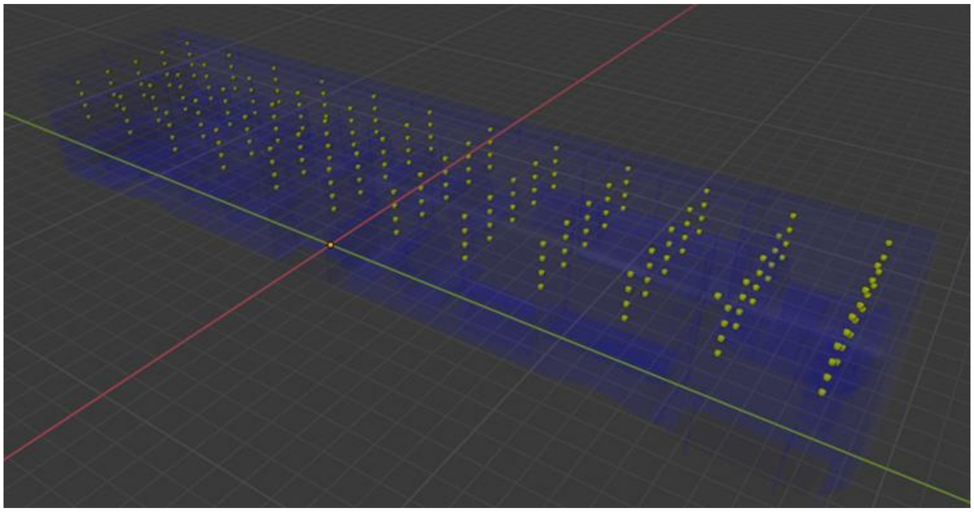

Figure 9 Candidate UVC source locations

5.2.3 Mercury UVC Source placement and coverage

5.2.3.1 NABI bus coverage analysis

Using the output of the point cloud and mesh model approaches, the optimum UVC source positions were determined. The model results were then adjusted for common sense i.e. prioritizing seats over the back wall etc. The final placements were then adjusted to account for real-world hooks etc. – which only slightly reduced coverage estimates from the original optimum models. The final UVC source placements are shown in Figure 10 and Figure 11.

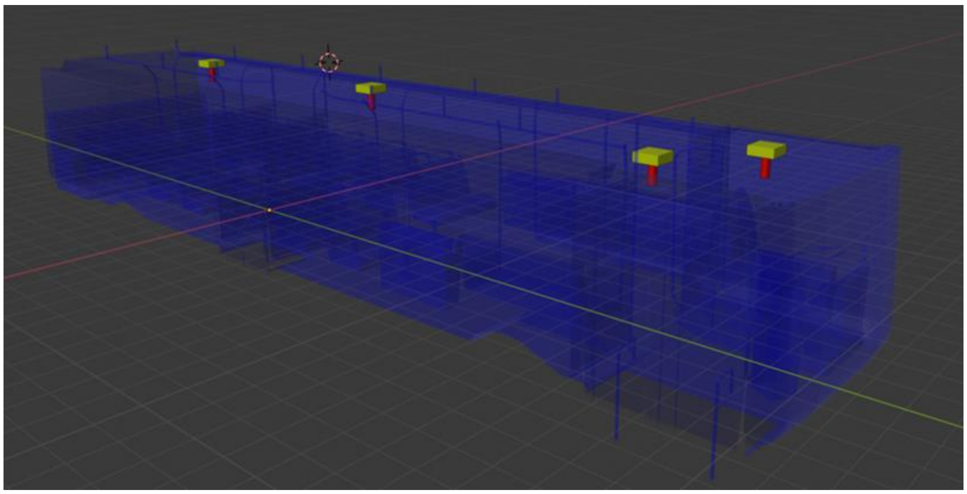

Figure 10 UVC source placement (Perspective View)

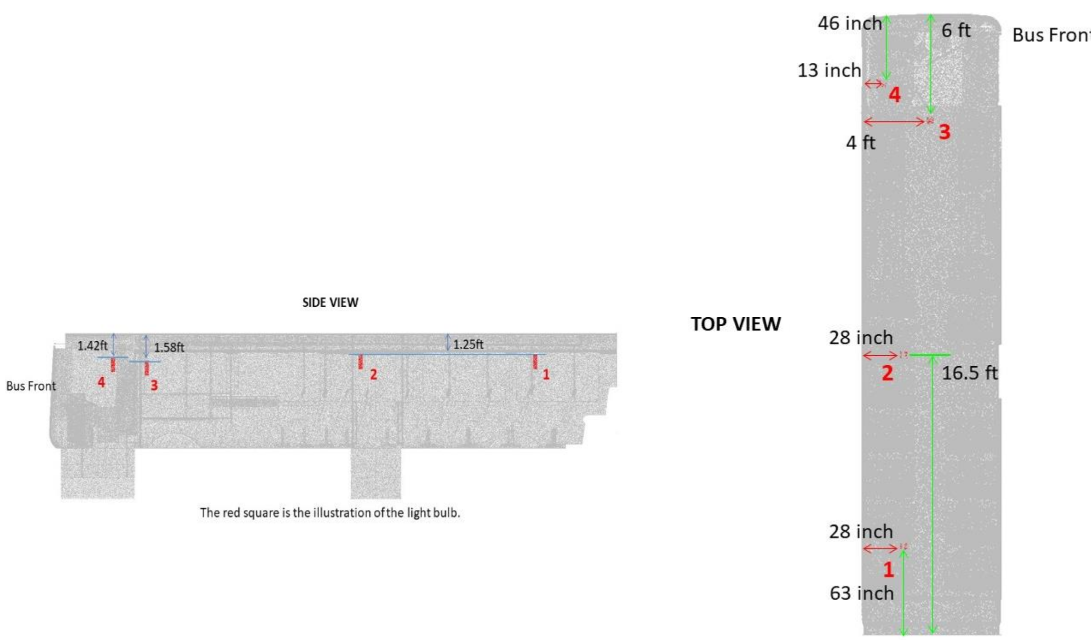

Figure 11 UVC source placement (left) profile view and (right) plan view

Although increasing the number of UVC sources can improve the coverage, more sources would also increase the logistics and cost. The model only showed a modest increase of one or two percent by adding a fifth source. Therefore, considering the minimal coverage impact, logistics, and cost - ultimately it was decided to use four UVC sources on the NABI bus.

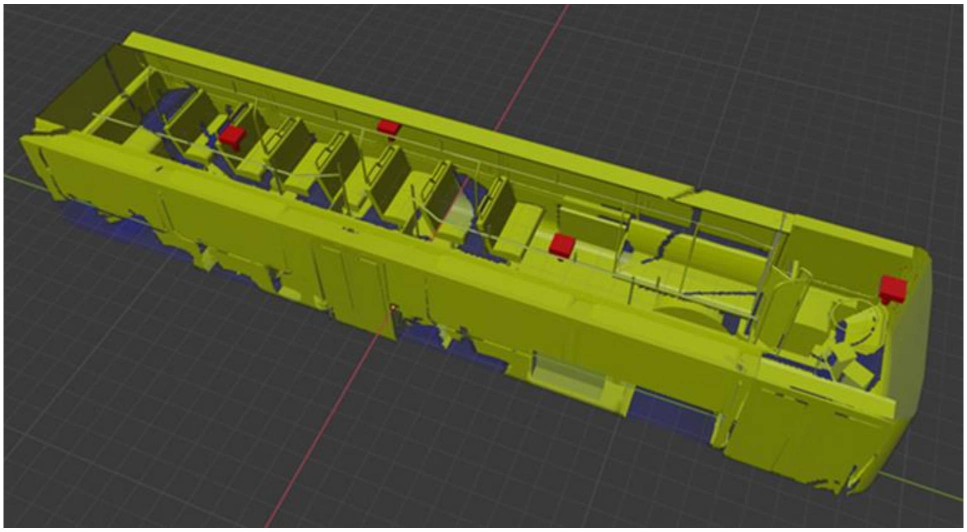

Figure 12 Overall Bus Interior Coverage

Combining the aforementioned four UVC sources, the percent of areas receiving a line of sight dosage (visible points) is 65.61% as shown in Figure 12. Generally speaking, seats, windows, and the aisle surfaces were covered by the UVC light, and the main occluded/blocked areas were under the seats.

As part of the analysis, the research team grouped parts of the bus together to extract and differentiate these groups from the overall light coverage estimate. These groupings provide a more detailed understanding of the line of sight dosages. The breakdown is as follows:

- Shell - the percent of visible points is 73%. Figure 13 shows that most of the non-visible parts are occluded by the seats.
- Seats - the percentage of the visible points is 58%. The seats tended to be occluded by each other because of the shorter distance between them. We can see clearly from the Figure 14, some seats are not covered by the UV lights.
- Windows - the percent of visible points is 93%. Windows Figure 15 (inside the bus) received highest UV coverage of any group.
- Railings - the percentage of visible points is 48%. The coverage for railing is only about 48% due to the proximity of the railing to the ceiling and the fact that sources were hung (below) from the railings as shown in Figure 16 and Figure 17. With UV disinfection - there are areas that get direct line of sight treatment but then there are others that

rely completely on “indirect” light. As shown in Figure 17, by zooming in on the top handrail it’s clear (yellow is direct light) that a significant portion of the handrail would completely rely on glancing or reflected light.

The percentage of coverage calculated by the LiDAR model are not “absolutes” as they do not take into account the reflected and indirect coverage. The research team acknowledges that reflected and indirect light would likely increase the UVC coverage.

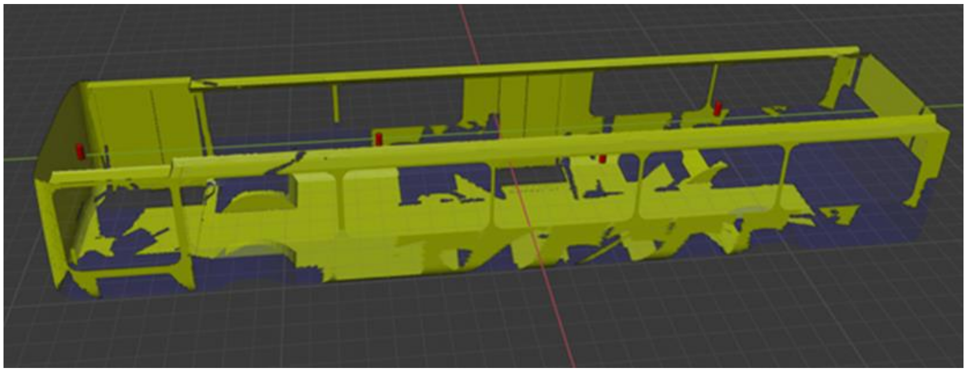

Figure 13 Bus Shell Coverage

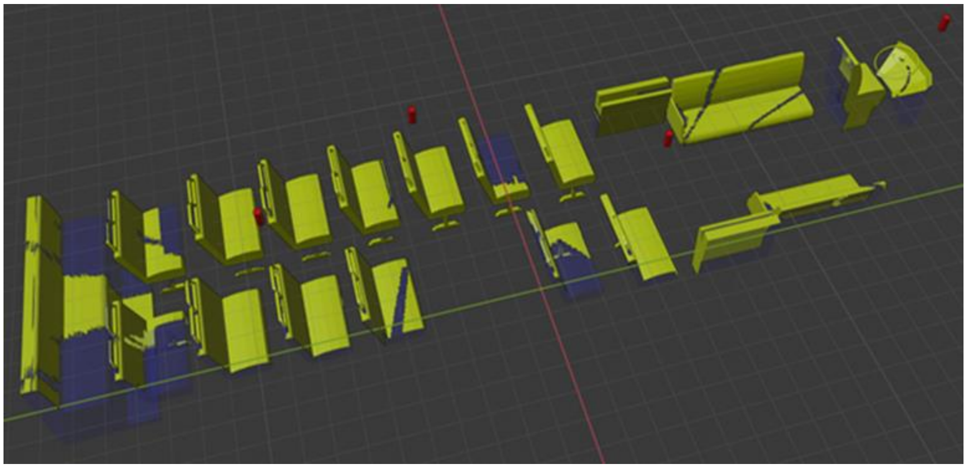

Figure 14 Seat Coverage Analysis

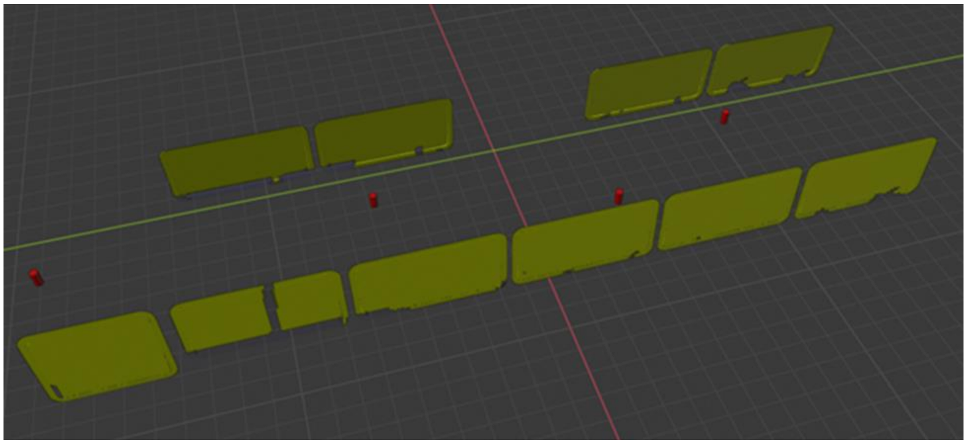

Figure 15 Window Coverage Analysis

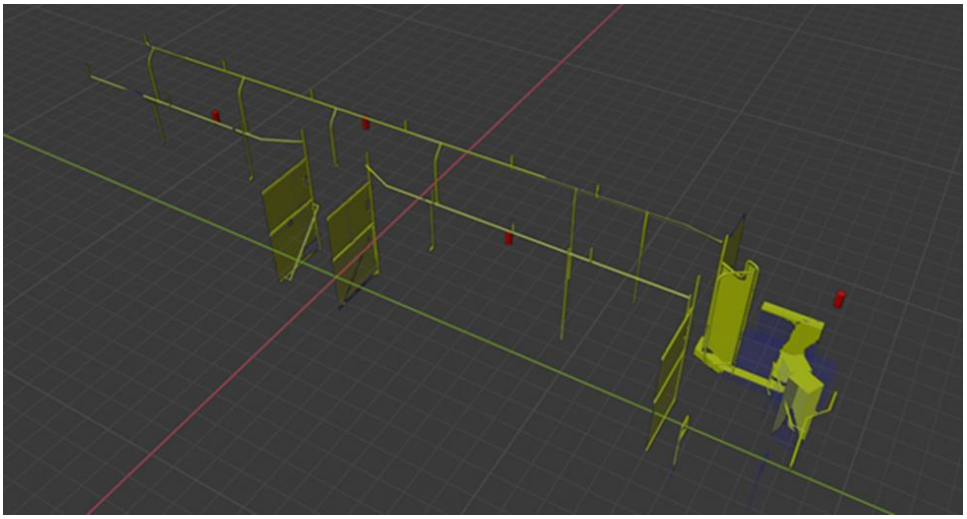

Figure 16 Railing Coverage Analysis

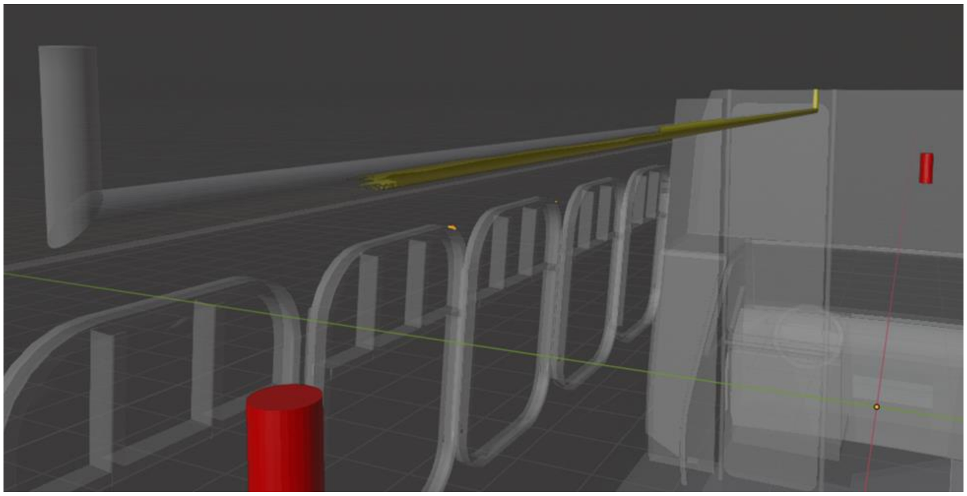

Figure 17 Close-up of railings showing how top portion of railing isn't receiving light

5.2.3.2 *Mini-bus (paratransit) bus coverage analysis*

The line of sight analysis yielded 50%, 65%, and 70.88% total maximum UVC coverage for deploying 1, 2, and 3 UVC sources respectively. Since the internal space for a paratransit bus is smaller than an NABI bus, three UVC sources would provide a coverage to disinfect the bus. The position for the three UVC sources to achieve maximum coverage is illustrated in Figure 18 and Figure 19:

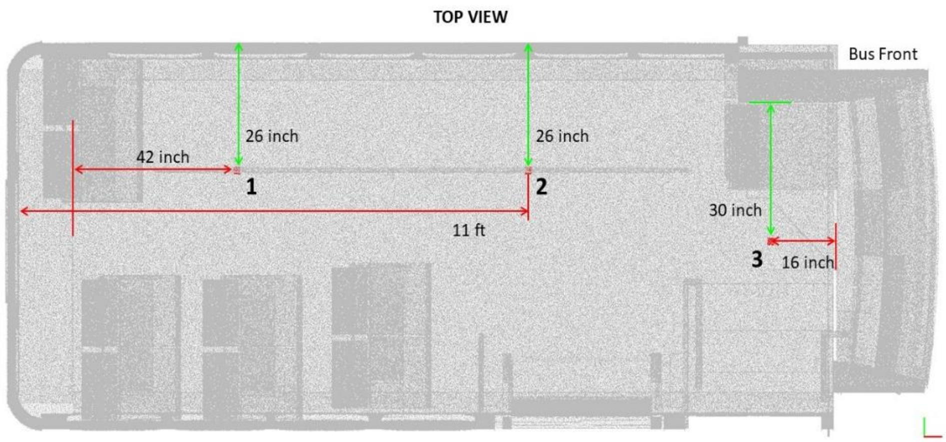

Figure 18 Plan view of UVC source locations (plan view)

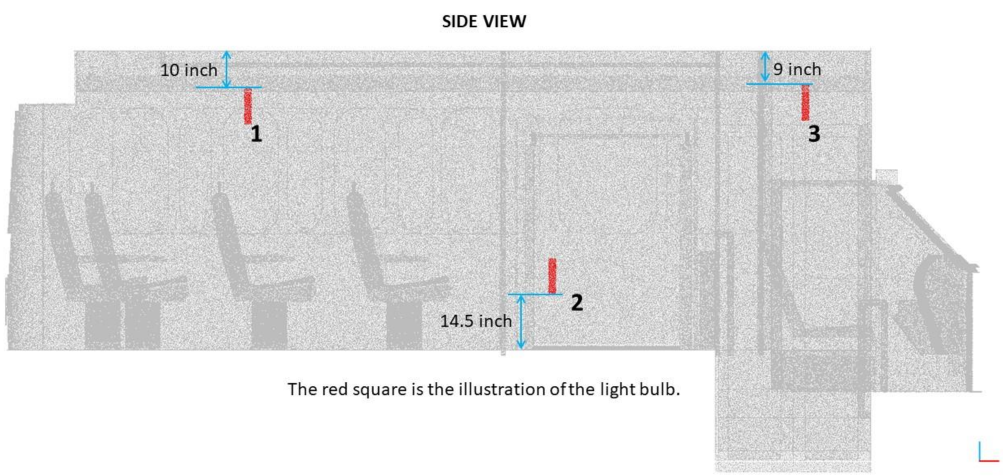

Figure 19 Profile view of UVC source locations (profile view)

As discussed in the Spectrometer section, the research team acknowledges that indirect coverage will likely increase these estimates based on field observations. The total coverage for three UVC sources is 70.88% and the visual representation is illustrated in Figure 20 and Figure 21:

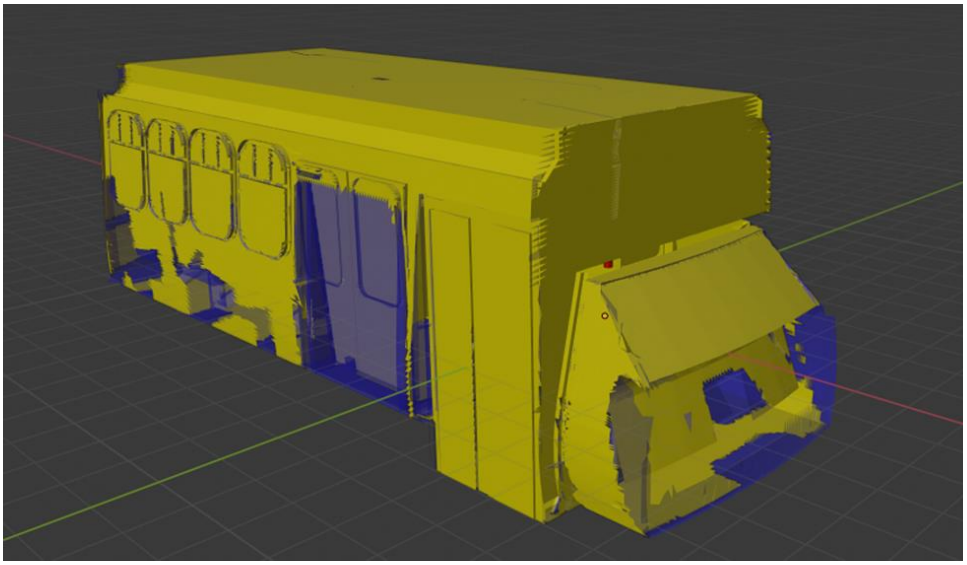

Figure 20 Mini-bus interior coverage (see through view)

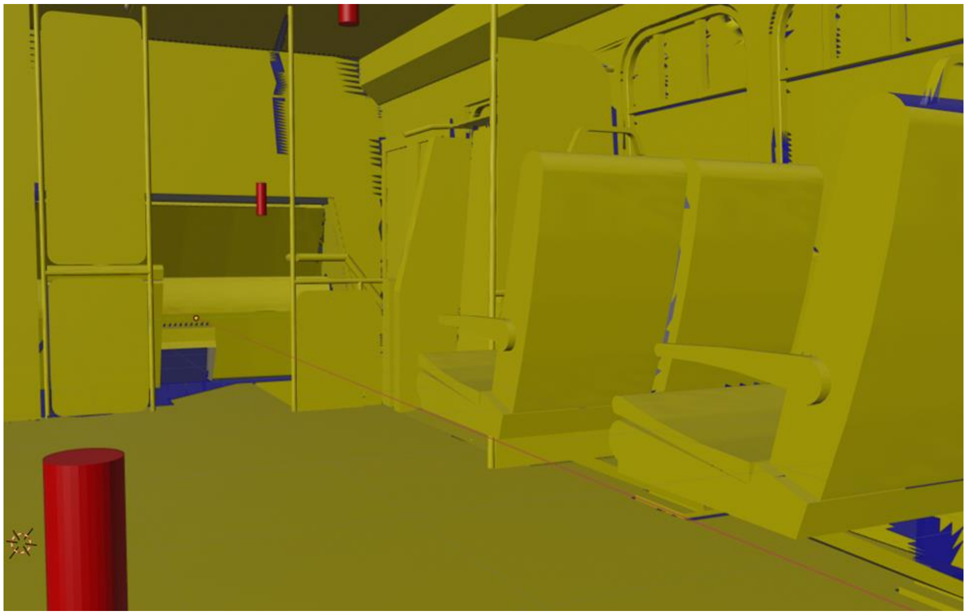

Figure 21 Overall mini-bus interior coverage

As discussed in the Spectrometer section, the research team acknowledges that indirect coverage will likely increase these estimates based on field observations. Coverage by group:

a) Shell - Figure 22 Coverage for the bus shell: 81%
b) Seats - Figure 23 and Figure 24 Coverage for the seats: 45%
c) Windows - Figure 25 Coverage for windows: 82%
d) Railings - Figure 26 Coverage for railings: 62%

The percentage of coverage calculated by the LiDAR model are not “absolutes” as they do not take into account the reflected and indirect coverage. Visual review of the model results shows an overall favorable coverage where nearly all the tops and fronts of the seats receive coverage, but the backs of some seats and the underneath area do not receive coverage. However, any gap in coverage of a critical or high touch surface like a seat or railing raises concerns. These results indicate there is ambiguity in the overall results and that field testing using a spectrometer will be required to measure actual dosages received especially in shadowed areas.

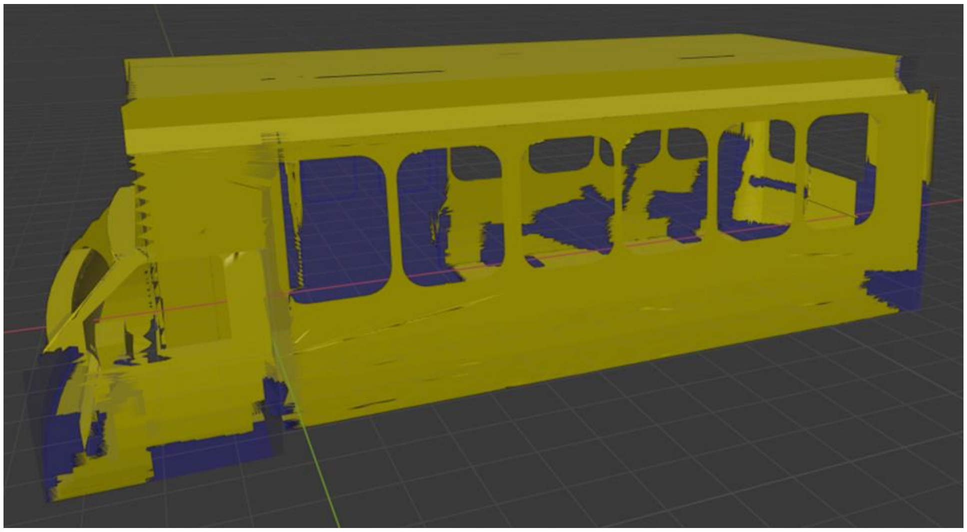

Figure 22 Coverage of bus shell analysis

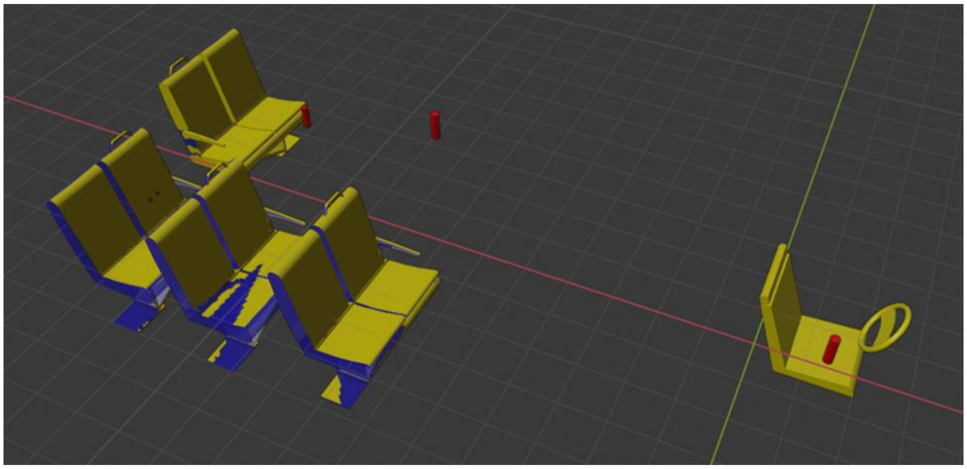

Figure 23 Front of seats coverage analysis

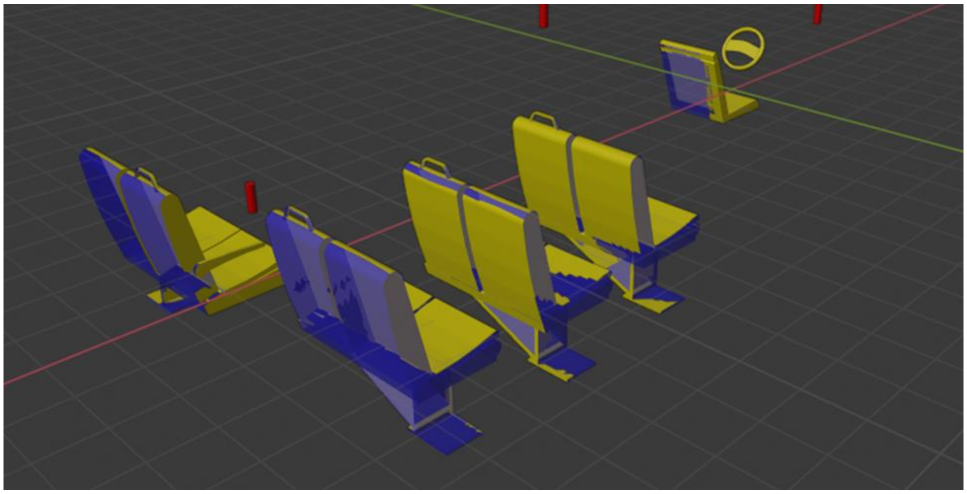

Figure 24 Back of seats coverage analysis

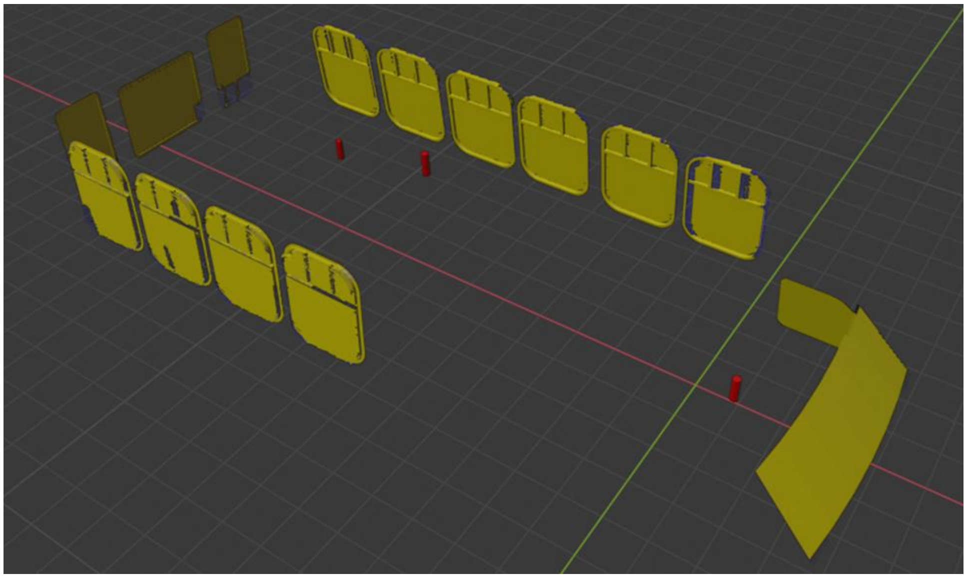

Figure 25 Window coverage analysis

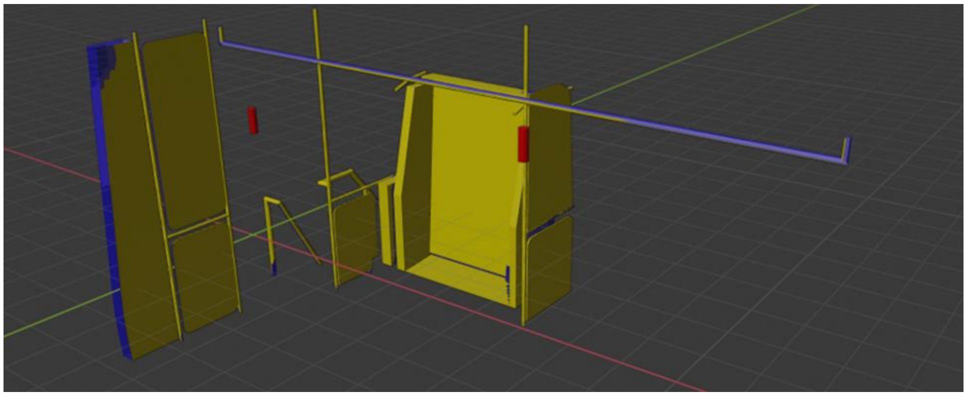

Figure 26 Railing coverage analysis

5.2.4 Pulsed Xenon Source Analysis

This report is UVC source agnostic. However, since the research team was only able to identify two potential pulsed Xenon UVC vendors, and one of those products was not applicable for buses due to size, specific information regarding operation for the Puro M1-2 unit is included here as reference.

As shown in Figure 27 and Figure 28, the M1-2 does not follow standard bulb irradiance but instead has two heads with a directional beam angle. The two heads result in a beam angle coverage of 340 degrees resulting in a small zone that will not receive direct line of sight irradiance.

Product Specifications

Illumination

Light Source	Proprietary Pulsed Xenon Lamp
Pulse Interval	1 UV Flash every 6 seconds
Wavelengths	UV-C (200-280nm) Germicidal UV-B (280-320nm) Germicidal UV-A (320-400nm) Antibacterial
Range	10' x 10' coverage for M1-1 20' x 10' coverage for M1-2
UV Bulb Rated Life	> 2 Million UV Flashes

Electrical System

Input Voltage	110V AC
Max Current	3.5 Amps for M1-1 7 Amps for M1-2
Average Power	60W during operation of M1-1 120W during operation of M1-2
Power Connection	3-prong grounded plug

Physical

Weight	11.4 lbs for M1-1 14 lbs for M1-2
Housing/Finish	Brushed Aluminum
Optics	Single patented UV Light Engine with transmissive UV lens and Xenon UV lamp
Beam Angle	170º for M1-1 340º for M1-2

Figure 27 M1-2 product specification[20i]

[i] Photo Credit: Image by Puro via https://purolighting.com/wp-content/uploads/2020/07/Puro-Sentry-M1-Spec-Sheet.pdf

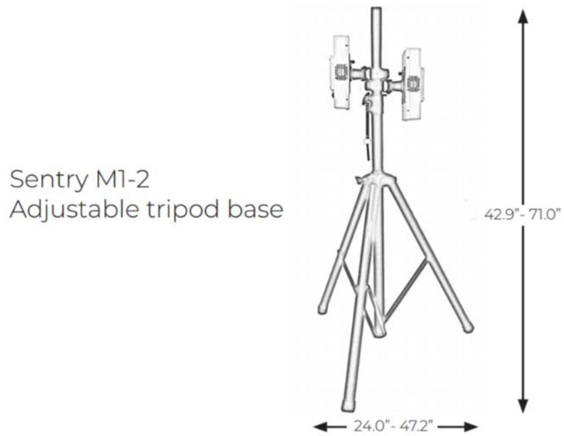

Figure 28 M1-2 product dimensions showing two head configuration[20, ii]

As per the APTA white paper on disinfection and cleaning and the NY MTA, a sample placement for a railcar is shown in Figure 29. The area where the 340-degree coverage is missed, is covered by offsetting the adjacent unit to ensure full coverage. A similar offset strategy can be used for buses.

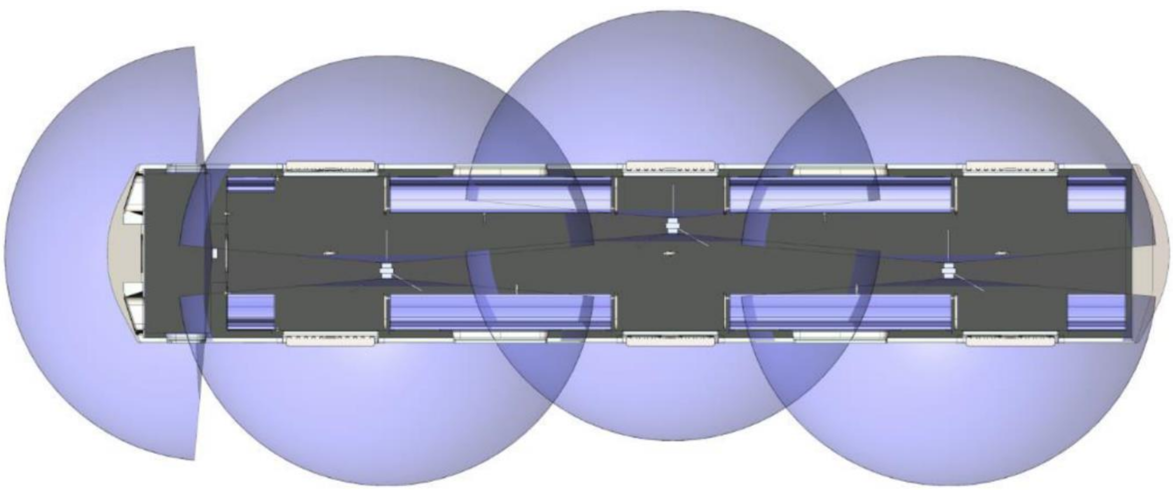

Figure 29 Sample railcar configuration from APTA white paper[60, iii]

The information presented here has been collected during phone interviews with the vendor:

- M1-2 units are recommended to be spaced 7.5 ft. on center (15 ft. between two units). Therefore, three of the double sided M1-2 units should be more than enough to cover a 40-ft NABI bus and two units should sufficiently cover one mini-bus.[17]
- Recommended that they be oriented so that the bulb on each side of the tripod is facing one side of the bus's windows to reduce the 5 degrees of "dead space" on either end of

[ii] Photo Credit: Image by Puro via https://purolighting.com/wp-content/uploads/2020/07/Puro-Sentry-M1-Spec-Sheet.pdf
[iii] Photo Credit: Image by APTA via Cleaning and Disinfecting Transit Vehicles and Facilities During a Contagious Virus Pandemic

the 170-degree range of the units. Whether the units are facing the windows, or are in a front/back facing configuration should not matter since any areas not receiving direct line of sight from the missing 5 degrees on either side will be covered through reflection of the UV light.[17]

- In order to better cover the driver seat area and avoid the polycarbonate glass panel sitting behind the driver seat from filtering out too much UV light, it is recommended that the tripod be placed in a position such that one of the two lamps mounted on the tripod can be angled in a way that would direct light onto the driver area while the other lamp be angled such that it would cover the passenger area behind the driver.[17]

Based on the reliance on indirect and reflected light, the model placement optimization for direct line of sight coverage was not used to determine locations. Instead, placement was based on previously identified locations from the Mercury units as well as referencing the vendor recommendations. These locations were used to generate direct line of sight coverage analysis, which is provided in the next section for reference only. The research team acknowledges that indirect coverage likely increases these estimates, and will be discussed in the Spectrometer section.

5.2.4.1 Pulsed Xenon NABI bus coverage analysis

The pulsed Xenon source line of sight analysis yielded 53.72% total UVC coverage for the 40-ft NABI bus. As previously discussed, these locations were not modeled for optimal placement due to the reliance on reflected light which the model wasn't able to simulate. Therefore, placement was based heavily on the vendor recommendations. The positions for the pulsed Xenon UVC sources are shown in Figure 30 and Figure 31.

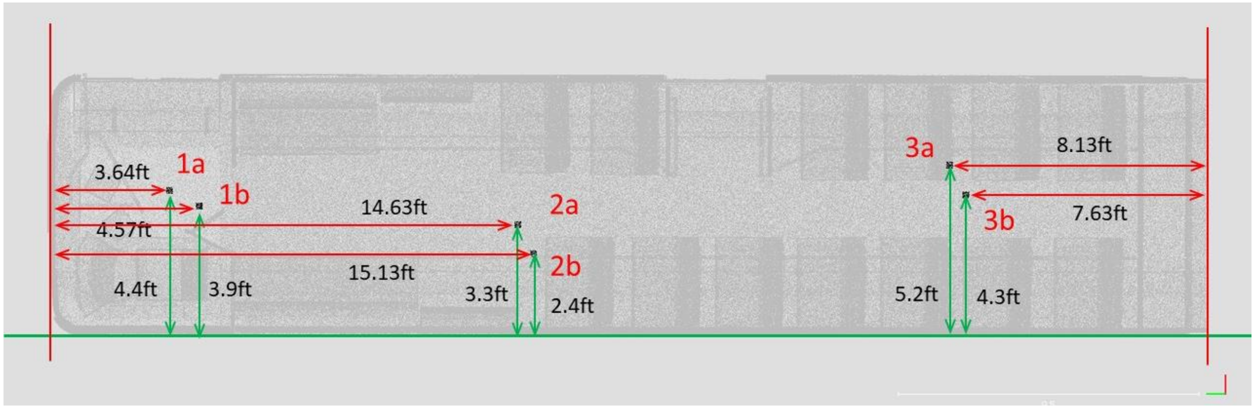

Figure 30 Plan view of UVC source locations (plan view)

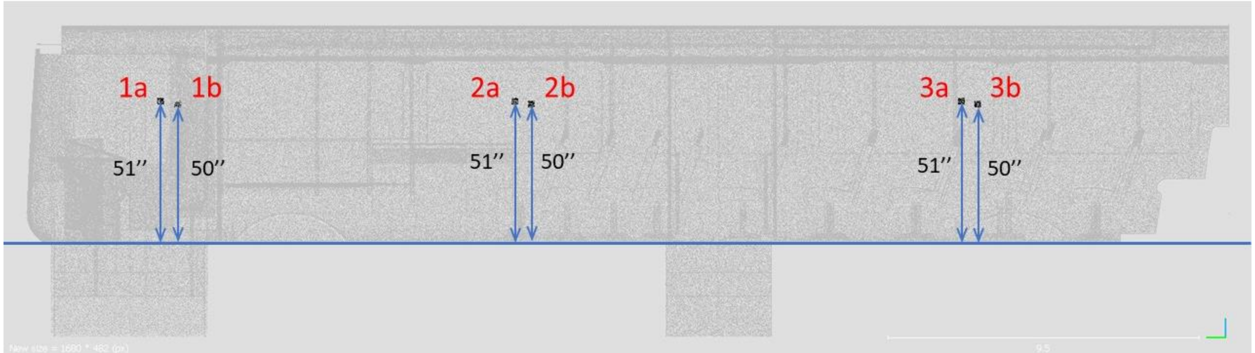

Figure 31 Profile view of UVC source locations (profile view)

The individual coverage of each source is illustrated in Figure 32, Figure 33, and Figure 34 with the final combined coverage shown in Figure 35.

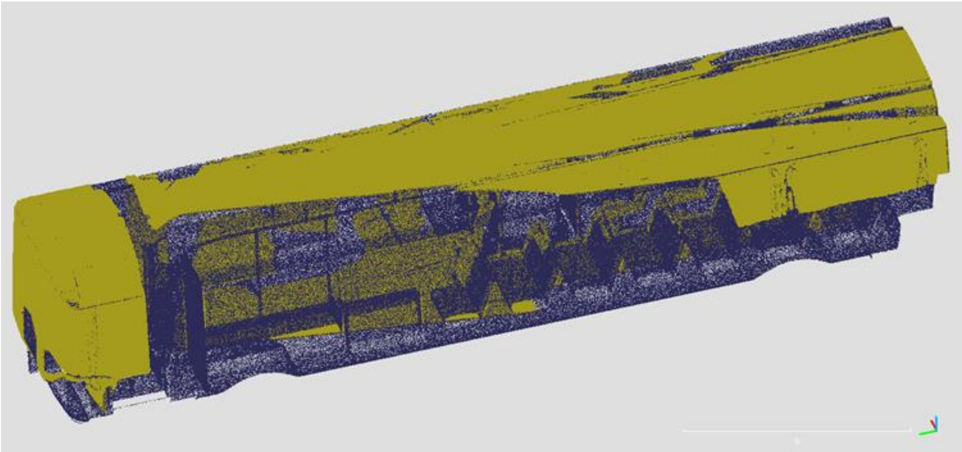

Figure 32 Light 1 (1a+1b), coverage: 29.90%

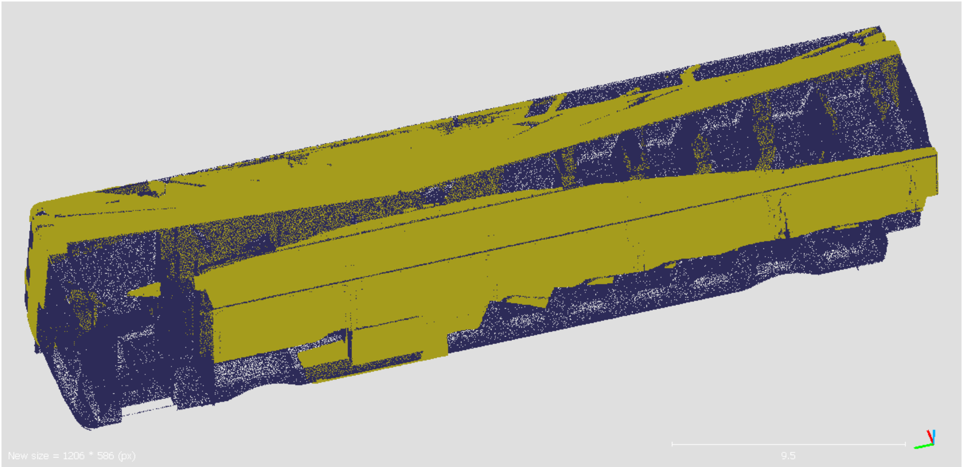

Figure 33 Light 2 (2a+2b), coverage: 27.21%

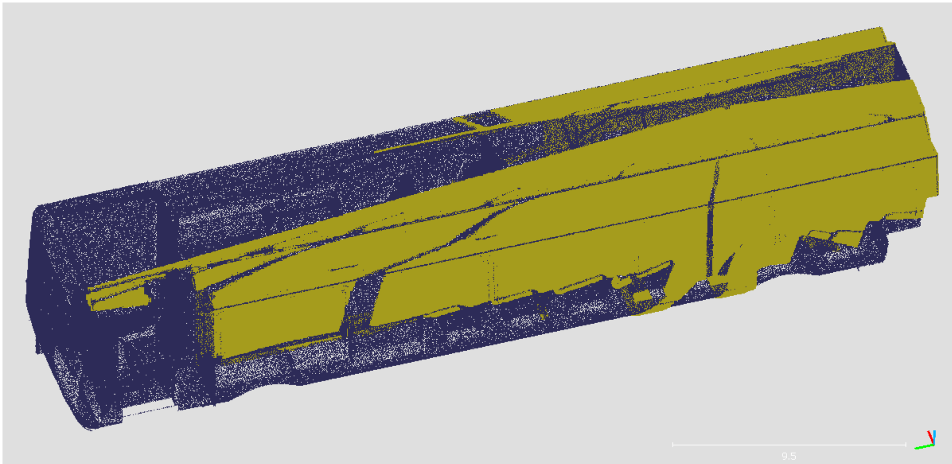

Figure 34 Light 3 (3a+3b), coverage: 24.09%

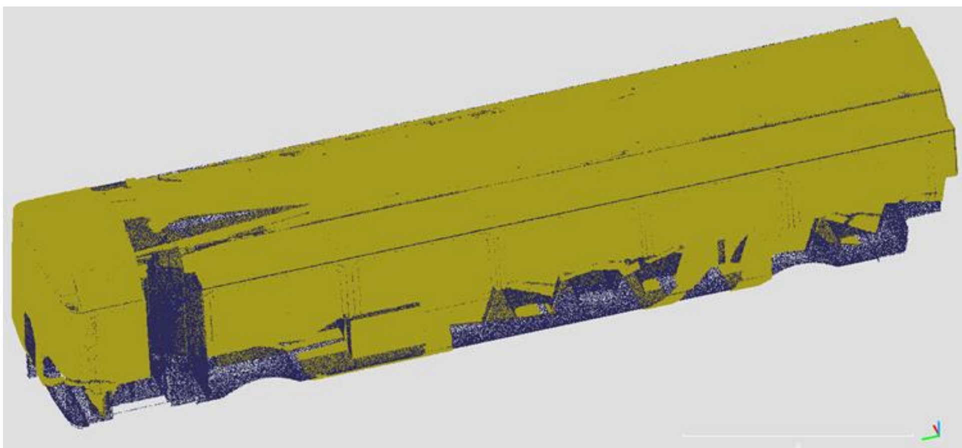

Figure 35 Combine light 1, 2, 3, coverage: 53.72%

As discussed in the Spectrometer section, the research team acknowledges that indirect coverage will likely increase these estimates based on field observations. Coverage by group:

a) Shell - Figure 36 Bus shell, coverage 64.29%
b) Seats - Figure 37 Seats, coverage, coverage 41.24%
c) Other -Figure 38 Other parts, coverage 27.74%

The percentage of coverage calculated by the LiDAR model are not “absolutes” as they do not take into account the reflected and indirect coverage.

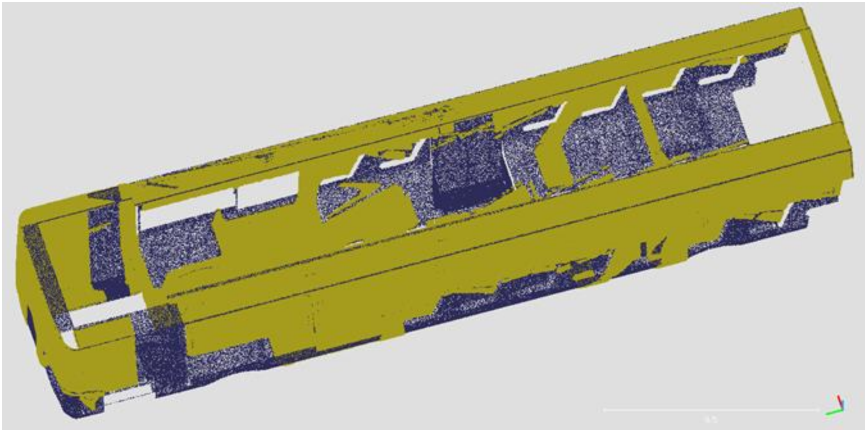

Figure 36 Coverage of bus shell analysis

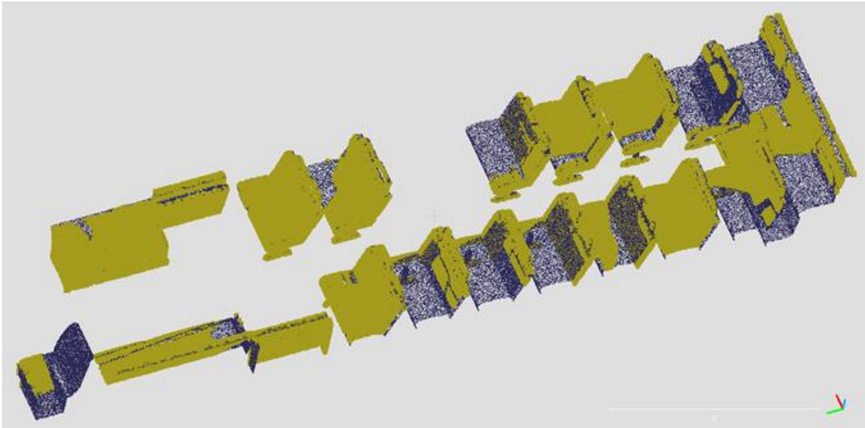

Figure 37 Seat coverage analysis

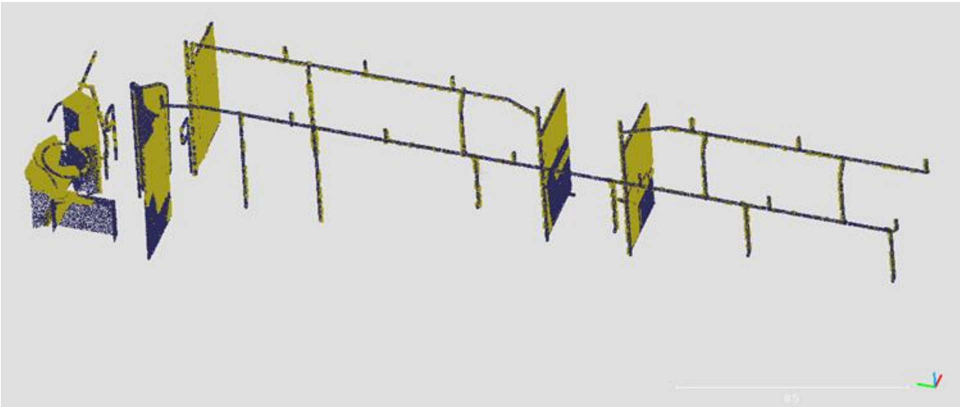

Figure 38 Railing coverage analysis

5.2.4.2 Pulsed Xenon Mini-bus (paratransit) bus coverage analysis

The pulsed Xenon source line of sight analysis yielded 59.11% total UVC coverage for the mini-bus, using a two stand deployment placement. As previously discussed, these locations were not modeled for optimal placement due to the reliance on reflected light which the model wasn't able to simulate. Therefore, placement was based on the previously identified locations from the Mercury units as well as the vendor recommendations. The positions for the pulsed Xenon UVC sources are shown in Figure 39 and Figure 40:

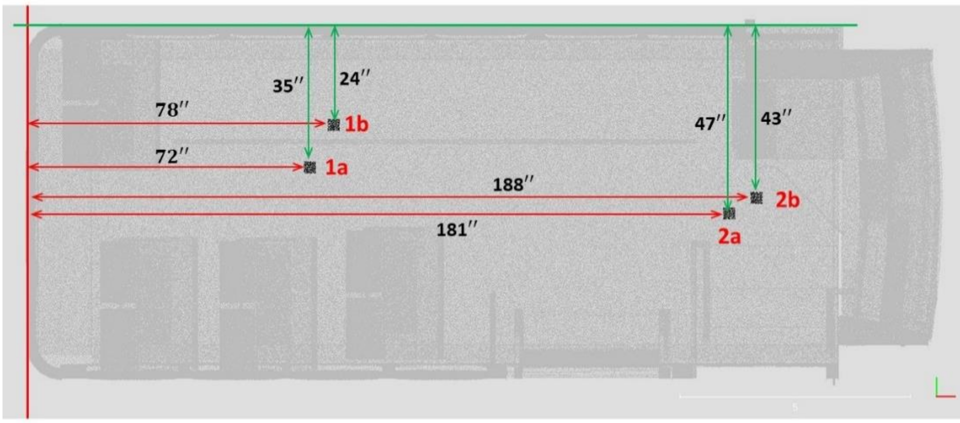

Figure 39 Plan view of UVC source locations (plan view)

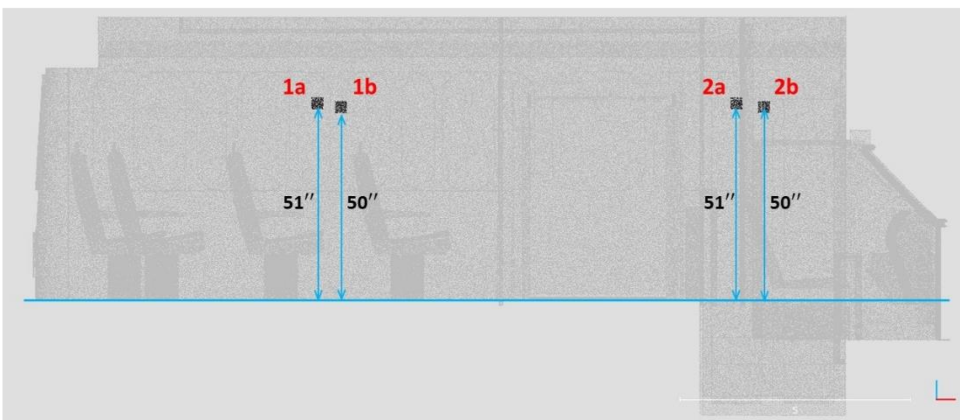

Figure 40 Profile view of UVC source locations (profile view)

As discussed in the Spectrometer section, the research team acknowledges that indirect coverage will likely increase these estimates based on field observations. The individual source coverage is shown in Figure 41. The total coverage for UVC sources is 59.11% as shown in Figure 42.

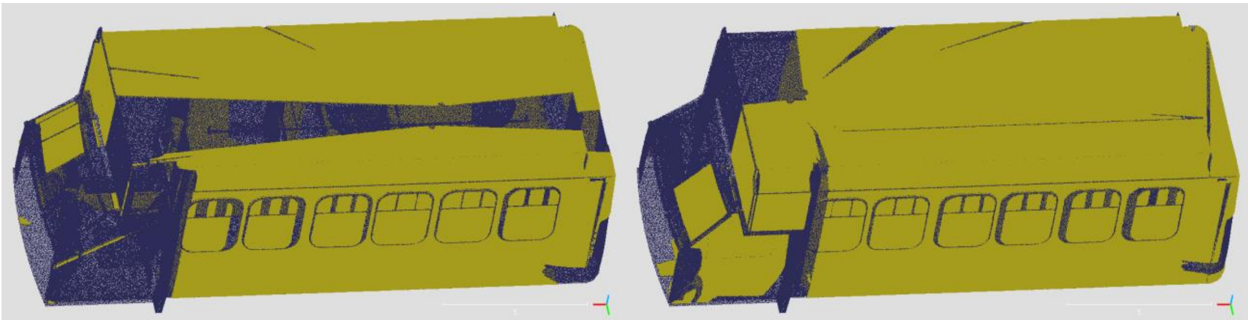

Figure 41 Left image of source one model showing 40.81% coverage; and Right image of source two model showing 44.89% coverage

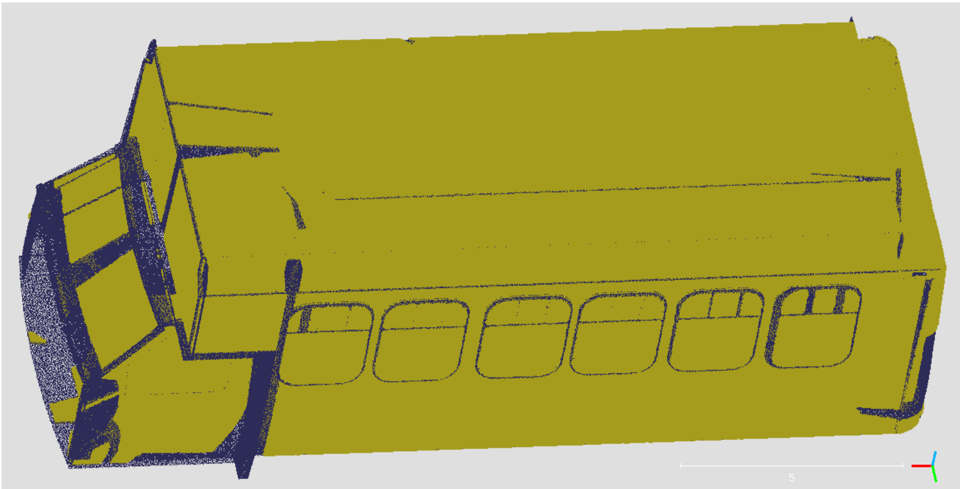

Figure 42 Overall Source one and two combined result 59.11% coverage

As discussed in the Spectrometer section, the research team acknowledges that indirect coverage will likely increase these estimates based on field observations. Coverage by group:

a) Shell - Bus shell, coverage 67.34%
b) Seats - Figure 43 Seats, coverage, coverage 36.50%
c) Other - Other parts, coverage 37.90%

The percentage of coverage calculated by the LiDAR model are not "absolutes" as they do not take into account the reflected and indirect coverage. However, these results appear to be less favorable than those observed from the Mercury UVC source model.

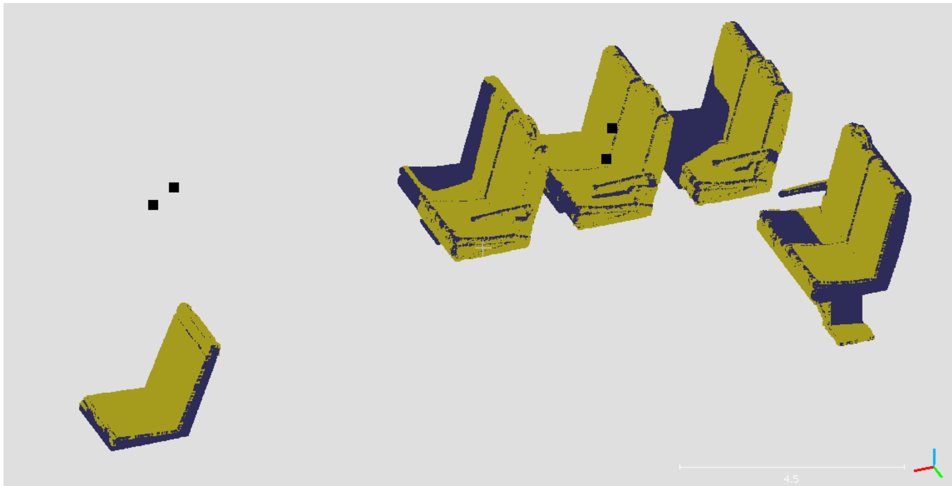

Figure 43 Seat coverage analysis

5.2.5 Spectrometry Measurements

According to the LiDAR model seats, windows, and the aisle surfaces were largely covered by the UVC light, but the main occluded/blocked areas were under or behind the seats. However, blocked areas also included critical high-touch areas such as armrests, backs of seatbelts, tops of handrails near the ceiling, and the back of some seats. The percentage of coverage calculated by the LiDAR model are not "absolutes" as they do not take into account the reflected and indirect coverage. The research team acknowledges that reflected and indirect light would likely increase the UVC coverage. In addition to field verification of irradiance dosage, the spectrometer was also used to evaluate shadowed areas. Therefore, the research team perform field spectrometer to measure the intensity of exposure throughout the bus based on the LiDAR model results and to evaluate if shadowed areas receive a kill dosage.

Data collection protocols: Five spectra were collected at each sampling location with five individual scans averaged to collect one spectra. The five spectra were averaged, and standard deviations calculated periodically to quantify variability in the light measurement. Where possible the front face of the fiber optic used to bring light into the spectrometer, was pointed in such a way as to appear flat to the surface being measured. This was not always possible as location such as the top of a handrail, which was curved. In these instances, the fiber was moved as close as possible to the surface being measured so as to create a parallel surface orientation.

Vehicle Measurement Approach: In each vehicle the light positions were selected before sampling locations. Once the lamps were installed on the bus they were illuminated and then light sampling locations selected as describe below.

Location selection: Locations were chosen specifically because they were either in projected high touch, high contact, or potential low/no light line of sight areas or even because possible light shielding effects and to be tested. We also selected sights thought to be potential sources of light leakage, different window glass types and seals. Low light/no light locations included under seats and behind seatbelts or in pouches present to contain fastening devices.

Measurement device: An Ocean Insights Maya 2000 Pro Solid-State Spectrometer was used to quantify the delivered dose. Maya 2000 Pro is an extra-sensitive spectrometer for absorbance, transmission and low light measurements including fluorescence and Raman. Flexible – connect accessories to the Maya2000 Pro and take advantage of triggering capabilities for more complex applications. Sensitivity was driven by a high performance back-thinned 2D CCD detector, capable of measuring low light levels down to hundredths of uW/cm2 even at integration times as short as 25 mS.

It was originally calibrated for both wavelength and intensity by the manufacturer against a NIST traceable source. It was fitted with a cosine corrector to account for the flat fiber optic input, in a device looking for input from a lens. The continuous wave source was measured in a controlled laboratory situation as well as on the busses. Intensity measured at fixed distances confirmed that the measurements could be quantified as a function of distance once an adequate integration time was determined for the intensity for the UV source. The sensitivity of the spectrometer was significant enough to measure light at levels approaching < 0.01 uW. Maximum measurable intensity was determined to be 1mW even with very short integration times. All intensities were corrected for sampling time so values are reported as uW/(sec-cm2).

Laboratory calibration: The research team tested the device in house to verify the calibration performed by the manufacturer. Specifically the wavelength was verified against multiple Mercury vapor light sources, all producing the same emission profiles.

5.2.5.1 Field measurement protocol

The research team developed a rapid and reproducible protocol for field measurements of UVC light exposure at a targeted wavelength of 200-300 nm. Previously selected locations were marked using high contrast laboratory tape and labeled using an alpha-numeric identification scheme. Once confirmed, locations were pre-recorded in a field notebook and confirmation pictures were taken using a digital camera. Two team members were dispatched for measurement acquisition, one individual operating the Maya Pro 2000 Spectrometer inside the vehicle, and a second individual outside the vehicle operating the OceanView software in Absolute Irradiance mode on a laptop computer. The computer was connected to the spectrometer using an 18’ cord, which enabled the team member to move freely inside the vehicle and minimize UVC exposure time. To ensure that data acquisition accurately corresponded to the correct sample location, the two team members communicated via hands-free headset. The team member inside the bus would position the spectrometer in the appropriate location and instruct the team member outside of the bus to record five (5) replicate acquisitions. Once completed, the data files were named to correspond with the location, and the team member was instructed to proceed to the next location. This protocol allowed for rapid data collection, a larger sample size, and additional replicate measurements. Confirmation tests were conducted by repeating measurements of both high and low UVC intensity regions.

5.2.5.2 Data obtained continuous wave (CW)

Spectrometry measurements were obtained using an Ocean Insight Maya Pro 2000 High-Sensitivity Spectrometer with a continuous wavelength range of 200.034 – 313.71 nm. The acquisition parameters are as follows: 0.025 second integration time, 2068 pixels per spectrum, and five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location.

Electric dark correction (e.g. background intensities in the absence of light) and non-linearity correction were applied to wavelength intensities across the spectrum. The spectrum peak intensity was observed at 253.3 nm. As discussed earlier in this report, based on previously published literature a peak intensity of 25 µW/cm2 was determined as a reasonable and conservative threshold for disinfection at the targeted wavelength of 253 nm for a continuous exposure duration of 7 minutes.

5.2.5.3 Mini-bus Vehicle

Sample number: 22 measurement locations

Locations: Sample locations were selected to assess UVC intensity in the following scenarios: high touch regions, direct line of sight to UVC source, indirect line of sight to UVC source, potential reflected light areas, shaded areas based on the LiDAR model, and areas with protective shields (e.g. polycarbonate partitions).

Figure 44 Select positions of spectrometer measurements and light source

Figure 44 shows select positions of spectrometer measurements and light source position on the mini-bus. Spectrometer measurements were collected on high touch surface such as railings, as well as shaded interior positions described below.

5.2.5.3.1 One-Mercury UVC source results

The first series of measurements were collected in 15 locations using a single UVC source hung from the overhead hand railing at the middle of the bus. Four locations received irradiance of less than 25 µW/cm^2, which has been identified as the threshold for disinfection at the targeted wavelength of 253 nm for a duration of 7 minutes i.e. disinfection/kill dosage. The locations with obscured line of sight to the light source included: (G) steering wheel, (L) seatbelt anchor behind the last row of seats, and (N) the polycarbonate partition adjacent to the wheelchair ramp, opposite the side facing the light source. All other locations received light with an intensity greater than 25 µW/cm^2 indicating that these locations received a sufficient disinfection/kill dosage.

Table 1 UVC Spectrometer measurements for one-lamp configuration

Light Source: 1 UV-C Lamp

	Replicate Data Acquisitions							
Location	**1**	**2**	**3**	**4**	**5**	**Mean**	**Stdev**	**%RSD**
A	893.53	880.41	867.25	857.86	831.83	866.18	20.98	2.42%
B	13.62	11.09	--	--	--	12.36	1.27	10.24%
C	103.14	102.70	101.70	101.27	--	102.20	0.75	0.73%
D	253.87	263.31	274.42	280.65	287.80	272.01	12.12	4.46%
E	613.31	641.28	669.12	689.32	--	653.26	28.69	4.39%
F	79.99	81.60	81.78	83.62	84.12	82.22	1.49	1.81%
G	1.97	2.00	2.06	2.04	2.18	2.05	0.07	3.52%
H	60.39	61.46	63.05	64.32	65.11	62.87	1.75	2.78%
I	51.04	55.24	55.77	57.17	58.61	55.57	2.55	4.59%
J	71.84	72.24	72.65	80.04	--	74.19	3.39	4.57%
K	71.57	72.70	74.50	75.81	77.48	74.41	2.12	2.84%
L	0.60	0.61	0.63	0.63	0.55	0.60	0.03	4.87%
M	80.64	86.00	90.08	94.49	97.36	89.71	5.96	6.64%
N	0.59	0.54	0.58	0.59	--	0.58	0.02	3.59%
Background	0.90	0.94	1.02	1.00	1.00	0.97	0.04	4.62%

Table 1 shows UVC Spectrometer measurements for one-lamp configuration reported in µW/sec-cm^2. Five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location. Mean, standard deviation (Stdev), and percent RSD are reported for each location. Erroneous acquisitions were excluded for locations B, E, J, and N.

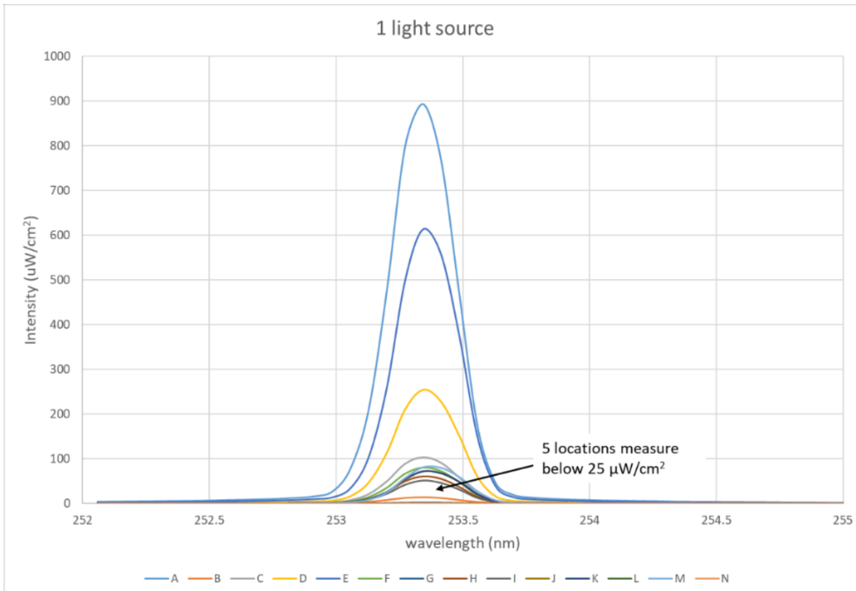

Figure 45 UVC spectra shown for all locations on the mini-bus using one-lamp

Figure 45 shows UVC spectra shown for all locations on the mini-bus using one-lamp configuration. Light intensity measurements shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents a unique sample location within the bus.

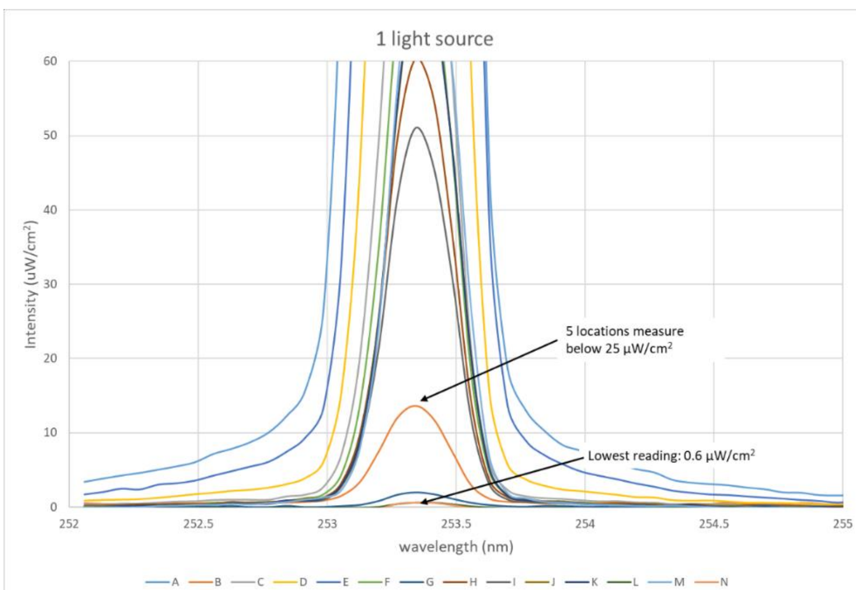

Figure 46 UVC spectra highlighting the locations with peak intensities below the 25 µW/cm^2

Figure 46 shows UVC spectra highlighting the locations with peak intensities below the 25 µW/cm^2 threshold for disinfection. The lowest detected intensity in a shaded region was 0.6 µW/cm^2, located in behind the rear-most passenger seat and behind a polycarbonate glass partition.

Figure 47 Select positions of low intensity spectrometer measurements on the mini-bus using a single UVC source configuration.

5.2.5.3.2 Two-Mercury UVC source results

For the two UVC source configurations, the lamps were placed equidistant from each other for optimal coverage corresponding to the positions determined by the LiDAR model. The location markers from the single source configuration were left in place and the exact locations were measured using two UVC sources. Intensity readings increased in all locations, with the exception of position L located on seatbelt anchor behind the last row of seats. This position did not receive sufficient kill dosage using this two source configuration.

Table 2 UVC Spectrometer measurements for two-UVC source configuration

Light Source: 2 UV-C Lamps

	Replicate Data Acquisitions							
Location	**1**	**2**	**3**	**4**	**5**	**Mean**	**Stdev**	**%RSD**
A	501.71	551.16	595.69	647.20	705.62	600.28	71.34	11.88%
B	339.57	343.91	346.37	349.11	352.40	346.27	4.38	1.27%
C	172.39	177.42	176.49	178.65	181.54	177.30	2.99	1.68%
D	835.34	843.89	845.97	856.88	863.12	849.04	9.83	1.16%
E	325.38	323.52	321.58	321.16	317.75	321.88	2.55	0.79%
F	536.12	566.96	578.98	575.01	578.67	567.15	16.11	2.84%
G	248.16	251.51	251.56	250.65	250.64	250.50	1.24	0.49%
H	192.41	245.56	255.34	255.75	259.08	241.63	25.02	10.35%
I	165.64	165.15	164.13	166.13	163.56	164.92	0.95	0.58%
J	112.99	121.69	123.45	125.21	121.99	121.07	4.23	3.49%
K	34.80	36.76	37.51	38.67	35.41	36.63	1.40	3.82%
L	1.53	1.59	1.25	1.38	1.30	1.41	0.13	9.27%
M	135.37	129.13	128.72	130.88	136.09	132.04	3.11	2.35%
N	5.43	6.39	6.35	7.21	9.79	7.03	1.49	21.17%

Table 2 shows UVC Spectrometer measurements for two-UVC source configuration reported in µW/sec-cm^2. Five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location. Mean, standard deviation (Stdev), and percent RSD are reported for each location.

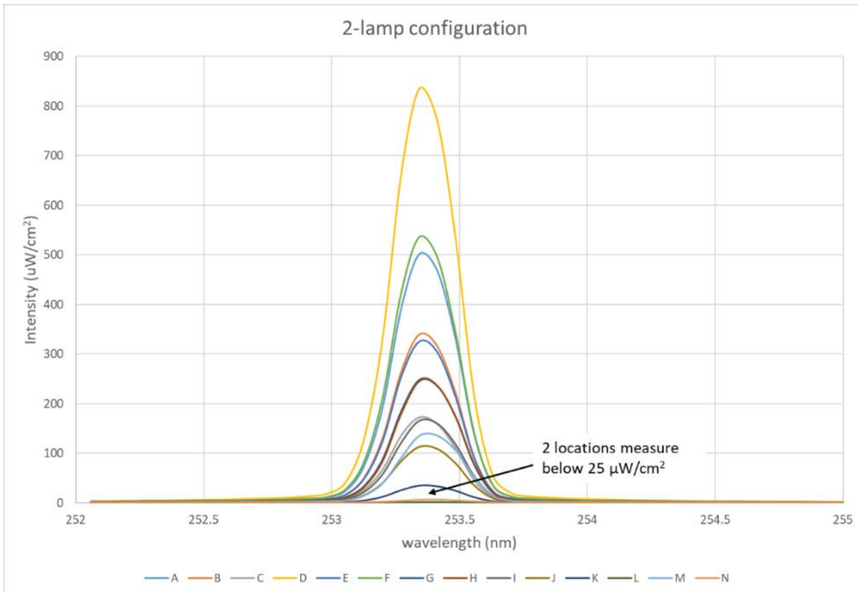

Figure 48 UVC spectra shown for all locations on the mini-bus using two-lamps

Figure 48 shows UVC spectra shown for all locations on the mini-bus using two-lamp configuration. Light intensity measurements shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents a unique sample location within the bus.

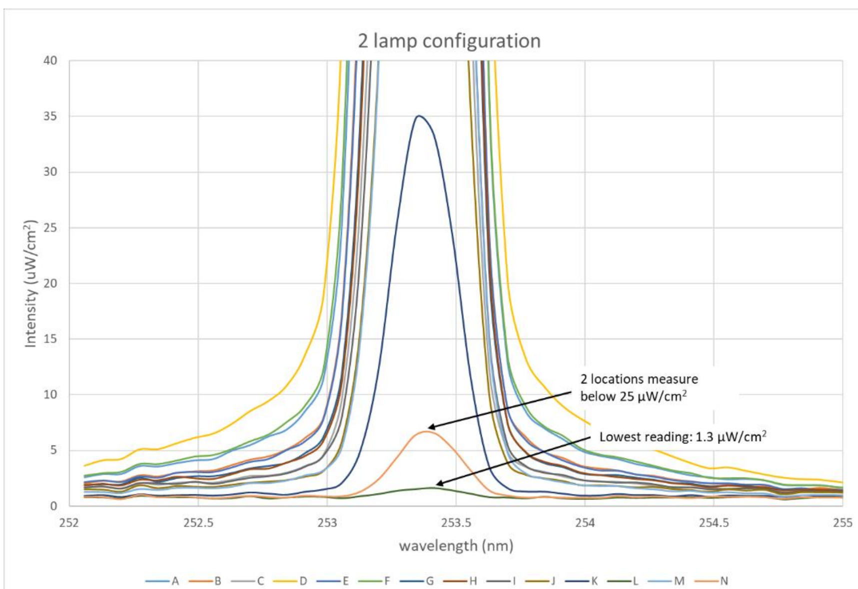

Figure 49 UVC spectra highlighting the locations with peak intensities below the 25 µW/cm2

Figure 49 shows UVC spectra show highlighting the locations with peak intensities below the 25 µW/cm^2 threshold for disinfection. The lowest detected intensity in a shaded region was 1.3 µW/cm^2, located at position L which was on the back side of the rear-most passenger seat.

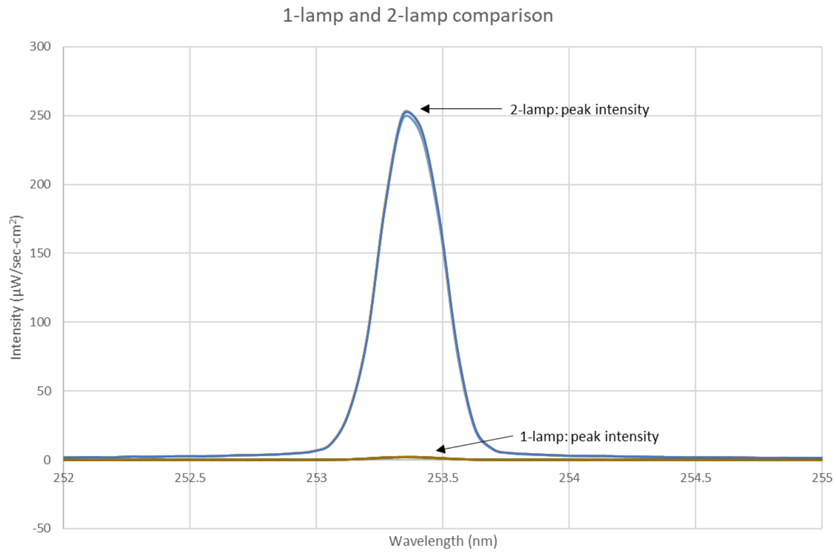

Figure 50 UVC spectra showing the intensity comparison between one and two sources for replicate measurements on the steering wheel

Figure 50 shows UVC spectra showing the intensity comparison between one and two sources for replicate measurements at position G on the mini-bus, which was on the steering wheel. Light intensity measurements are shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents five data acquisitions per location.

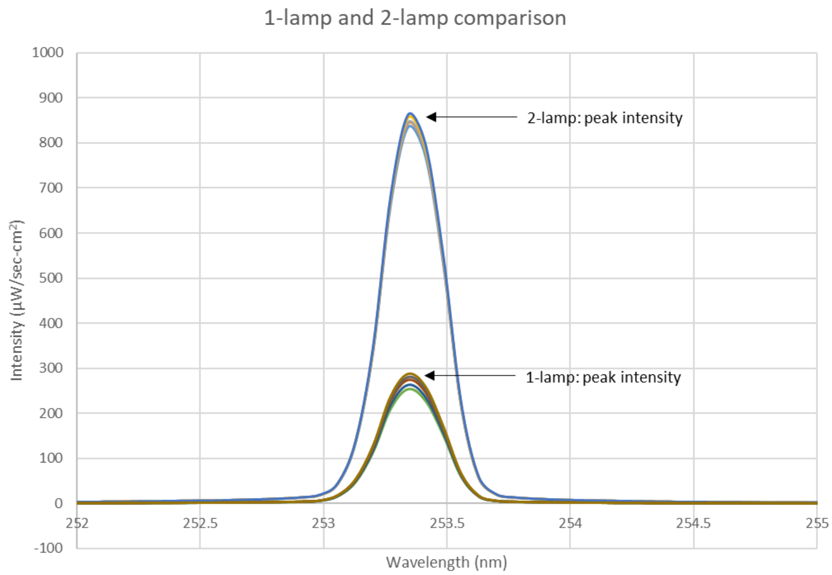

Figure 51 UVC spectra showing the intensity comparison between one and two sources for replicate measurements between two windows

Figure 51 UVC spectra showing the intensity comparison between one and two sources for replicate measurements at position D on the mini-bus, which was located between two windows along the passenger wall at mid-bus. Light intensity measurements are shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents five data acquisitions per location.

5.2.5.3.3 Three-UVC source results

For the three UVC source configuration, an additional source was placed on the floor of the bus, centrally located and equidistant to the two hanging sources. Only one location (position L described above) from the two source configuration did not received adequately detectable irradiance, and was repeated using the three configuration. Eight (8) additional positions were marked and measurements were taken using the three source configuration. These positions were presumed to be low light regions and included: back side of seatbelts, shaded area inside the arm rest, and wheelchair straps inside the wall mounted storage bag. Light in the desired wavelength range was detected in each location, but was below 25 µW/cm^2 for the back of seatbelt and the strap storage bag.

Table 3 UVC Spectrometer measurements for three-lamp configuration

Light Source: 3 UV-C Lamps

Location	Replicate Data Acquisitions 1	2	3	4	5	Mean	Stdev	%RSD
I	553.64	554.78	556.88	557.14	557.28	555.94	1.47	0.26%
L	0.91	1.15	0.99	1.15	1.09	1.06	0.09	8.91%
O	11.71	11.59	11.55	11.20	11.24	11.46	0.20	1.76%
P	93.24	91.97	92.39	91.66	92.65	92.38	0.55	0.59%
Q	80.06	79.36	80.57	80.93	80.60	80.30	0.55	0.68%
R	5.64	5.86	6.21	6.47	6.78	6.19	0.41	6.61%
S	1.89	1.88	2.02	1.96	1.93	1.94	0.05	2.63%
T	584.50	588.84	596.07	599.63	600.05	593.82	6.15	1.04%
U	98.65	95.89	96.60	96.31	95.94	96.68	1.02	1.05%
V	131.20	124.62	124.99	--	--	126.94	3.02	2.38%

Table 3 shows UVC Spectrometer measurements for three-lamp configuration reported in μW/sec-cm^2. Five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location. Mean, standard deviation (Stdev), and percent RSD are reported for each location. Erroneous acquisitions were excluded for location V.

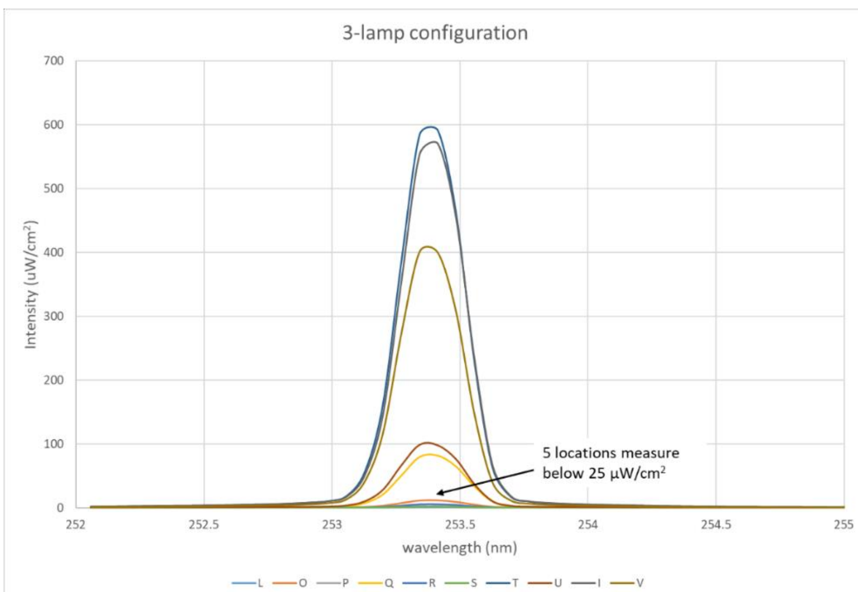

Figure 52 UVC spectra shown for all locations on the mini-bus using three-lamps

Figure 52 shows UVC spectra shown for all locations on the mini-bus using three-lamp configuration. Light intensity measurements shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents a unique sample location within the bus.

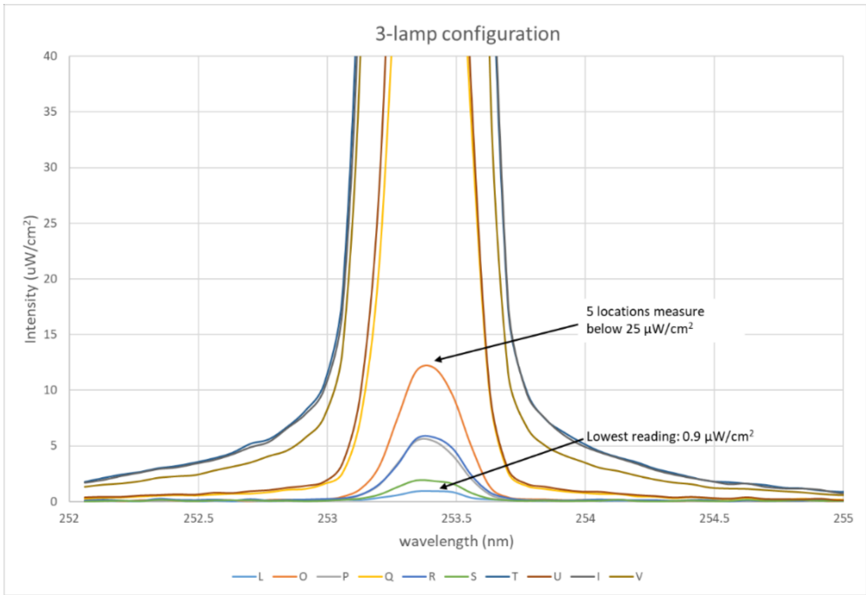

Figure 53 UVC spectra highlighting the locations with peak intensities below the 25 µW/cm^2

Figure 53 shows UVC spectra show highlighting the locations with peak intensities below the 25 µW/cm^2 threshold for disinfection. The lowest detected intensity in a shaded region was 0.9 µW/cm^2, located at position L, which was on the back side of the rear-most passenger seat.

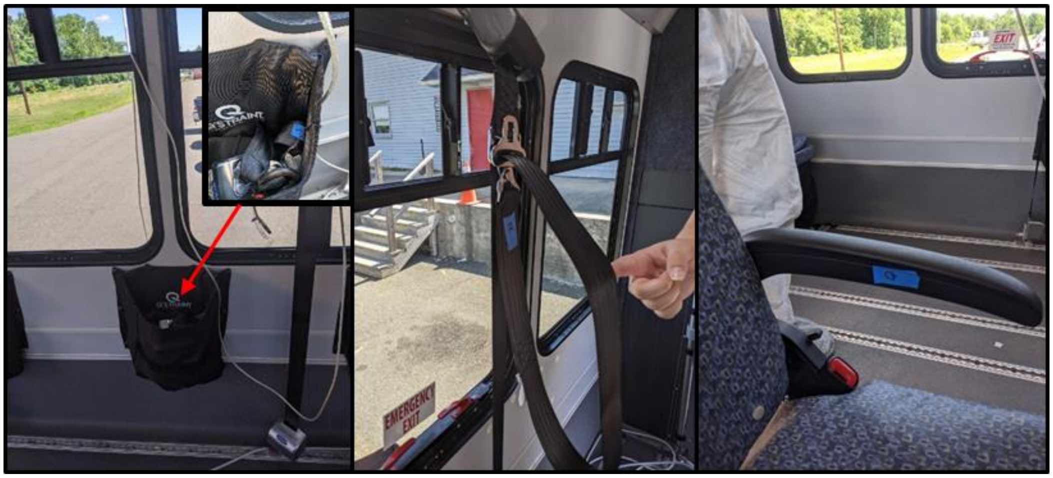

Figure 54 Select positions of spectrometer measurements on the mini-bus using a three-UVC source

Figure 54 shows select positions of spectrometer measurements on the mini-bus using a three-UVC source configuration. Images show: wheelchair straps inside the wall mounted storage bag, back side of seatbelts, and area inside the arm rest.

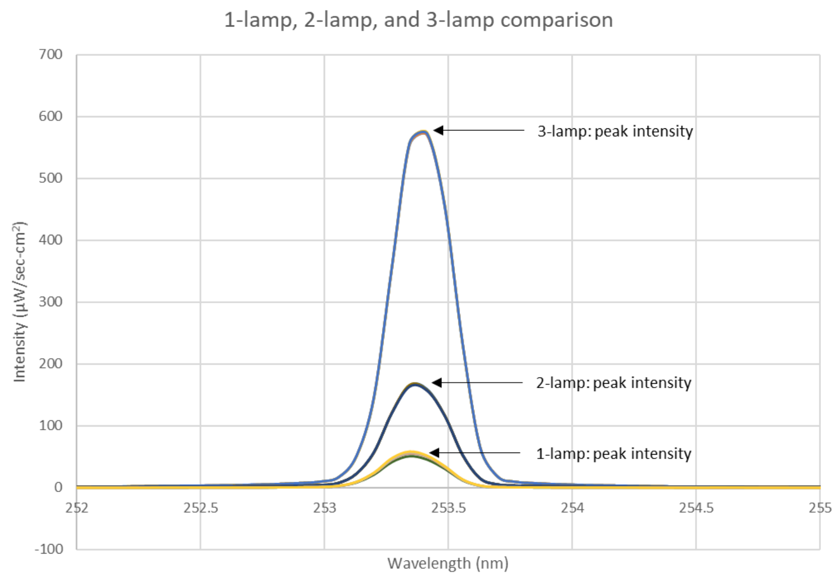

Figure 55 UVC spectra showing comparison between one, two, and three UVC sources

Figure 55 shows UVC spectra showing the intensity comparison between one, two, and three UVC source configurations for replicate measurements at position I on the mini-bus, which was located at mid-bus, on the floor, at 33 in. line of sight to the floor mounted source. Intensity measurements are shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents five data acquisitions per location.

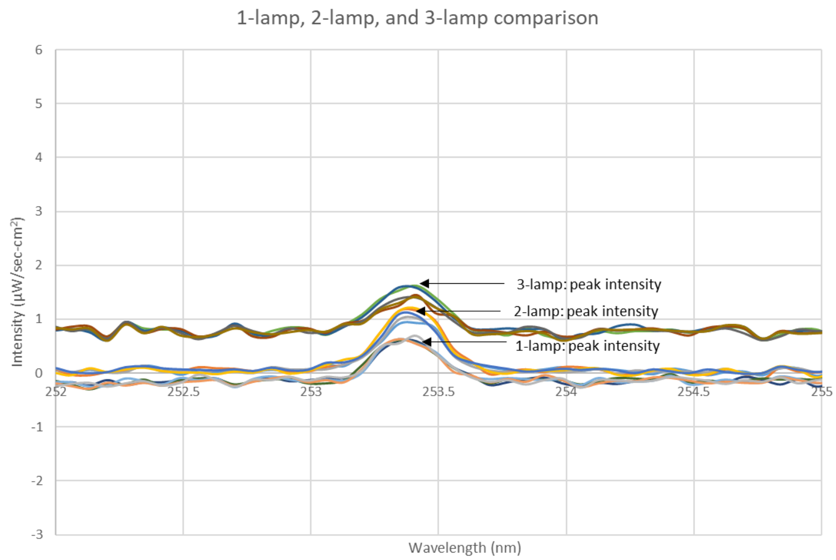

Figure 56 UVC spectra showing the intensity comparison between one, two, and three UVC sources behind rear-most passenger seat

Figure 56 shows UVC spectra showing the intensity comparison between one, two, and three UVC source configurations for replicate measurements at position L on the mini-bus, which was located behind the rear-most passenger seat on the mini-bus. Intensity measurements are shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents five data acquisitions per location.

5.2.5.3.4 Light leakage measurement

Light leakage was assessed by taking spectrometer measurements outside transparent surfaces of the vehicle. Background measurements were collected in outdoor ambient light prior to acquisition. To assess light leakage, three (3) UVC sources were simultaneously illuminated inside the bus and all doors and windows were securely closed. Spectrometer measurements were collected perpendicular to the windows with the spectrometer probe held flush against the transparent surface. Ten (10) representative windows were measured, including: windshield, driver window, passenger window and upper sliding portions, entry doors, and rear exit doors. No light was detected in the target wavelength (200-300 nm) for any transparent surface indicating light did not leak during operation of the UVC sources.

Table 4 UVC Spectrometer measurements for light leakage

Location	Description	Replicate Data Acquisitions 1	2	3	4	5	Mean	Stdev	%RSD
1	Front windshield	-8.72	-8.83	-8.73	-8.82	-8.75	-8.77	0.05	0.59%
2	Windshield (side window)	-8.72	-8.76	-8.78	-8.74	-8.74	-8.75	0.02	0.26%
3	Passenger door	-8.67	-8.76	-8.56	-8.59	-8.57	-8.63	0.08	0.98%
4	Wheelchair access door	-8.67	-8.64	-8.63	-8.6	-8.59	-8.63	0.03	0.37%
5	First row passenger window (lower)	-8.54	-8.64	-8.6	-8.56	-8.54	-8.58	0.04	0.51%
6	First row passenger window (upper)	-8.47	-8.58	-8.53	-8.55	-8.51	-8.53	0.04	0.49%
7	Rear Door	-8.52	-8.5	-8.54	-8.53	-8.53	-8.52	0.02	0.18%
8	Fourth row passenger window (lower)	-8.51	-8.44	-8.59	-8.54	-8.46	-8.51	0.06	0.71%
9	Driver window	-8.57	-8.51	-8.49	-8.47	-8.56	-8.52	0.04	0.51%

Peak wavelength (nm): 253.343

Table 4 shows UVC Spectrometer measurements for light leakage using one-lamp configuration reported in µW/sec-cm^2. Five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location. Mean, standard deviation (Stdev), and percent RSD are reported for each location. All measurements were below background intensity and no light was detected through any window.

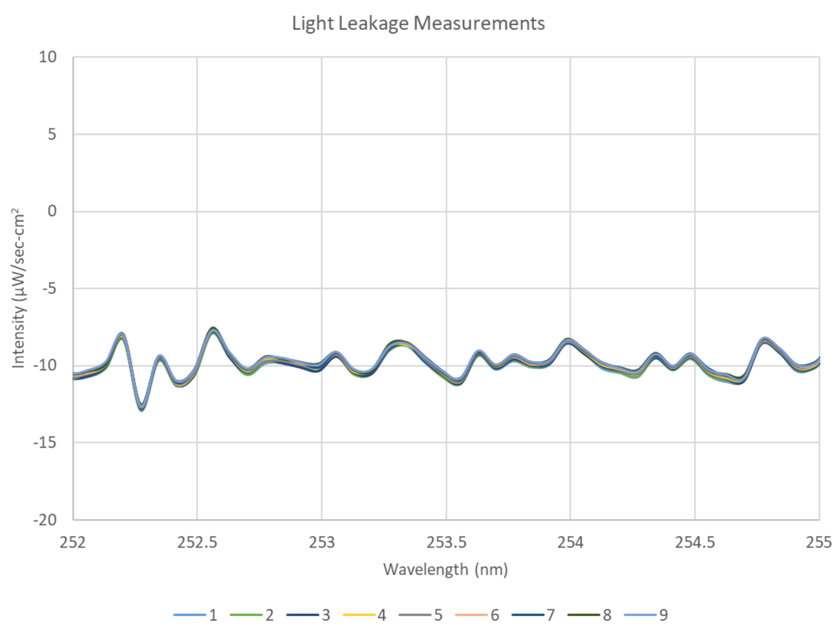

Figure 57 UVC spectra for light leakage measurements

Figure 57 shows UVC spectra for light leakage measurements shown for all representative exterior windows on the mini-bus using one-lamp configuration. Light intensity measurements shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represents a unique sample location taken through the window glass on the bus.

5.2.5.4 NABI Bus

Sample number: 31 measurement locations

Locations: Sample locations were selected to assess UVC intensity in the following scenarios: high touch regions, direct line of sight to UVC source, indirect line of sight to UV source, potential reflected light areas, shaded areas based on the LiDAR model, and areas with protective shields (e.g. polycarbonate partitions). The NABI locations were selected after concluding the small vehicle (Mini-bus) UVC spectrometer study, and emphasis was placed on assessing low light regions and surfaces with potential for receiving reflected light.

For the four-UVC source configuration, three of the sources were placed in the passenger cabin, approximately equidistant from each other for optimal light coverage corresponding to the positions determined by the LiDAR model, and the fourth light was positioned above the driver's seat area. The specific locations are as follows: source one was at the rear, source two was directly across from the side entrance door, source three was suspended at the front of the bus adjacent to the first passenger seat, and source four was directly above the driver's seat. Positions A-O were obtained using three sources in the passenger cabin. To capture positions P-Z and AA-EE, the rear light (#1) was repositioned above the driver's seat and subsequently referred to as source four. The logic behind this configuration is based on the intensity of light decreasing with distance from the source, where $I \propto 1/d^2$. Therefore, a source at the rear of the bus will not supply sufficient light to enhance the spectrometry measurements made at the front of the bus.

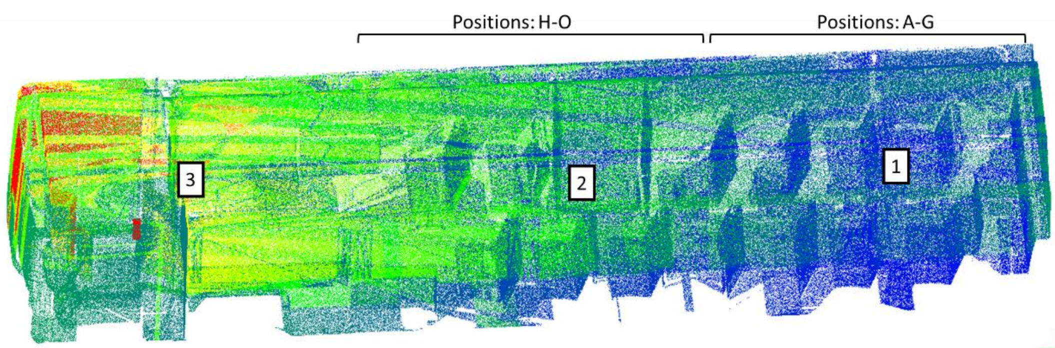

Figure 58 Four UVC source configuration #1: Positions A-G and H-O were measured using sources 1, 2, and 3.

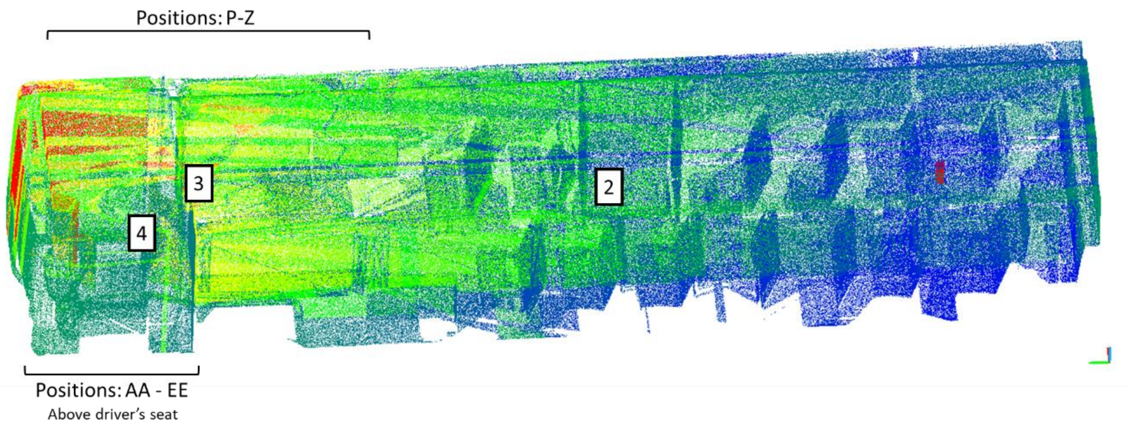

Figure 59 Four UVC source configuration #2: Positions P-Z and AA-EE were measured using sources 2, 3, and 4.

Figure 60 Select positions of spectrometer measurements in 40-ft NABI bus

Figure 60 shows select positions of spectrometer measurements in 40-ft NABI bus. Images taken from the rear of bus looking toward the front. Yellow arrows indicate regions where intensity measurements were acquired.

5.2.5.4.1 Four-UVC source results

Of the 31 measurement locations, only 6 received insufficient light based on the disinfection criteria previously described (25 µW/cm^2 at the targeted wavelength of 253 nm for a duration of 7 minutes). These locations include, the back of the rear-most passenger seat, the wall shaded by two adjacent seats, floor beneath seats, the area shielded by the polycarbonate partition perpendicular to the side entrance door, and the underside of the driver's dashboard. All other locations received an intensity greater than 25 µW/cm^2. In all cases, UVC is detectable, however the efficacy is uncertain for locations with measurements below 25 µW/cm^2. Proximity to the source and direct line of sight are the determining factors in whether sufficiently high intensity reaches a specific location. We observe a close approximation of the inverse-square law ($I \propto 1/d^2$) in the spectrometry measurements, where light intensity decreases with increased line of sight. With modified placement of the sources, such as moving a central lamp to the floor of the bus at specified height, direct un-obscured light may reach the previously shaded areas.

Table 5 UVC Spectrometer measurements for 40-ft NABI

Light Source: 4 UV-C Lamps

	Replicate Data Acquisitions							
Location	1	2	3	4	5	Mean	Stdev	%RSD
A	232.13	233.35	232.89	232.51	232.88	232.75	0.46	0.20%
B	26.11	26.99	25.81	22.05	21.91	24.57	2.41	9.80%
C	3.84	4.00	4.05	4.48	4.42	4.16	0.28	6.70%
D	92.23	98.32	101.45	108.11	106.29	101.28	6.37	6.29%
E	195.52	193.42	196.47	198.01	200.01	196.69	2.49	1.27%
F	106.37	99.97	100.12	102.61	102.49	102.31	2.59	2.53%
G	12.30	12.28	12.39	12.53	12.70	12.44	0.18	1.41%
H	14.98	14.71	13.95	13.77	13.62	14.21	0.60	4.24%
I	92.99	93.54	93.88	104.67	103.25	97.67	5.78	5.91%
J	282.46	284.53	284.55	286.05	287.89	285.10	2.02	0.71%
K	472.92	469.48	476.07	473.35	478.35	474.03	3.36	0.71%
L	52.07	54.03	55.10	56.41	57.38	55.00	2.07	3.77%
M	731.04	756.96	764.57	769.48	775.50	759.51	17.30	2.28%
N	129.70	116.31	139.09	169.78	168.45	144.67	23.75	16.41%
O	148.23	148.66	149.34	150.96	151.12	149.66	1.32	0.88%
P	4.84	5.00	5.26	5.38	5.24	5.14	0.22	4.25%
Q	105.20	103.06	103.30	102.43	95.83	101.96	3.58	3.51%
R	76.37	76.92	76.94	77.30	78.57	77.22	0.82	1.07%
S	19.26	17.04	17.24	17.24	--	17.70	1.05	5.92%
T	9.14	13.47	10.20	13.22	--	11.51	2.17	18.84%
U	172.73	172.71	172.68	170.72	169.83	171.73	1.37	0.80%
V	310.39	317.84	324.60	329.76	336.87	323.89	10.27	3.17%
W	26.66	26.86	27.93	27.27	27.94	27.33	0.59	2.17%
X	225.48	221.66	220.58	215.37	215.30	219.68	4.36	1.99%
Y	457.01	445.85	444.91	446.52	450.55	448.97	4.98	1.11%
Z	540.16	542.70	538.95	543.32	543.25	541.68	2.00	0.37%
AA	481.08	479.44	479.46	476.81	475.51	478.46	2.25	0.47%
BB	980.68	980.65	980.66	980.65	980.66	980.66	0.01	0.00%
CC	216.63	209.34	213.41	210.76	208.22	211.67	3.38	1.60%
DD	167.03	165.75	165.51	165.40	--	165.92	0.75	0.45%
EE	38.73	38.54	38.37	38.36	39.09	38.62	0.30	0.79%

Peak wavelength (nm): 253.343

Table 5 shows UVC Spectrometer measurements reported in µW/sec-cm^2. Five scans were averaged at each specified wavelength for each acquisition. Five acquisitions were made at each location for a total of 25 replicate acquisitions per location. Mean, standard deviation (Stdev), and percent RSD are reported for each location. Erroneous acquisitions were excluded for locations S, T, and DD.

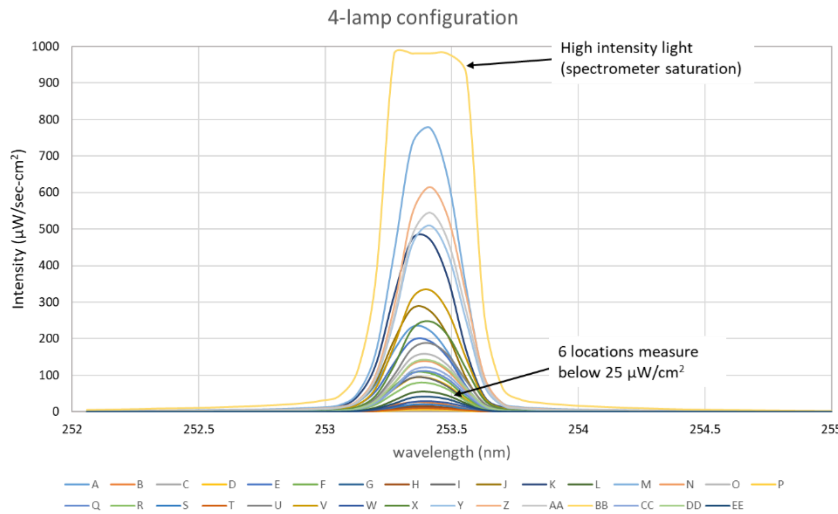

Figure 61 UVC spectra shown for all locations on 40-ft NABI bus.

Figure 61 shows UVC spectra shown for all locations on 40-ft NABI bus. Light intensity measurements shown for wavelength range of 252-255 nm, with peak intensity at 253.3 nm. Each curve represent a unique sample location within the bus. Position BB, indicated by the upper arrow, received high intensity light above the saturation limit for the spectrometer, hence the flattened peak.

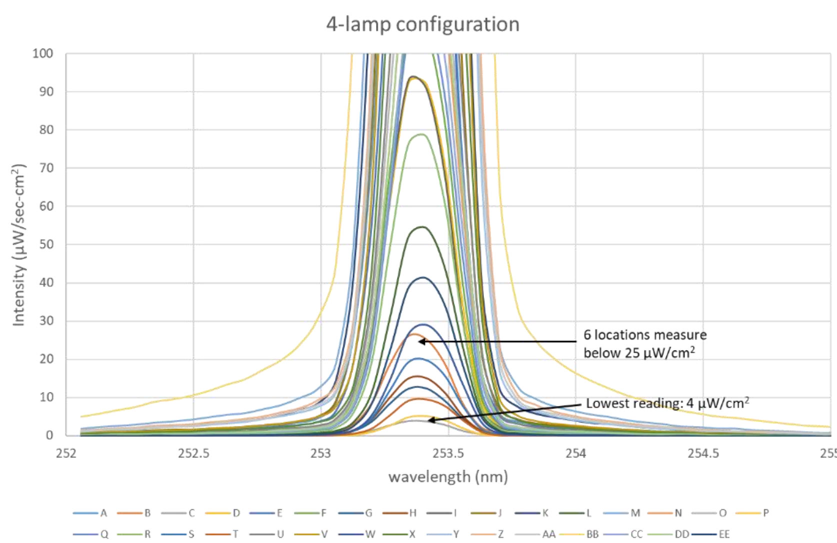

Figure 62 UVC spectra highlighting the six locations with peak intensities below the 25 μW/cm²

Figure 62 shows UVC spectra show highlighting the six locations with peak intensities below the 25 µW/cm^2 threshold for disinfection. The lowest detected intensity in a shaded region was 4 µW/cm^2, located beneath the driver's dashboard. In all cases, UVC is detectable, however the efficacy is uncertain.

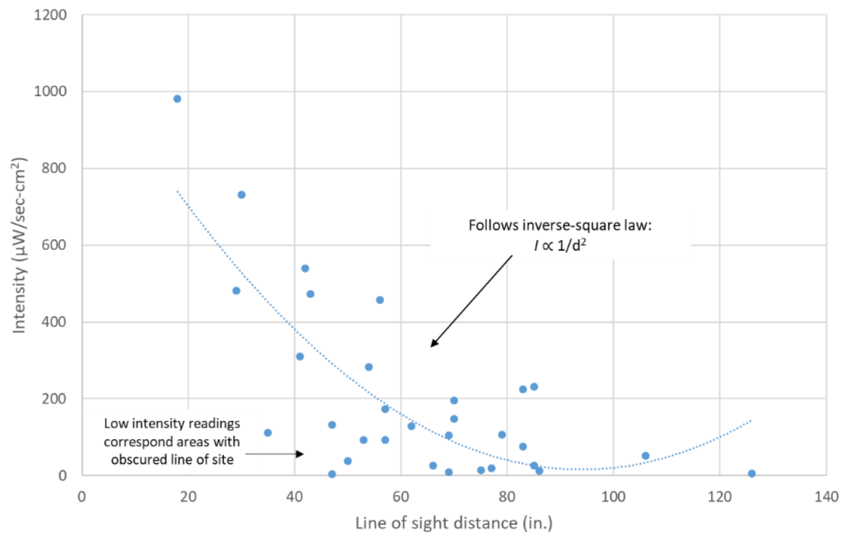

Figure 63 Intensity of light vs. line of sight distance for all sample locations on the NABI bus

Figure 63 shows Intensity of light vs. line of sight distance for all sample locations on the NABI bus. Line of sight was determined based on proximity to the closest light source with the least obscured light. Data were fit with a second order polynomial and approximately follows the inverse-square law for the intensity of light. Low intensity readings offset from the trend line correspond to locations with obscured line of sight.

5.2.5.5 Pulsed Xenon Spectrometer Results

Prior to data acquisition, the Maya Pro 2000 Spectrometer was calibrated using the pulsed Xenon UVC source in a controlled laboratory environment. The pulsed Xenon source was placed roughly 12 inches from the spectrometer inlet. It was characterized for both the intensity and wavelengths of light emitted during an individual pulse of light. The same Maya Pro 2000 Spectrometer was used for pulsed light acquisition as was used for the previously acquired UVC measurements using the CW source. However, it was operated in an automatic data acquisition mode, enabling effective capture of the pulsed light. Spectrometer measurements were collected over a contiguous wavelength range of 200 – 656 nm. The pulse duration was estimated based on laboratory exposure tests, and measurement parameters were adjusted to capture pulses over a range of integration windows from 25 mS to 200 mS). The research team was able to measure light emitted from the pulsed Xenon UVC source, placed side-by-side with the Mercury UVC source, and demonstrate the difference in the emission spectrum for each source. The continuous wave unit uses a Mercury vapor source which produces a line spectrum of very distinct wavelengths, with a peak maximum at a wavelength of ~254 nm in the UV range. In contrast, the pulsed system uses Xenon gas and produces a broad continuous spectrum from about 200 - 700 nm, extending from the UV to visible light range. The maximum wavelength detected by the spectrometer was 656 nm, and therefore all graphs are shown within the range of 200-650 nm. For the pulsed source, some data were collected with high intensity signals being attenuated, when the ability of the spectrometer to follow the high light emission intensity, is exceeded. The overall peak patterns were preserved and allowed for direct comparison.

The full duration of a single pulse was estimated to be about 60 mS based on readings taken using a 25 mS time window with two spectra being averaged. This creates a 50 mS window of time in which a single pulse can measured. Our data shows that this pulse of light is detected over two integration windows (i.e. intervals of time). When looking at a series of acquisition data we observed the intervals when light is not present vs. when it is present. Therefore, the research team used the absence of light as a benchmark for the window of time prior to the first pulse acquisition. The two subsequent acquisitions will have a split signal, with most of the light recorded in the first acquisition/capture. Therefore, the reported data represent a close approximation of the measured intensities (in $\mu W/cm^2$), but with a potential signal reduction of up to 18% calculated based on successive acquisitions.

Following laboratory calibration and optimization of the acquisition parameters, the pulsed Xenon source was taken to the mini-bus and measurements were made at four positions inside the bus. As shown in Figure 64, the pulsed Xenon source was placed directly below the Mercury source to approximate equal line of sight distances between the spectrometer and both UVC light sources. Four additional positions outside the bus were measured to check for light leakage, using the same light source configuration.

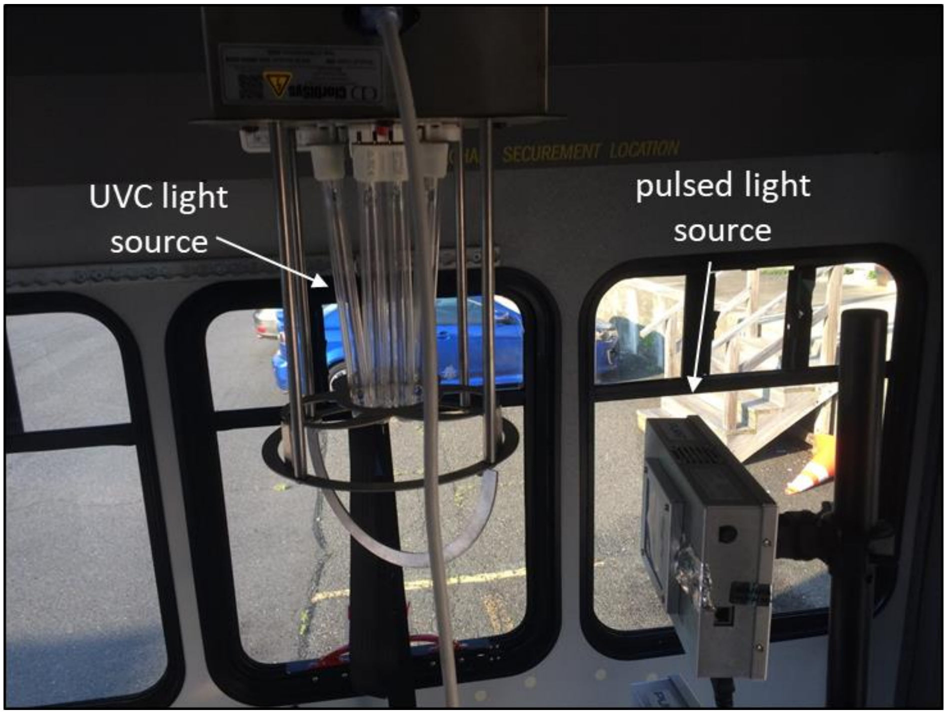

Figure 64 Photograph showing the proximity of the UVC Mercury source to the pulsed Xenon source.

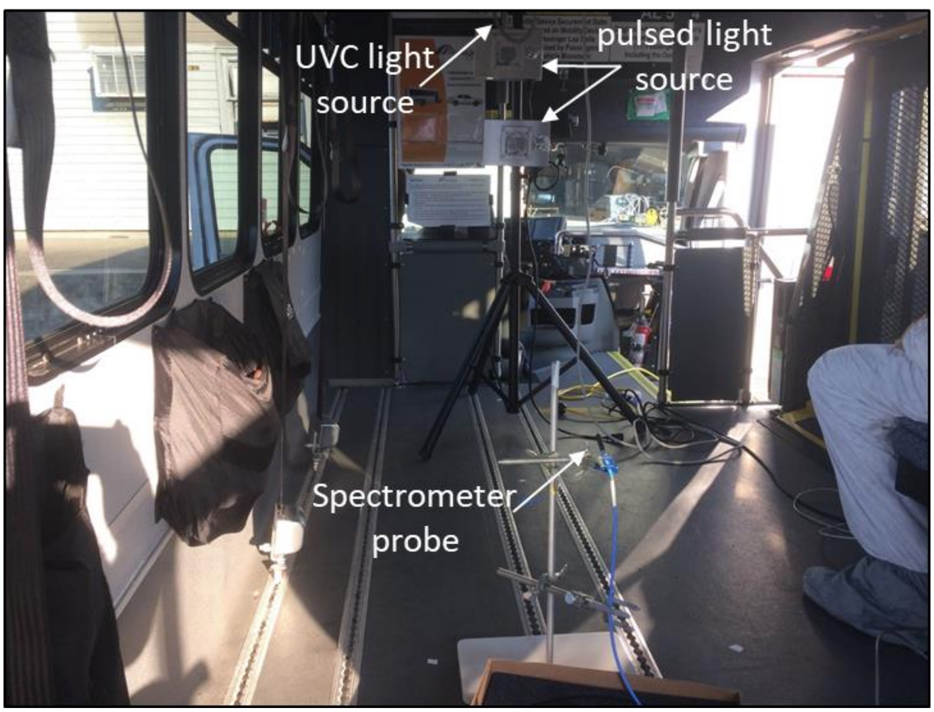

Figure 65 Photograph showing the pulsed Xenon source unit set up

The pulsed Xenon source setup is shown in Figure 65 with both sources directed at the back of the bus or toward the spectrometer inlet. The Mercury UVC source was positioned out of view, but directly above the Xenon source (see Figure 64). The two sources were placed as close to one another as the location and equipment would allow. The Spectrometer probe was set up for measurements at position “I”.

Additional measurements were collected at positions B, C, D, and E, which have been previously described in the CW Mercury Source UVC section. The pulsed Xenon source was not able to penetrate shielded areas any better than the Mercury source, indicating that polycarbonate partitions require either a direct line of sight or an alternative disinfection method.

For the purpose of summarizing our findings, the research team focused this discussion on position I, which was positioned in closest proximity and direct line of sight to the pulsed source. This location was anticipated to yield the highest light intensity to be delivered and therefore represents the maximum possible dosage deliverable (based on our assessment). At position I on the minibus, the observed maximum intensity across the contiguous spectrum was determined to be approximately 35 uW at a wavelength of 467 nm, the peak emission wavelength. This observation was independent of the integration window, as long as the integration time was sufficiently high to encompass the estimated pulse duration. As previously described, we tested various acquisition parameters (e.g. 75 ms vs. 35 ms integration time windows Figure 66 and Figure 67). At 75 ms integration time, the signal intensity is approximately half of the intensity recorded with a 35 ms integration window, as the overall peak intensity is divided by the number of milliseconds within the acquisition window.

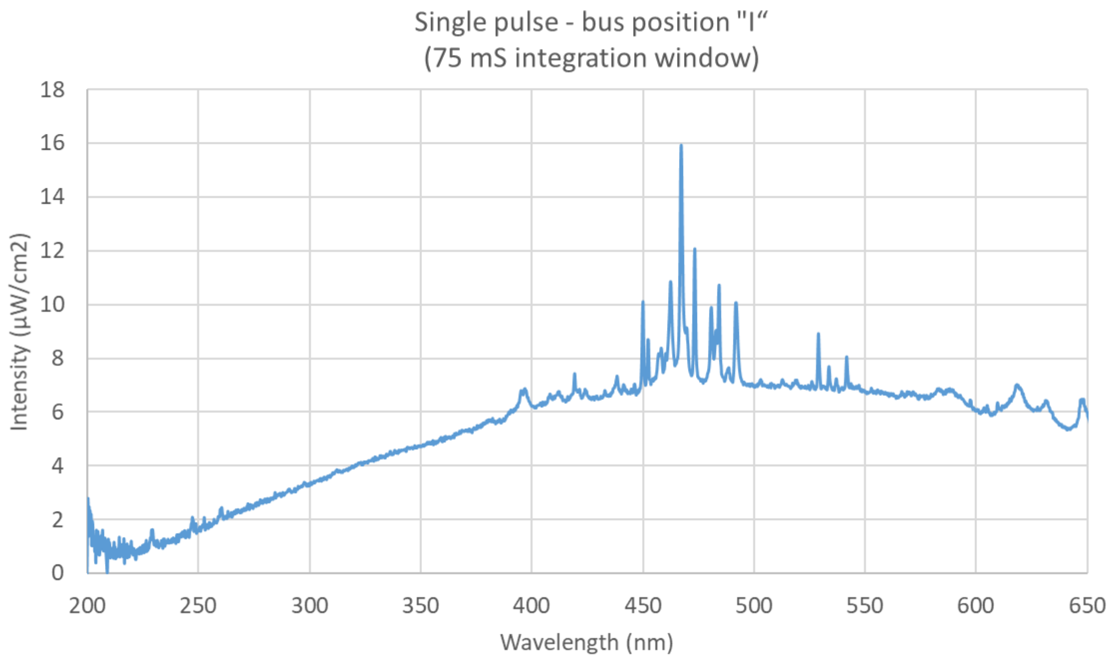

Figure 66 Single pulse Xenon spectrum, captured from bus position I using a 75 mS integration

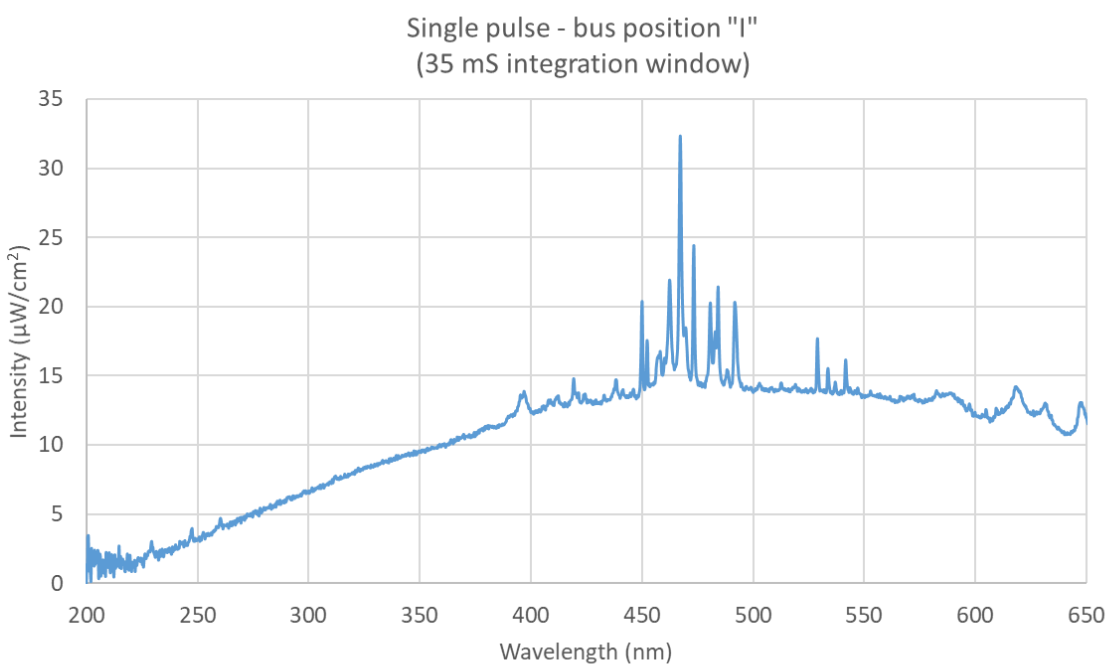

Figure 67 Single pulse Xenon spectrum, captured from bus position I using a 35 mS integration

The research team also conducted a direct comparison of the light intensity emitted from the Mercury UVC and the pulsed Xenon sources. Both units were placed in close proximity to one another on the bus, with the same line of sight distance to the spectrometer. Each spectrum was collected while operating one light source at a time. An additional spectrum was collected while operating both light sources simultaneously, to show the combined effect. In this case, peak light intensities are preserved in both the UVC range (Mercury peak wavelength = 254 nm) and the visible light range (pulsed Xenon source peak wavelength = 467 nm).

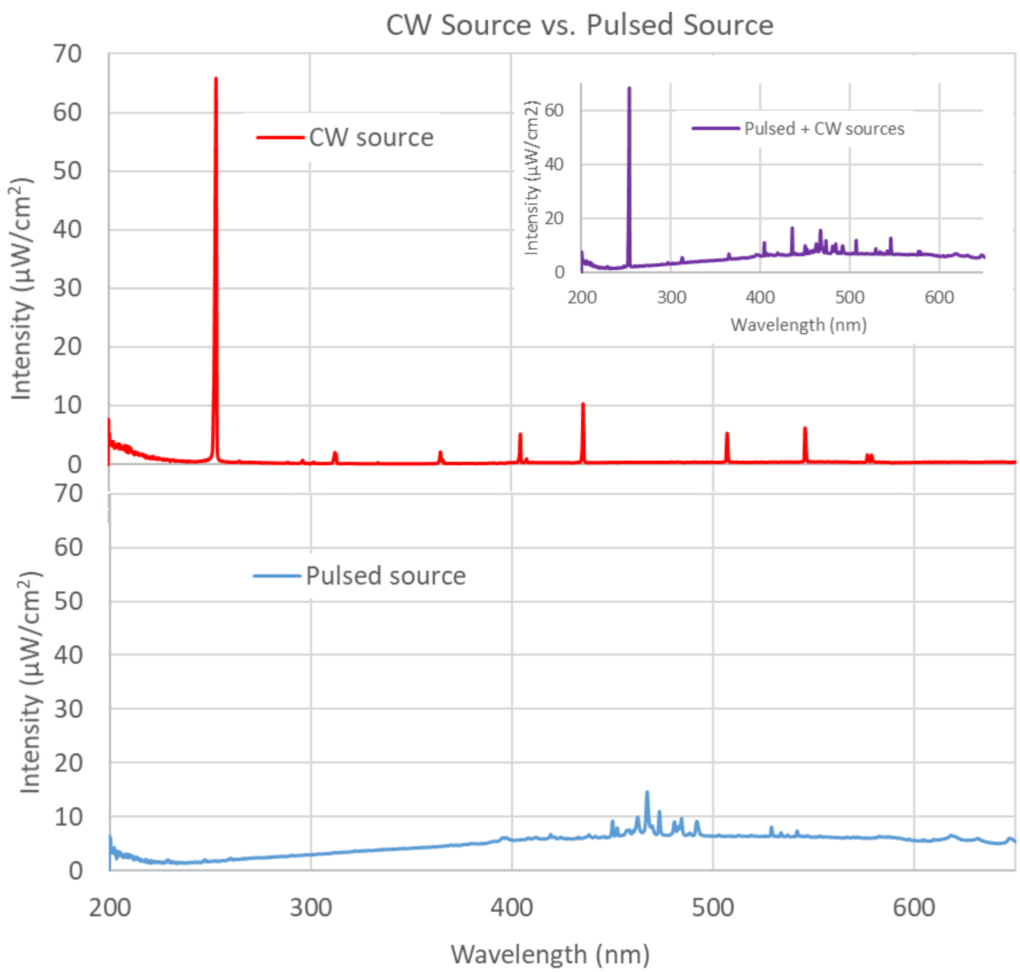

Figure 68 Comparison of the Mercury vs. the pulsed Xenon source spectrum

Overall, the pulsed unit produces a wider spectrum but is less intense in the 254 nm wavelength. The pulsed Xenon delivers a 60 ms dose roughly every 6 seconds which is much less exposure time than the Mercury "continuous" wave source. However, the wider range spectrum of the pulsed Xenon should be an advantage. Therefore, the research team can't calculate a direct efficacy comparison. That being said, the 254 nm wavelength at 8-ft a 3.65 uW/cm2 per pulse dose was also measured with a 35 ms integration time. With pulses occurring once every 6 seconds, that would be 1.1 mJ/cm2 delivered in 30 minutes versus the required 10.6 mJ/cm2 to achieve disinfection. Where the 10.6 mJ/cm2 was identified earlier in this report as a reasonable yet conservative dosage required to achieve kill.

[3.65 uW/cm2 * 60 second per minute / 6 seconds between pulses * 30 minutes / 1000 uW per mW = 1.1 mJ/cm2]

At least at the 254 wavelength a kill dosage does not appear to have been achieved. As previously stated, the broader spectrum should contribute to the yet to be determined efficacy impacts. Nevertheless, the pulsed source manufacturer recommends a 30-minute run time which also implies that there is no obvious advantage for disinfection run time. If 30 minutes is required for disinfection, there is no obvious advantage gained by using a pulsed source and a 30-minute run time would cause a greater difficulty in implementation. Additionally, light leakage was observed in the 300-400 nm range creating a very small but measurable potential risk to those around the bus, during a disinfection cycle.

Figure 68 represents the comparison of the Mercury vs. the pulsed Xenon source spectrum. Top: Red line shows Mercury source with peak UV range intensity at 254 nm. Bottom: Blue line shows pulsed Xenon source with peak intensities in the visible light range (~400-500 nm). Inlay: purple line showing spectrum collected while both sources were operating simultaneously.

One of the concerns with the pulsed Xenon having much of its spectrum in the visible, was the potential for light to bleed through the bus windows. The overall maximum intensity was recorded through the lift door window at ~1.9 $\mu W/cm^2$, followed by the rear window at 1.4 $\mu W/cm^2$. The windshield allowed the least amount of light to pass with only 0.13 $\mu W/cm^2$ at 467 nm. However, the front windshield and driver's side window were not in direct line of sight, as shown in the previous photographs. There are some noticeable differences in the glass types that might contribute to the observed spectrum as evidenced in figure 69, especially in the 325nm-400nm range. Based on the testing set up, we presume that the light detected through the front of the bus was reflected, and therefore potential leakage should be based on measurements collected at back window and lift door. With the short pulse duration and the low intensities (~ 0.5 $\mu W/cm^2$ at 390 nm), this bleed is not thought to create a significant health risk due to intermittent exposure. However, this is certainly a visual distraction for the NJ TRANSIT garage environment and a strobe distraction for bus drivers in the garage.

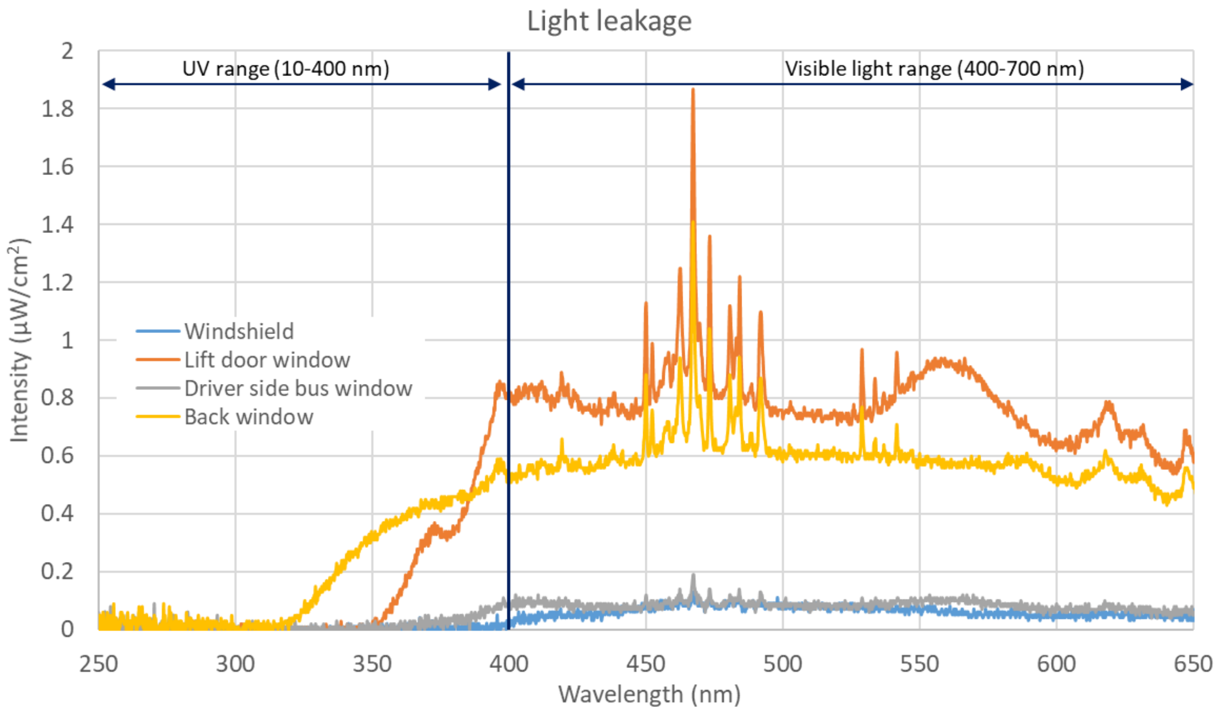

Figure 69 UV and visible light spectra for light leakage

As shown in Figure 69 is the UV and visible light spectra for light leakage measurements shown for four representative exterior windows on the minibus using the pulsed light source. Light intensity measurements shown for wavelength range of 250-650 nm, with peak intensity in the visible light range.

5.2.6 Catalog of UV disinfection systems

In this task, the research team generated a catalog of commercially available UV disinfection fixtures or systems. The list was generated using internet search engines, as well as input from NJ TRANSIT, EOSHI, and CAIT regarding potential vendors, including those that have been identified from media or past experiences. For reference, the research team collected a variety of parameters from the vendor websites.

The previously documented efforts of this research project were largely based on small portable UVC source characteristics - independent of a specific vendor. However, it's important to note that each product (i.e. semi-portable products that were developed for buildings or hospital rooms) will have significantly different performance and size. Therefore, the research team wanted to summarize commercially available products and collect general features to create representative samples i.e. similar size units and intensities. If an agency decides to pursue UVC for surface disinfection, these sample units can then be used in the future via the earlier developed LiDAR model to estimate the number of units required for equivalent UV coverage. Below is an initial list of potential UVC products with company name, website, phone number, email, and other characteristics.

5.2.6.1 Portable (Less than 50lbs)

5.2.6.1.1 Lantern UV Disinfection System

- ClorDiSys Solutions, Inc. (Lebanon, New Jersey)[iv]
- 50 Tannery Rd Suite #1, Branchburg, NJ 08876
- 908-236-4100
- https://www.clordisys.com/lantern.php
- Overall Dimensions: 14" H x 10" L x 10" W
- Weight: 10 lbs.
- Power: 115 VAC, 60 Hz, 1 Amps *(note this is lower than literature as per correction from vendor)*
- Cost: $3,900


Figure 70 Lantern UV System

"The Lantern UV Disinfection System is an easily transportable UV-C generator designed for use in any healthcare, laboratory, or research setting with emphasis on **use within emergency response vehicles**. It is used to provide a rapid and highly effective method to disinfect surfaces and components to reduce the transfer of dangerous organisms. The Lantern can be **used in both the upright and inverted positions such that it can be hung from railings or hooks.** The Lantern can also be used in doctor's offices where it can be used to disinfect both patient and waiting rooms during evening hours. The Lantern produces UVC output of 150 mw/cm2 to get a calculated 99% reduction of MRSA in 1 minute and spores like Clostridium difficile in 6 minutes within a 4ft distance."[18]

[iv] Photo Credit: Photo by ClorDiSys Solutions, Inc. via https://www.clordisys.com/lantern.php

5.2.6.1.2 Helo F1 UV Disinfecting Fixture (no flange)

- Puro UV Disinfection Lighting[v]
- 12340 W Cedar Dr., Lakewood CO 80228
- 877-452-8785
- https://purolighting.com/products/
- Dimensions: 2.9” H x 5.6” L x 8.6” W
- Weight: 2.6 lbs.
- Power: 110VAC, 3.5A, 120W *(please note this is power as reflected from vendor website)*
- Cost: $3,174.38

Figure 71 Helo F1 UV Fixture

“The Helo F1 disinfects a whole room, delivering disinfection from above. The unit can be ordered for installation in a drop-in grid ceiling, recessed in a hard ceiling, surface or wall mounted, or used as a portable, table top unit. It emits broad spectrum UV light to eliminate up to 99.9% of the bacteria, viruses, and fungi in a space1. In rooms that have been cleaned of mold, the unit will help control return growth if used routinely. The unit can be ordered for manual commissioning or integration into the facility Building Automation System (BAS). Manual commissioning can be done with the assistance of a local rep using a Setup Wizard. Units integrated into BACnet are programmed through the BAS dashboard.”[19]

5.2.6.1.3 Sentry M1-2 Mobile UV Disinfecting Unit

- Puro UV Disinfection Lighting[vi]
- 12340 W Cedar Dr., Lakewood CO 80228
- 877-452-8785
- https://purolighting.com/products/
- Tripod Mounted Dimensions: 42.9” – 71.0” H x 24.0”
- Weight: 14 lbs.
- Power: 110VAC, 7A, 120W *(please note this is power as reflected from Puro website)*
- Cost: $6,547.50

Figure 72 Sentry M1-2 Mobile UV Unit

“With the Sentry M1, protection follows you. The Sentry M1 is an affordable mobile UV disinfecting unit designed for easy positioning and simple control. It emits broad-spectrum UV light to eliminate up to 99.9% of the bacteria, viruses, and fungi in a space. In rooms that have been cleaned of mold, the unit will help control return growth if used routinely. The compact unit has a Single or Two Single UV Light Engines in a lightweight, miniaturized design. Mounted on a tripod base, the M1 unit has a telescoping neck and adjustable UV head angle for perfect spot treatment where contamination is suspected.”[20]

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[v] Photo Credit: Photo by Puro via https://purolighting.com/products/
[vi] Photo Credit: Photo by Puro via https://purolighting.com/products/

5.2.6.1.4 Industrial Portable 300W Surface & Air Sanitation Cart UVCART300

- Cello Lighting[vii]
- 2570 N. 1st Street, 2nd floor, San Jose, CA, 95131
- 888-588-8849
- https://www.cellolighting.com/
- Dimensions: 60" H x 12" L x 12" W
- Weight: 24 lbs.
- Power: 120V, 2.5A, 60 Hz, 300W
- Cost: $2,250

✓ "Proven UVC Technology kills 99.9% of bacteria and viruses
✓ Surface & Air Disinfection
✓ Can only be used in unoccupied rooms
✓ Lightweight and easy to carry
✓ Timer and Remote control
✓ 100 ft control range that works through walls
✓ Mobile app controls on and off from anywhere
✓ Coverage up to 6,000 sq. ft."[21]

Figure 73 Industrial Portable 300W UVCART300

5.2.6.1.5 Diversey MoonBeam 3 UVC Disinfection Device

- Diversey[viii]
- 1300 Altura Road, Suite 125, Fort Mill South Carolina, 29708
- 803-746-2200
- https://diversey.com/en/solutions/infection-prevention/uv-c-disinfection/moonbeam-3
- Dimensions: 44" H x 15" L x 15" W
- Weight: 39 lbs.
- Power: 120V, 3.2A, 50/60 Hz
- Cost: $32,746[22] - $36,999[23]

Figure 74 Diversey MoonBeam 3 UVC Device

"A game-changing angle for targeted disinfection – This portable, powerful solution disinfects quickly, reliably and responsibly. MoonBeam3 is designed for fast, on-demand disinfection of high-touch surfaces in patient rooms, operating rooms and bathrooms and can be used on patient care equipment, fixtures, keyboards, monitors and work stations on wheels (WOWs).Three individually-adjustable, articulating arms can be positioned at almost any angle to target the UVC light, enabling improved UVC dosing with reduced energy. Users can position the heads to optimize UVC dosing of surfaces and equipment. This flexible device is easily positioned throughout a room or facility to enable fast and effective disinfection cycles."[24]

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vii Photo Credit: Photo by Cello via https://www.cellolighting.com/
viii Photo Credit: Photo by Diversey via diversey.com

5.2.6.1.6 Sanidyne Prime UVC Portable - 143W UV Output

- Atlantic Ultraviolet Corporation[ix]
- 375 Marcus Boulevard, Hauppauge, N.Y. 11788-2026, USA
- 631-273-0500
- https://ultraviolet.com/sanidyne-ultraviolet-portable-area-sanitizer/
  Dimensions: 31.5” H x 14” L x 12.13” W
- Weight: unknown
- Power: 120V, 143W

Figure 75 Sanidyne Prime UVC Portable

“The Sanidyne® Prime and Sanidyne® Prime Remote have been carefully conceived in order to provide germicidal ultraviolet disinfection for air and exposed surfaces of an unoccupied area, by means of 8 STER-L-RAY ® High Output (HO) Germicidal Ultraviolet Lamps. These special lamps generate high levels of germicidal ultraviolet radiation lethal to infectious microorganisms such as bacteria, mold, and virus.

The ultraviolet disinfection dosage is a function of time and intensity to which the air and surrounding surfaces are exposed. Our UV Application Specialists would be happy to perform the necessary calculation to ensure the sanitizer we provide is appropriate for your particular application.”[25]

5.2.6.1.7 SPECTRA 500 UV Disinfection System

- Spectra254[x]
- 3 Corporate Drive, Danbury, CT
- 203-796-5315
- https://www.spectra254.com
- Dimensions: unknown
- Weight: 41 lbs.
- Power: unknown
- Cost: unknown

Figure 76 SPECTRA 500 UV Disinfection System

“The Spectra 500 disinfection system is designed for emergency vehicles, using four high-output UVC bulbs to eliminate pathogens on surfaces. INDEPENDENTLY TESTED & VERIFIED

- ✓ Designed for Emergency Vehicles – the only product designed specifically to decontaminate vehicles in five or ten minutes.
- ✓ One Click Remote Control – 5, 10, 15 minute cycles
- ✓ Four custom built UVC Bulbs with protective FEP sleeves
- ✓ Compact Mobile and Easy to Move – weighs only 41 lb (19 kg) and measures only 49 inches (125cm) in height.”[26]

[ix] Photo Credit: Photo by Atlantic Ultraviolet Corporation via https://ultraviolet.com
[x] Photo Credit: Photo by Spectra254 via https://www.spectra254.com

5.2.6.2 Larger UV Systems (Greater than 50lbs)

5.2.6.2.1 Torch Tower[xi]

- ClorDiSys Solutions, Inc. (Lebanon, New Jersey)
- 50 Tannery Rd Suite #1 Branchburg, NJ 08876
- 908-236-4100
- https://www.clordisys.com/torch.php
- Dimensions: 23" W x 68" H x 23" D
- Weight: 72 lbs
- Power: 110-240VAC, 6A, 50/60 Hz
- Cost: $25,000

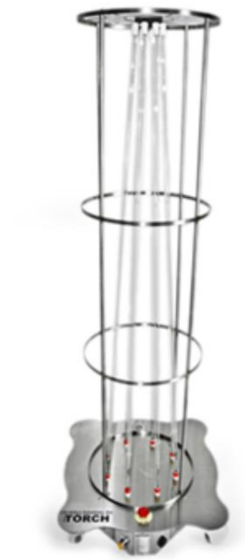

Figure 77 Torch Tower

"The TORCH Tower is an inexpensive, easily transportable, powerful disinfection system designed for use in any healthcare, pharmaceutical, manufacturing, laboratory, or research setting. It is used to provide a rapid and highly effective method to disinfect surfaces, components, room surfaces and common touch points to reduce the transfer of dangerous organisms. It also offers a way to disinfect components without removing them from the room, which helps minimize the chance for cross-contamination. The TORCH contains **eight high powered UVC lamps to provide quick disinfection times. It simply plugs into any standard wall outlet.** The TORCH produces an efficient UVC output of 12 mJ/minute (200 µw/cm^2) to get a calculated 99% reduction of MRSA in 10 seconds. A 99% reduction of spores like *Clostridium difficile* can be achieved in 5 minutes within a distance of 10 feet. A recent study shows that traditional UV systems such as the TORCH provide similar results as expensive Pulsed Xenon Ultraviolet Light Systems. Click here to read the full study The TORCH system is designed to be so economical that multiple units are affordable enough to place into a room at the same time **to eliminate shadow areas and maximize coverage** for the most thorough disinfection process."[27]

[xi] Photo Credit: Photo by ClorDiSys Solutions, Inc. via https://www.clordisys.com/torch.php

5.2.6.2.2 LightStrike Germ-Zapping Robot

- XENEX Disinfection Services [xii]
- 121 Interpark, Suite 104, San Antonio, TX 78216
- 800-553-0069
- https://www.xenex.com/our-solution/lightstrike/
- Dimensions: unknown
- Weight: unknown
- Power: unknown
- Cost: unknown

"LightStrike Germ-Zapping Robots is the first disinfection system of its kind to deliver intense germicidal action from 200-315nm. It's a user friendly robot that's intensely pathogen deadly. How intense is it? The LightStrike Germ-Zapping Robots deliver up to 4,300x more germicidal UV pathogen killing intensity than UV-C mercury vapor* and can disinfect an entire patient room in as little as 20 minutes. From the power of our technology, to our rigorous scientific approach — intensity is what sets us apart. It's why Intensity Matters."[28]

Figure 78 LightStrike Germ-Zapping Robot

5.2.6.2.3 Tru-D SmartUVC

- Tru-D SmartUVC [xiii]
- 743 S. Dudley, Memphis, TN 38104
- 800-774-5799
- https://tru-d.com/
- Dimensions: 28.75" W x 64" H x 34.65" D
- Weight: 181 lbs
- Power: 110V approx. 14 Amps [29]
- Cost: approx. $87,000+ [29]
- Note bars on the side are bolts to the frame and can be used to lift and carry unit [29]

Figure 79 Tru-D SmartUVC

"Tru-D SmartUVC delivers an automated, measured dose of UVC to consistently disinfect a room from a single position, eliminating human error and documenting disinfection results for each cycle. Using patented technology, Tru-D provides thorough room disinfection ensuring the entire room is disinfected every time. During the disinfection cycle, **Tru-D's microprocessors and instrument-grade sensors measure the necessary amount of UV energy that is reflected back to the robot.** Tru-D automatically shuts down and notifies the operator via audio and/or text message that the disinfection cycle is complete."[30]

[xii] Photo Credit: Photo by Xenex via https://www.xenex.com/our-solution/lightstrike/
[xiii] Photo Credit: Photo by Tru-D via https://tru-d.com/

5.2.6.2.4 MRS33-8 Mobile UV Unit

- American Ultraviolet [xiv]
- 212 South Mt. Zion Road, Lebanon, IN 46052
- 800-288-9288
- https://www.americanultraviolet.com/uv-germicidal-solutions/pharmacy-laboratory-mobile.cfml
- Dimensions: 47" H x 20" W x 20" L
- Weight: 80 lbs.
- Power: 120-220V, 4A/2.2A
- Cost: approx. $9,995 [31]

"This unit uses 360 degree motion sensors as a safety precaution and features eight (8), 33" slimline UVC lamps optically centered around a highly polished reflector for maximum intensity. System controls are located directly on the unit, which allows utilization of a touchscreen with 3 pre programmed disinfection cycle times, and the option to manually set disinfection cycles times."[32]

Figure 80 MRS33-8 Mobile UV Unit

5.2.6.2.5 MRS45-12 Mobile UV Unit

- American Ultraviolet [xv]
- 212 South Mt. Zion Road, Lebanon, IN 46052
- 800-288-9288
- https://www.americanultraviolet.com/uv-germicidal-solutions/pharmacy-laboratory-mobile.cfml
- Dimensions: 67" H x 26" W x 26" L
- Weight: 95 lbs.
- Power: 120-220V, 4A/2.2A
- Cost: approx. $14,995[33]

"This unit uses 360 degree motion sensors as a safety precaution and features twelve (12), 45" slimline UVC lamps for maximum intensity. System controls are located directly on the unit, which allows utilization of a touchscreen with 3 pre programmed disinfection cycle times, and the option to manually set disinfection cycles times."[32]

Figure 81 MRS45-12 Mobile UV Unit

[xiv] Photo Credit: Photo by American Ultraviolet via https://www.americanultraviolet.com
[xv] Photo Credit: Photo by American Ultraviolet via https://www.americanultraviolet.com

5.2.6.2.6 UV-C High Power Disinfection System Mobile

- XtraLight[xvi]
- 8812 Frey Rd, Houston, Texas USA 77034
- 888-627-2137
- https://www.xtralight.com/
- Dimensions: 60" H x 30" W x 20" L
- Weight: 64 lbs.
- Power: 120V, 60 Hz, 320W
- Cost: approx. unknown

Figure 82 UV-C High Power System

✓ "Mobile UV-C system to disinfect and rid spaces of microorganisms
✓ Uses eight germicidal UVC lamps with ceramic caps
✓ Easy UVC lamp change out
✓ Wheeled stand for easy placement of unit
✓ 20 ft 5-15p power cord (standard on 120V)
✓ Protective case to hold device and PPE
✓ On/off switch
✓ Secondary power switch with WiFi enabled timer and on/off
✓ settings controlled via IOS or Android App
✓ Occupancy sensor."[34]

5.2.6.2.7 Optimum-UV Enlight System

- Ultraviolet Devices, Inc. (UVDI)[xvii]
- 26145 Technology Drive, Valencia, CA 91355, U.S.A.
- 800-288-9288
- https://www.uvdi.com/
- Dimensions: unknown
- Weight: unknown
- Power: unknown
- Cost: approx. unknown

Figure 83 Optimum-UV Enlight System

"Optimum-UV Enlight® System combines powerful ultraviolet technology with smart data reporting, ensuring that you maximize your facility's investment and get the efficacy you're counting on.

✓ 99.992% C. difficile Kill in 5 minutes and over 35 other HAI-causing pathogens
✓ Intuitive Touch Screen Operating System
✓ Smart Data System for Robust Data Collection."[35]

[xvi] Photo Credit: Photo by XtraLight via https://www.xtralight.com/
[xvii] Photo Credit: Photo by UVDI via https://www.uvdi.com/

5.2.6.2.8 Industrial Portable 1000W Surface & Air Sanitation Cart UVCART1000

- Cello Lighting [xviii]
- 2570 N. 1st Street, 2nd floor, San Jose, CA, 95131
- 888-588-8849
- https://www.cellolighting.com/
- Dimensions: 59.3” H x 12.8” L x 45.7” W
- Weight: 100 lbs.
- Power: 120V, 10A, 60 Hz, 1000W
- Cost: unknown

Figure 84 Industrial Portable 1000W UVCART1000

- ✓ “Proven UVC Technology kills 99.9% of bacteria and viruses
- ✓ Surface & Air Disinfection
- ✓ Can only be used in unoccupied rooms
- ✓ 10x the lamp life of conventional UVC Units
- ✓ 50% less energy consumption than other units
- ✓ Timer and Remote Control
- ✓ Mobile app controls on and off from anywhere
- ✓ Casters for easy transport
- ✓ Coverage up to 20,000 sq. ft.
- ✓ Steel Construction”[36]

5.2.6.2.9 GermFalcon

- Dimer UVC Innovations [xix]
- Los Angeles, CA, USA
- 562-754-6260
- https://www.germfalcon.com/
- Dimensions: unknown
- Weight: unknown
- Power: unknown
- Cost: approx. $100,000[37]

Figure 85 GermFalcon

“The Honeywell UV Cabin System is roughly the size of an aircraft beverage cart and has UVC light arms that extend over the top of seats and sweep the cabin to treat aircraft surfaces. Properly applied, UVC lights deliver doses that medical studies find reduce various viruses and bacteria, including SARS CoV and MERS CoV. It can treat an aircraft cabin in less than 10 minutes for approximately $10 per flight for midsize to large airline fleets. Results vary based on UV dosage and application, and no testing has been done specifically on protection against COVID-19.”[38],[39]

[xviii] Photo Credit: Photo by Cello via https://www.cellolighting.com/
[xix] Photo Credit: Photo by Dimer via https://www.germfalcon.com/

5.2.6.3 Summary of Findings for UV Disinfection Products

The research team identified several UV products that might be suitable for transit surface disinfection. This is not a 100% comprehensive list as there are other vendors that, for our purposes, are equivalent or similar to the products that are already included in our catalog. At some point the research team would simply be duplicating very similar information. Also, some vendors use standard Philips, GE, or equivalent bulbs. Therefore, the nature of the UVC disinfection is the same but the product might have additional features on the device such as motion/occupancy sensors, timers, remote controls, UV sensors, onboard computers/processors, etc. Furthermore, working with NJ TRANSIT for the purposes of this project the acceptable setup logistics time was limited to approximately 5 units or less; there are many small products that would likely require too many units to be practical to achieve the range of dosages required.

In addition to the acceptable setup time, by limiting the acceptable disinfection time required to roughly 7 minutes per bus; the handheld units would largely be eliminated due to the labor time required to pass a device over all the surfaces. Plus, for handheld units there would also be further considerations of worker exposure. Conceptually, with proper PPE worker safety can be controlled. However, the issue remains that for most buses the time to use a small handheld unit would likely be beyond the time NJ TRANSIT would be able to practically commit per bus. However, it’s worth mentioning that the handhelds can be used closer to the surface (inches away) and thereby impart a high intensity UV dosage. This could speed up disinfection for small focused areas, areas that have lots of shadowing, or sensitive instruments such as control panels. Unfortunately, this would be active (vs passive) disinfection and subject to higher user variability based on how fast the operator passes over an area.

The practical nature of the garage/depot environment requires portability, ruggedness, simplicity of use including cable management, and power availability (generator or portable battery) to avoid running extension cords throughout the facility. General observations:

- Different UVC disinfection devices use about the same irradiance mechanisms but with varying intensities and device characteristics. Some products have additional features such as motion/occupancy sensors, timers, remote controls, UV sensors, onboard computers/processors, etc.
- Many units identified weighed more than 100 lbs. Although equipped with wheels, the weight would limit usability and maneuverability while positioning and carrying onto and off a bus especially for buses with stairs or even bi-level trains.
- Many portable units were identified that can likely be used in an inverted position - that illuminate from above - simplify light distribution throughout the cabin and help ensure broader coverage on surfaces.

- Only two vendors were identified that use pulsed Xenon technology. There are conflicting claims regarding the efficacy of pulsed Xenon in comparison to constant on Mercury UV bulbs.
- If a UV source or a combination of sources draws more than 15-20 amps this will likely max-out a typical circuit or portable power device. There are significant advantages to units drawing lower power.
- Handhelds may still be appropriate for smaller vehicles such as Sedans or for operator/driver areas on the buses. A more detailed review and testing effort for handhelds may be warranted to expand those tools for NJ TRANSIT.

Conceptually, the intent was not to identify a specific vendor for deployment but instead on the overall ability of UVC to provide the irradiance, or more specifically, energy over duration of time required to disinfect. To define what UV surface disinfection would look like, or even if the agency wants to proceed with the capital investment, with what dosage, what operational protocol, and ultimately what does that mean for fleet wide deployment each night. A variety of devices were identified as reference to ensure that a commercially available product exists that matches the operational parameters required. Fundamentally, there were several products identified that might be suitable for UVC surface disinfection - any number of devices were identified that could be used with differing durations and placements.

5.2.7 Ultraviolet light long-term impacts (life span) on materials

A significant amount of literature exists regarding UV degradation of plastics. However, the majority of past research focuses on wavelengths found in sunlight and not UVC. Over time, UV will cause many plastics to chalk, become brittle, discolor, and crack as well as cause loss of strength in fibers/fabrics. Common anecdotal comments regarding UV exposure imply a 10% reduction in life. "If the plastic would normally last about ten years, and it's exposed to germicidal UVC light the entire time, it would probably need to be replaced in 9 years."[40] Although widely stated, the research team was unable to identify any data or research to support this claim. Although not quantified, several plastic suppliers and manufactures state that UVC is more likely [than UVA and UVB] to affect plastics.[41] Based on the higher energy of UVC, it's reasonable to expect it to breakdown the molecular bonds more than other wavelengths.

The Business and Institutional Furniture Manufacturer's Association (BIFMA) HCF 8.1 Health Care Furniture Design – Guidelines for Cleanability identified 28.8-29.1 J/cm2 as an expected cumulative UVC (254 nm) exposure at a weekly dosage for seven years.[42],[43] This dosage was based on a hospital furniture's useful life span requirement and a weekly dosage required to kill certain bacteria - representing a furniture design target and not necessarily a damage threshold. However, the 28.8 J/cm2 is widely used in standardized testing and therefore is a common reference point.

Earlier in this report, the research team recommended a conservative but reasonable estimate of 10.6 mJ/cm2 to achieve a 1-log (90% reduction) kill rate. However, due to uneven distribution produced by only using three or four UVC sources, some surfaces were measured to receive as much as 200uW/cm2. Using an assumed 7-minute duration, this would result in an 84 mJ/cm2 dosage. Although some areas of the bus will receive an excess UV dose; the extra exposure is unavoidable unless more but lower powered UVC sources are used to more evenly distribute the light.

[200uW/cm2 *60 seconds per minute * 7 minutes / 1000 uW per mW = 84 mJ/cm2]

Using the BIFMA 28.8 J/cm2 as a reference along with the 10.6mJ/cm2 to 84 mJ/cm2 of expected real-world dosages - the BIFMA guidance would be exceeded in 2716 to 342 treatments respectively. This means that in as little as 1 to 7 years the BIFMA guidance would be exceeded. In comparison to the BIFMA guidance in the healthcare setting, a seven-year life means many plastics may have already reached the end of their useful life for other reasons. However, this is not likely the case for a transit asset.

[28.8 J/cm2 / 10.6 mJ/cm2 * 1000 mJ/J = 2,716 treatments]

[28.8 J/cm2 / 84 mJ/cm2 * 1000 mJ/J = 342 treatments]

"Damage to Common Healthcare Polymer Surfaces from UV-C Exposure," which specifically focused on UVC and used the BIFMA guidance as a reference, found that some plastics fared much better than others. Ten plastic surfaces were tested including: Polypropylene (PP), Ultra-high molecular weight polyethylene (UHMW PE), Polytetrafluoroethylene (PFTE or Teflon), Clear polymethyl methacrylate (PMMA or clear acrylic), White polymethyl methacrylate (PMMA or white acrylic), Polyoxymethylene (Delrin), Polyester (polyethylene terephthalate or PET), Polycarbonate, Nylon, and Acrylonitrile butadiene styrene (ABS).[44] Furthermore, it should be noted that this study used a standard General Electric Mercury UVC source for testing. In Table 6 Qualitative summary of damage to common healthcare polymers from UV exposure, expected levels of damage are shown. These are measurable damages and do not imply that the material has lost function. For example, in the case of hardness, the researchers used nanoindentation for small scale measurements due to the high spatial resolution.[45] Although a loss of hardness was analytically measured the material is not likely to be brittle or break at this level of exposure, but it does demonstrate that bonds are changing and there is a decreased asset life.

Table 6 Qualitative summary of damage to common healthcare polymers from UV exposure[45,44, xx]

Sample	Overall Damage	Microscopy	Roughness	L*A*B* Color	Whiteness	Contact Angle	Hardness
Polypropylene	Minor	Minor	Minor	Minor	Minor	Minor	Moderate
Ultra-high molecular weight polyethylene	Minor	Minor	High	Minor	Minor	Minor	Minor
Polytetrafluoroethylene	Moderate	Moderate	Moderate	Minor	Minor	Moderate	Moderate
Clear polymethyl methacrylate	Moderate	Moderate	Minor	Minor	Minor	High	Moderate
Polyoxymethylene (Delrin)	Moderate	High	Moderate	Moderate	Moderate	Minor	Moderate
Polyester	Moderate	Minor	Moderate	Moderate	Moderate	High	High
Polycarbonate	High	High	Moderate	High	High	High	Moderate
Nylon	High	Minor	High	High	High	High	Minor
Acrylonitrile butadiene styrene	High	Moderate	High	High	High	High	High
White polyethyl methacrylate	High	Minor	High	High	High	Moderate	Moderate

[xx] Table used with permission of Peter Teska Global Infection Prevention Expert of Diversey Inc.

The biggest expectation of damage is discoloration, typically a shift in color from white to yellow. Darker colored plastics are less likely to be noticeable but there would still be a color shift. The first damage will be discoloration followed by other changes such as becoming more rigid, brittle, cracking, or chalking. The discoloration represents the first stage of micro-damage; not functional damage which will occur in the future, well after the initial color change is observed.

Another study demonstrated that all organic materials are degraded by UVC radiation of 254 nm. However, the "main effect of UVC exposure was crater formation/mass loss as opposed to the cross-linking/bulk degradation reported for materials exposed to UVA and UVB. Since the photodegradation was localized at the surface, the mass loss was minimal with the depth of the created crater being measured in microns."[46] Furthermore, "solid materials performed better than porous/fibrous materials due to the minimal surface penetration by the UVC radiation. Of the materials tested, only aluminum foil and glass fibers were totally resistant to photodegradation."[46] This study was conducted with respect to UVC impact on HVAC systems including wiring and plastic drip pans. Therefore, based on the higher UVC intensity within the HVAC environment, and the less durable materials such as thin wire coatings, the study implies that it is highly likely that any damage will be minor and cosmetic.

Prior to becoming so damaged that it is brittle, plastic is more likely to experience several of the micro-damages including an increased surface roughness. The roughness may increase the cleaning difficulty and theoretically the effectiveness of disinfectants. "It is clear that at least for some plastics, excessive exposure to UV-C energy is likely to cause unacceptable levels of surface degradation that are visually impactful, and which may compromise the hygienic safety and/or use of the surface, which may represent an increased risk to patient safety, although this requires further study."[45]

Therefore, it's reasonable to expect that if UVC were to be applied daily that a majority of plastics found within a bus, including panels, seats, plastic handgrips, and Polycarbonate dividers, will have some level of damage (micro-damages) in as little as 1 years with the majority of surfaces in 7 years. It would likely vary by not only the type of plastic but also grade of material and additives during manufacturing – meaning that even different seat manufacturers would have a different performance. As per Table 6 above, it should be noted that ABS was identified as one of the worst performing plastics when exposed to UVC.

If UVC were to be applied daily, there would be some level of damage to the plastics. However, without accelerated UVC testing the research team cannot predict the decrease in useful life of the interior finishes. Based on a 7-minute daily dosage, an accelerated test could be conducted where 2 weeks could represent 8 years or more of exposure. Such a test would likely yield little more than visual observations or measurements that wouldn't necessarily translate to a precise functional life reduction or actionable item for NJ TRANSIT.

[14days * 24 hrs per day * 60 minutes per hour / 7 minutes per dose / 365 days per year = 7.89 years]

- The biggest expectation of damage is discoloration.
- Micro-damages may impact roughness which may increase the cleaning difficulty and theoretically the effectiveness of disinfectants.
- The research team cannot predict a decrease in useful life of the interior finishes. However, it is highly likely that any damage will be minor and cosmetic.

5.2.8 *Power and cable management plan*

The deployment of portable UVC devices for disinfection onboard a bus poses many logistical issues. For example, buses generally are not equipped with 120 V outlets, therefore power for equipment must come from generators and extension cords. Furthermore, each of the 16 garages house 200 buses on average, with a turnaround of only a few hours to refuel and perform daily service before the buses return to the road. This effectively means that an equivalent of 24hrs of UVC lamp on-time would be required per garage every night. This has implication on equipment needs for simultaneous disinfection, storage of UVC equipment, power draw, dedicated staffing, and other impacts on nightly service and garage operations.

Portable batteries are unlikely to be a practical power supply for the UVC sources for any number of reasons. First, the battery recharge time generally takes longer than the effective discharge (functional) time of a battery. This is not always the case, but rapidly discharging and charging batteries can also lead to overheating. If the discharge rate of the battery pack is very fast - this can damage the battery. More specifically, it can damage it in a way that can cause failure to properly recharge, deep-cycle discharge shortening the overall battery life, and possibly create a dangerous battery overheating problem. Increasing the size of the battery pack is a potential solution. However, given the increased weight, required recharging time, deep-cycle discharge, and the usage rate, it's unlikely that a practical scenario exists for a fleet wide deployment. Since the garage has electrical power as well as access to gasoline; using a generator or even ceiling-mounted cable reels would be practical and more simplistic.

During the testing described earlier in this report, 3 to 4 UV sources were used to disinfect 65.61% to 70.88% of the interior surfaces. With each source only drawing approximately 1 amp, a small low emissions low noise generator of less than 1000 Watts could be used. For the purposes of our testing the research team used a 3250 Watt generator. During the testing, we measured 453 Watts of power draw for three UV sources. This implies that even at 50% load the generator could be used to simultaneously disinfect three buses (9 UVC sources) depending on the UVC source selected. As per the generator specifications, 3.5 gallons of fuel will provide 9.7 hours of operation at a 50% load. This supports the scenario of staging the next bus while still UVC disinfecting the previous bus – i.e. setup, run for required duration, start setup on next bus while first is disinfecting, start disinfection on second bus, take down from first and move to third, and so on. A small generator and single nightly refueling could support an employee to disinfect two or three buses simultaneously.

[3250 Watt generator / 453 Watts for three UVC sources * 0.50 for 50% load = 3.6 sets of equipment] Roughly 3 buses at same time

Power can be delivered from the generator to the bus interior via extension cords. It is recommended to select a 50-ft length with a heavy 12-gauge wire to accommodate a 15 amp draw terminating in at least 3 outlets as shown in Figure 86. The cable should be heavy duty, commercial grade, outdoor rated, and preferably yellow in color with lighted LED plug for increased visibility. Furthermore, for ease of use and to assist with the logistics it should be of the auto retracting type for quick grab and go power as well as simple rewind when moving to the next bus.

Figure 86 Example of auto retracting cord reel with 12AWG x 50-ft and triple glow outlets

From the main power supply cord to individual UVC sources - either plug directly into the triple-outlet or use a simple 25-ft manual extension spool as shown in Figure 87 to reach the back of the bus. Since the second reel is to be used inside the bus it will not be subject to as much wear and tear from closing the doors, it can therefore be of lighter grade. Plus, it wouldn't be carrying the full power load so a lighter gauge wire should suffice. Therefore, the first UVC source or two can be plugged into the primary supply cord; while other UVC sources, midway and back of the bus can be plugged into the into the secondary spool.

Figure 87 Example of extension cord reel 25-ft manual hand crank 16/3 AWG

5.2.9 Concept of Operations

The UVC disinfection staff will have a power source (generator) and a rolling cart as shown in Figure 88 with everything required to deploy the UVC source.

- Power source (generator)
- Rolling Cart (see Figure 88 below)
  - Eye protection
  - Disposable gloves
  - UV sources (three UV sources for mini-bus and 4+ for larger buses) with safety chain or cord with hook
  - 50-ft auto retracting cord reel
  - 25-ft manual hand crank cord reel (used for larger buses)
  - Pedestal – to elevate UV source

Figure 88 Rolling cart with UVC sources and supplies

Although unlikely to be exposed to the UVC light, a long sleeve shirt and pants are strongly suggested for the staff. Since the bus has yet to be disinfected, it's therefore implied to have potential risk for exposure of live virus, a face mask should be worn at all times.

The following is a description of the concept of operations for the mini-bus:

- Safety first; put on PPE, specifically eye protection and disposable gloves. Place caution sign in area that warns employees that may be in the vicinity of the UV safety risk and PPE required. Ideally signage "Caution Ultraviolet Light Safety Glasses Required" or similar should be positioned near the doors of the bus being disinfected.

Figure 89 Caution signage warning that safety glasses are required

- Start generator, following all manufacturer instructions.
- Position 50-ft auto retracting cord reel near generator. Plug into outlet and pull several lengths of cord from the reel. Proceed to lay cord on ground leading into the bus and place the 3-outlet just behind driver area.

- UVC Source 1: Retrieve first UV source and carry onto the bus placing it temporarily on the ground near the rear of the bus. *NOTE: It's important to start in the rear of the bus to minimize the potential of bumping into UVC source once placed.* Carefully unwrap the cable and avoid accidentally hitting the bulbs. Carefully lift and invert the source, hanging it from the horizontal grab rail at the permanent etched mark*. Place safety chain/cord around rail and attach hook. Lay cord along windows to avoid trip hazard and then plug it into the 3-outlet cord near driver.

Figure 90 Inverted UVC source positioned near the back of the bus

- Place pedestal on permanent etched mark* on floor across from wheelchair lift. Make sure the pedestal is stable/level and that no debris is under it.
- UVC Source 2: Retrieve second UVC source and carry onto the bus placing it on top of the pedestal near the center of the bus. Carefully unwrap the cable and avoid accidentally hitting the bulbs. Lay cord along windows to avoid trip hazard and then plug it into the 3-outlet cord near driver.

Figure 91 UVC source positioned on pedestal near center of bus

- UVC Source 3: Retrieve third UVC source and carry into the bus placing it temporarily on the ground near the driver area. Carefully unwrap the cable and avoid accidentally hitting the bulbs. Carefully lift and invert the source, hanging it from the hook near the driver area. Attach safety chain/cord to hook. Lay cord out of the walkway to avoid trip hazard and then plug it into the 3-outlet cord near driver.

Figure 92 Inverted UVC source with safety chain

- Proceed to the back of the bus carefully passing the other UVC sources.
- Activate each UVC source starting from the rear and working towards the front. *NOTE: UVC sources should be set with a 45-60 second delay to allow employee time to secure vehicle and exit.*

- Carefully exit the vehicle. Proceed to driver's side, temporarily reentering through driver door to close and secure the main hinged door. Exit the vehicle then lock and close the driver's door to prevent accidental entry.
- Proceed to front of vehicle, through the safety of the windshield visually inspect to ensure all three UVC sources illuminated.

* All locations would be permanently marked/etched to ensure consistency of placement

Figure 93 Illuminated UVC source observed through the windshield

A similar procedure but in reverse was used for removal. Care was taken to ensure that cables were spooled and power cords neatly wrapped in preparation for next use. A comparable procedure was also used for the NABI bus but in that scenario four UVC sources in specific predetermined locations for that bus layout. The following durations were observed for placement and removal of UVC sources, not including the 7-minutes of UVC source run time:

- Mini-bus = setup 5 minutes + take down 3 minutes
- NABI = setup 7 minutes + take down 5 minutes

The research team acknowledges that there would be some variability in the setup and take down times from the field tests.

5.2.9.1 Notes for Pulsed Xenon Source

This report is UVC source agnostic. However, since the research team was only able to identify two potential pulsed UVC vendors, and one of those products was not applicable for buses due to size, specific information regarding operation for the Puro M1-2 unit is included here as reference. The information presented here has been collected during phone interviews with the vendor:

- 30 minutes is the recommended and default disinfection or "run" time. Devices can be pre-set to either 15 or 30-minute operation time. [17]
- 10-15-minute cool down period after each 30-minute disinfection in order to prolong the longevity of the bulbs.[17]
- 30 minutes is the recommended disinfection time for each unit for most pathogens, although 15-20 minutes is likely all that is needed to kill SARS-CoV-2. The full 30 minutes of disinfection provides extra time needed for the areas not receiving direct contact from the light but only receiving contact through reflective light.[17]

Figure 94 Pulsed Xenon UVC source placement on mini-bus

The following durations are estimated for placement and removal of the pulsed Xenon UVC sources, not including **30 minutes of run time**:

- Mini-bus = setup 3 minutes + cool down 15 minutes (can include take down and next bus setup)
- NABI = setup 5 minutes + cool down 15 minutes (can include take down 3 minutes and next bus setup)

5.2.10 Fleet Wide Deployment Cost Comparison

5.2.10.1 Spray and air-dry chemical disinfection

The concentrated disinfectant costs about $9.65 per gallon (possibly will be more expensive in the future with pandemic demand). Manufacturer instructions generally recommend 2 oz per gallon of water; "for use as a one-step, general, hospital disinfectant, fungicide, virucide, cleaner: Pre-clean heavily soiled areas. Apply use solution of 2 oz of this product per gal. of water."[47] Knowing that it takes approximately 50 oz of diluted solution to disinfect a bus (i.e. about 1/3 of a gallon) – the disinfectant cost would be $0.06 per bus.

[$9.65 per gallon / 128 oz per gallon * 2 oz concentrate yields a gallon of solution / 128 oz per gallon * 50 oz used per bus = $0.06 per bus]

Assuming the cost of disinfectant, hand sprayers, supplies, etc. to be comparable to similar consumable items from the UVC disinfection scenario, the labor + UVC equipment would become the main factors.

NJ TRANSIT estimates that it takes a single employee approximately 2 minutes for a mini-bus and 3 minutes per 40-ft bus to disinfect via the spray chemical disinfectant application. Using 5 minutes as a more conservative estimate indicates that each disinfection employee would be able to disinfect twelve 40-ft buses per hour.

[60 minutes per hr / 5 minutes per bus = 12 buses per hour]

For the purposes of this analysis the rate for full sized buses was used throughout for all scenarios. There will be some error as the mini-buses are quicker to disinfect, but the articulated-buses will take longer to disinfect. This applies the error uniformly as to cause minimal impact to the overall comparison.

Validation of estimates; one of the NJ TRANSIT garages currently contracts COVID disinfection efforts which provides a precise estimate of the time required. It has been found that "with 3 staff, sometimes 4 employees, they average 164 to 174 buses a night between 8pm to 1pm"[48] Therefore the range would be between 8.2 and 11.6 buses per hour. On average this is approximately 10 buses per hour, which is slightly less than the previous estimate. Therefore, for analysis purposes the 10-buses per hour average rate was used to make the analysis more accurate.

Worst case [164 buses / 4 employees / 5 hours = 8.2 buses per hour]

Best case [174 buses / 3 employees / 5 hours = 11.6 buses per hour]

Average [(8.2 + 11.6 buses per hour) /2 = 9.9 buses per hour] roughly 10 buses per hour

Using the same 7-hr shift (approximate effective time for 8-hr shift less lunch and breaks) requirement as the UVC scenario - to disinfect all the 40-ft buses in a 200-bus garage in a 7-hour shift, would require 2.1 fulltime equivalent staff dedicated to disinfection.

[200 buses per garage / 10 buses per hour / 7-hr shift per staff = 2.86 staff] NOTE factor of safety assume 3 FTE

This estimate is probably deemed accurate as it is close to real-world observations from the garages with the extra COVID disinfection effort. Thus, for all 16 garages this would be approximately 48 dedicated disinfection staff. The three staff per garage estimate was confirmed with NJ TRANSIT as an accurate assessment of the increased labor requirement since COVID-19 began.

[3 staff per garage * 16 garages = 48 total staff]

- 48 dedicated disinfection staff
- disinfectant cost $0.06 per bus
- hand sprayers, PPE supplies, and other consumables assumed to be roughly comparable to similar items from other scenarios

5.2.10.2 Mercury UVC Disinfection

Each disinfection employee would likely be able to disinfect buses by staggering setup, disinfection, and take down for a maximum rate of approximately five 40-ft buses per hour or seven mini-buses per hour. The rate that buses can be treated would be roughly the same regardless of size because the UVC disinfection time relationship depends on the number of UVC sources deployed based on size.

[7 minutes setup + 7 minutes disinfection + 5 minutes removal = 19 minutes per bus] [60 minutes per hour / 19 minutes per bus *2 staggered staging -1 incomplete bus = 5 full sized buses per hour]

[5 minutes setup + 7 minutes disinfection + 3 minutes removal = 15 minutes per bus] [60 minutes per hour / 15 minutes per bus *2 staggered staging -1 incomplete bus = 7 mini-buses per hour]

As previously stated, for the purposes of the analysis the rate for full sized buses was used throughout for all scenarios. There will be some error as the mini-buses are quicker but the articulated buses will take longer to setup. This applies the error uniformly as to cause minimal impact to the overall comparison.

During field testing, the power draw for three UVC sources was measured at 453 Watts of power. Using the building's outlets as the source of power at an approximate cost of $0.19/kW-hr would results in a cost of $0.01 per bus.

[453 Watts * 7 minutes / 60 minutes per hour / 1000 W per kW * $0.19 per kW-hr = $0.01 cost of electricity per bus]

Alternatively, gas to run the generator for UVC disinfection would be nominal. Assuming three buses simultaneously disinfected with gas costing approximately $2/gallon and the generator running constantly during setup, disinfection, and removal for about 20 minutes per bus; at the consumption rate for 50% load stated above results in approximately $0.14 per bus.

[3250 Watt generator at 50% load = 1625 Watts < 453 Watts * 3 simultaneous buses = 1359 Watts] [3.5 gallons of fuel will provide 9.7 hours of operation at a 50% load] [3.5 gallons / 9.7 hours *$2 per gallon / 5 buses per hour = $0.14 per bus]

Furthermore, to disinfect all the 40-ft buses in a 200-bus garage in a 7-hr shift (approximate effective time for 8-hr shift less lunch and breaks) would require 6 fulltime equivalent staff dedicated to disinfection.

[200 bus garage / 5 buses per hour / 7-hr shift = 5.71 FTE] NOTE factor of safety assume 6 FTE

This estimate is probably low as it doesn't account for downtime and requires staff to be 100% productive for the entire shift. Ultimately it might be closer to six personnel. For all 16 garages this would be approximately 96 dedicated disinfection staff.

[16 garages * 6 FTE = 96 staff]

From an equipment perspective, to stagger disinfection it would require eight UVC sources to equip each of the six-staff identified, which results in 48 UVC sources per garage.

[8 UV sources * 6 staff = 48 UVC sources]

This automatically provides some equipment redundancy because some buses only require three sources. Furthermore, for all 16 garages this would be approximately 768 UVC sources.

[16 garages * 48 UVC sources = 768 sources]

From the catalog of UVC products there are any number of UVC units in the $2250 to $6550 range that might be appropriate. Using $4,400 as an estimate the expected capital expenditure before considering carts, generators, and extension cords would be roughly $3.4M in UVC sources.

[768 UVC sources * $4,400 = $3,379,000]

- 96 dedicated disinfection staff
- 768 UVC sources at an estimated at $3.4M
- Cost of generator fuel or electricity less than $0.14 per bus
- Support items including carts, generators, extension cords, bulb replacement (less than $70 each), and other expenses were not included at this time
- PPE supplies and other consumables assumed to be roughly comparable to similar items from other scenarios

5.2.10.3 Pulsed Xenon UVC Disinfection

For pulsed Xenon UVC sources, it was estimated that for a full-size bus using three UVC sources that the operational protocol would require 5 minutes setup + 30 minutes disinfection + 15 minutes cool down (which can also serve as 3 minute removal as well as the 5 minute setup time for the next bus). The research team reviewed the timing to develop a process that minimizes labor while maximizing one-time capital equipment costs. The research team acknowledges that this may not be the optimum cost-benefit scenario, but it minimizes labor with the assumption that capital is recouped over several years. See Figure 95 for a Gantt Chart representing a potential worker schedule for the pulsed sources. After thoroughly reviewing the timing, the research team estimates that over a 7-hr shift a single employee can stage and disinfect 42 buses (averaging six buses per hour) by rotating 21 pulsed UVC sources.

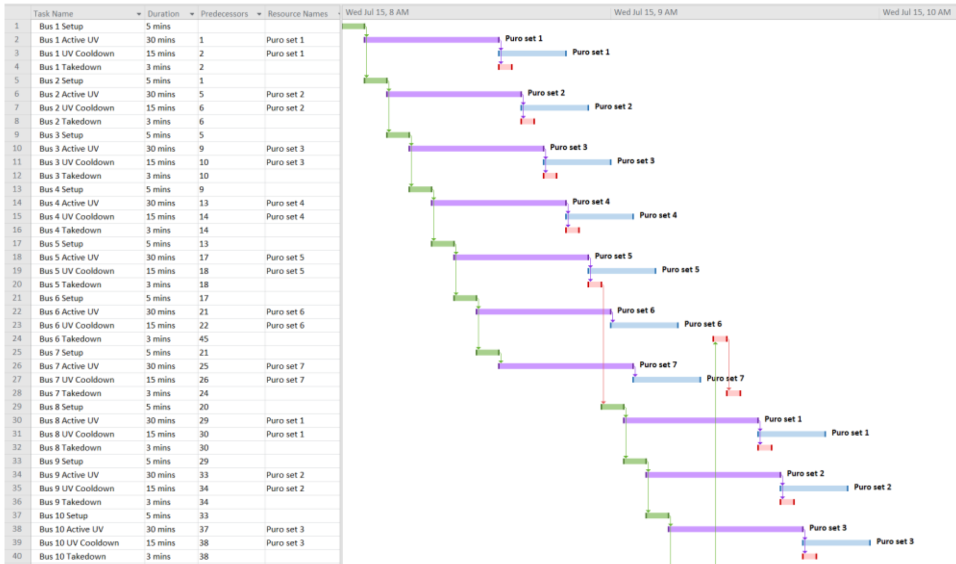

Figure 95 Gantt Chart for setup, run, removal of pulsed UVC sources - full chart shows 42 buses per shift which averages to 6 per hour

Furthermore, to disinfect all the 40-ft buses in a 200-bus garage in a 7-hr shift (approximate effective time for 8-hr shift less lunch and breaks) would require 5 fulltime equivalent staff dedicated to disinfection.

[200 bus garage / 42 buses per employee = 4.76 FTE] NOTE factor of safety assume 5 FTE

For all 16 garages this would be approximately 96 dedicated disinfection staff.

[16 garages * 5 FTE = 80 staff]

From an equipment perspective, to stagger seven sets (3 pulsed UVC per bus) disinfection it would require 21 pulsed UVC sources to equip each of the 5-staff identified which results in 105 UVC sources per garage.

[21 UV sources * 5 staff = 105 UVC sources]

This automatically provides some equipment redundancy because some buses only require three sources. Furthermore, for all 16 garages this would be approximately 768 UVC sources.

[16 garages * 105 UVC sources = 1,680 sources]

From the catalog of UVC products the pulsed UVC sources cost $6550. Therefore, the expected capital expenditure before considering carts, generators, and extension cords would be roughly $3.4M in UVC sources.

[1,680 UVC sources * $6,550 = $11,004,000]

- 80 dedicated disinfection staff
- 1,680 UVC sources at an estimated at $11M
- PPE supplies and other consumables assumed to be roughly comparable to similar items from other scenarios

5.2.10.4 Cost Comparison Discussion

In comparison to spray and air-dry disinfection cost analysis – there would be a substantial increase in staffing and capital expenditure required for UVC deployment; a detailed analysis including support items such as carts, generators, extension cords, bulb replacement (less than $70 each), and other expenses was not performed. Although valuable for budget planning, it's clear that from a macro perspective the overall cost for UVC disinfection would be substantially more than chemical disinfection.

- 48 dedicated staff for chemical disinfection versus 96 and 80 dedicated staff for Mercury and pulsed Xenon UVC respectively
- Equipment cost for UVC far exceeds hand or backpack sprayers
- PPE supplies and other consumables assumed to be roughly comparable to similar items from other scenarios

The research team acknowledges that there would be some variability in the setup and take down times from the field tests. However, this same variability would exist with the chemical disinfectant application too.

Furthermore, testing and analysis was performed using a bus configuration with a fairly open floor plan. It can reasonably be assumed that the overall effectiveness of UVC disinfection for a coach bus would be somewhat less effective. Furthermore, since the labor + equipment of UVC for surface disinfectant exceeded the labor time for the chemical disinfectant for an open floorplan, it is also reasonable to expect the labor + equipment to be equal to if not great for a coach bus. As the bus configuration is more complex the UVC disinfection becomes even less practical.

Efficacy being assumed to be roughly equivalent - the research team only envisions one circumstance where the UVC labor component would be roughly equal to chemical application for fleet wide deployment:

- If the chemical application method was substantially different such as spray and wipe as opposed to spray and air-dry. As per the manufacturer instruction "wipe dry with a clean cloth or allow to air dry."[47] The spray and wipe method would substantially increase the labor time by as much as double. The spray and air-dry method is compliant with the manufacturer instruction but NJ TRANSIT may consider that during a weekly spray and wipe cleaning to perform a more thorough cleaning and to remove any build-up.

Efficacy being assumed to be roughly equivalent - the research team only envisions one circumstance where the UVC labor component would be less than chemical application for fleet wide deployment:

- If the bus were to have permanently mounted UVC disinfection installed. This is probably not practical as a retrofit. At this time, the research team was unable to identify any permanent retrofit efforts for UVC surface disinfection by other agencies or companies. However, built in permanently mounted UVC is something that could be considered as a future requirement for the next generations of buses. In that scenario, more lights can be built-in and evenly distribute irradiance throughout the cabin and even cover more shadowed areas. The source may very well be small UVC LEDs throughout the bus shell, ceiling, and floor area. The increased capital expense may even be recouped by labor savings.

5.2.10.5 Bulb life cycle cost

If NJ TRANSIT were to adopt a portable UVC disinfection device there would be a number of life cycle costs such as electricity, repair, full unit replacement, and bulb replacement, as well as additional peripherals including but not limited to extension cords, carts, storage racks, and possibly generators. Also, since the bulbs don't have a protective lens it may be necessary to clean the bulbs to remove dust that accumulates over years of use and storage in a garage environment.

After the initial purchase, the most substantial life cycle cost beyond device replacement would be bulb replacement. As per Phillips website, a typical UVC Mercury bulb has a 9000 hour useful operational life.[49] However, each UVC device may have different sized bulbs or may require 3, 4 or even 8 bulbs – therefore the lifecycle cost is also highly variable and dependent of the final device selected. The previously documented efforts of this research project were largely based on small portable UVC source characteristics independent of a specific vendor. However, using a representative device to provide an estimate life based on four TUV PL-L 35W bulbs can be calculated, which will be consistent with the previously referenced UVC source quantities. Based on the operational profile discussed earlier, a 9,000-hour bulb life should last for six years of use.

[5 buses per hour * 7 hour shift * 7 minutes per bus = 245 minutes on-time per night]

[9,000 hours * 60 minutes per hour / 245 minutes on-time per night / 365 days per year = 6 years between each bulb replacement]

Replacement bulbs are estimated at approximately $70 per bulb but can likely be found for less from other third-party suppliers or via bulk purchasing. However, using $70 per bulb, the total cost to replace all of the bulbs within the estimated 768 devices (four bulbs per device) is approximately $215k every six years.

[768 UVC sources * 4 bulbs per unit * $70 per bulb = $215, 040 every six years]

- Approximately $215k will be required every six years to replace all Mercury bulbs at 9,000 hours useful life per bulb

5.3 HVAC and Disinfection of Air

The previous sections of this report addressed portable UVC sources for surface disinfection. This section of the report addresses air treatment and disinfection techniques. Air treatment is an important aspect of a broader strategy to manage exposure to COVID-19 and minimize risks for employees and passengers while the vehicles are in-service.

Recent briefings by the World Health Organization (WHO) suggests that COVID-19 is primarily transmitted through respiratory droplets, but also suggests that aerosolization is another possible mode of transmission.[50] These respiratory droplets can be expelled when a person coughs, sneezes, talks or sings.[51] Particles in the range of >5-10 μm diameter are considered respiratory droplets, while particles <5μm in diameter are considered aerosols.[52] The WHO has also suggested that airborne transmission of the virus may also be possible within indoor crowded spaces citing examples such as choir practice, inside restaurants, or attending a fitness class.[50] There have documented cases of COVID-19 transmission reported in enclosed spaces such as restaurants, nightclubs, and work. Droplet transmission within these environments is certainly a concern. WHO also mentions that aerosol transmission of the virus cannot be ruled out in these crowded inadequately ventilated spaces where infected persons may spend long periods of time with others.[53]

While there have only been limited cases specifically attributed to transit bus ridership, it may be inferred that having people in close proximity in an enclosed place such as a bus may put them at increased risk for airborne transmission of the virus. Certain countermeasures can be taken by transit agencies that may decrease risk of spreading the virus on vehicles. WHO has stated that more studies are urgently needed to investigate the significance of instances of potential airborne transmission happening outside of health care settings.[50] Furthermore, bus drivers could potentially be at greater risk than a transit passenger simply due to them being in an enclosed space longer. The Centers of Disease Control and Prevention (CDC) primarily endorses the use of cloth face coverings to help slow the spread of COVID-19,[54] they have also prepared a list of preventative measures specific to bus transit operators that can reduce their risk of infection.[55] This include the following items that are specific to exposure via reparatory or aerosol transmission:

- "Limit close contact with others by maintaining a distance of at least 6 feet, when possible.
- Consider asking bus passengers to enter and exit the bus through rear entry doors.
- Request passengers avoid standing or sitting within 6 feet of the bus driver."[55]

While all of the above precautions will likely reduce the chance of infection, other more proactive measures can be implemented on buses to passively treat the air. The research team has identified the following broad categories of air treatment/disinfection practices and technologies that may reduce exposure risk related to COVID-19:

- Increase fresh air and ventilation
- Upgrade HVAC air filters
- Installation of HVAC in-duct systems:
    - UV disinfection systems
    - Ion generator systems
    - Photocatalytic oxidizer systems

However, each of the aforementioned practices and technologies have their own advantages and disadvantages. The use of in-duct systems requires balancing numerous factors including: air flow velocity impacting disinfection contact time or even worsening the spread of virus, airflow restrictions impacting HVAC performance and equipment damage, release of disinfection agents at concentrations too low to be effective, and introduction of agents into breathing areas at a concentration too high to be deemed safe. With over 3,700 vehicles in NJ TRANSIT's fleet, the deployment of any new technology must be carefully weighed to ensure it safely achieves the desired results.

5.3.1 Fresh Air Exchanges and Power Vents/Hatches

There has been some discussion in the literature about shutting off HVAC systems. For example, one media outlet indicated that "During the epidemic period, it is not recommended to use air conditioning for vehicles. It is recommended to open windows for ventilation or use skylight exhaust fans to achieve the effect of rapid air exchange in the compartment."[56] Other articles referenced a Chinese restaurant where the spread of the virus was reportedly linked to the air-conditioning system, suggesting that such systems should be disabled.

The research team did indeed find reputable sources (CDC) **advising against recirculation mode** - but could not identify any research to support turning HVAC systems off.

For example, in May 2020 in response to the Chinese restaurant incident, Carrier released a white paper clearly stating that proper air management is essential and that the HVAC system should be used to introduce fresh air and provide filtration.[57] However, the paper also cautioned "that the **increase of the ventilation rate may cause an increase of load, and the HVAC unit**, if not properly sized, may not be able to provide sufficient cooling capacity."[57]

CDC guidance would also appear to support the idea of using the air conditioning on non-recirculation mode[58] to try to introduce as much fresh air as possible. CDC guidance for buildings is more comprehensive indicating to increase levels of outdoor air to increase the overall potential COVID-19 dilution,[59] thereby decreasing the potential risk of exposure. CDC also cites and recommends the American Society of Heating, Refrigerating, and Air-Conditioning

Engineers (ASHRAE) Guidance for Building Operations During the COVID-19 Pandemic guidelines for further information on ventilation recommendations.[59]

In agreement with Carrier and CDC guidance; American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) released guidance for mass transit operators, rail, and bus stating "Shutting off HVAC systems in vehicles is NOT recommended because there is no outside air introduction and no air purging. When conditions allow and it will not create safety and passenger comfort issues, the opening of operable windows is an option on some buses (e.g. most school buses) that can greatly increase the flow of air."[60]

Upon review the research team did not find any evidence suggesting that turning off a properly designed air handling system was appropriate. However, it does appear that increasing fresh air changes is advisable; though at minimum it will likely impact to the systems performance possibly to the point of damaging the equipment.

The research team contacted NFI Group. "NFI Parts™ is the parts arm of the NFI Group, providing replacement parts for **New Flyer transit buses, MCI motor coaches**, ARBOC cutaway vehicles, as well as the product lines for the previously acquired **NABI transit bus** and Orion parts businesses." [61]

NFI has a new retrofit kit to replace existing roof hatches with hatches with built in exhaust fans to draw more outside air into the bus see Figure 96. As long as the bus has a 24x24" manual Transpec roof hatch, the retrofit power vented safety roof hatch will replace the OEM part. **Each hatch provides 350 CFM of additional fresh air.** The hatch should be suitable for the NABI, MCI and presumably the mini-buses. The cost of the hatch is $750 but is **sold in pairs of two for $1,250**. **Installation time is approximately 4 hours to install both hatches on the NABI and should be approximately 2 hours for all other single hatch bus types.**

Figure 96 NFI Parts Power Vented Safety Roof Hatch Kit [xxi]

Fresh air enters the bus primarily from the fresh air intake of the HVAC unit as well as opened doors, opened windows, and other various seams. The HVAC is typically a rooftop or rear mounted air-conditioning unit. Some buses may be equipped with automated fresh air dampers. These dampers are particularly useful when trying to minimize energy consumption while heat loads are low. However, by reducing fresh air intake, it increases the amount of air being recirculated within the bus. Therefore, if the bus is equipped with a fresh air damper, they should be positioned to maximize fresh air as conditions permit. [62]

As per the World Health Organization "Increased ventilation rate, through natural aeration or artificial ventilation, preferably without re-circulation of the air."[63] Therefore, based on the premise that air dilution decreases the risk of COVID19 exposure, the research team recommends:

- avoid using recirculation mode on HVAC system,
- ensure HVAC dampers are set to maximize fresh air intake as conditions permit

One potential concern as per Carrier "It is important to manage airflow and airflow velocity in an occupied space. Research and ASHRAE guidelines point to an upper limit of air velocity in an occupied space of 40 fpm. To achieve this condition, the air needs to be properly blown by the HVAC system into the room, and properly distributed in the occupied space."[57] Another study concluded that "droplet transmission was prompted by air-conditioned ventilation. The key factor for infection was the direction of the airflow."[64] This finding, along with Carrier's statement regarding air velocity, should be carefully weighed when considering airflow velocity

[xxi] Photo Credit: Photo by NFI Parts via https://www.nfi.parts/cleanandprotect/

and aerosol distribution of virus within a space. Field tests could be conducted to measure air velocity throughout the bus to ensure that the hatch does not exceed airflow velocity. If 40 FPM at the occupant location is indeed the threshold used for buses too; making an assumption that the vent outlet is about 12" diameter and as per NFI the hatch produces 350 CFM of airflow – this can be used to estimate the outlet velocity at 445 FPM. However, even if it does produce an approximate velocity of 445 FMP, the impact on overall airflow and velocity within the occupied space is unknown.

The NJ TRANSIT fleet is made up of approximately 1600 MCI, 1325 NABI, 85 Articulated, and 500 Minibuses. The NABI and Articulated buses have two hatches each and the rest only have one. Therefore, the approximate cost to upgrade the entire fleet with the power vented roof hatch would be approximately $3.5M requiring nearly 10,000 labor hours.

[(1325 NABI + 500 Minibuses) *$750 = $1,368,750]

[(1325 NABI + 500 Minibuses) *2hrs = 3,650 hrs]

[(1600 MCI + 85 Articulated) * $1250 = $2,106,250]

[(1600 MCI + 85 Articulated) * 4 hrs = 6,740 hrs]

Therefore, along the premise of air dilution decreasing the risk of COVID-19 exposure, the research team finds value in the fresh air hatch <u>contingent upon air flow tests</u>:

- Approximate cost to upgrade the entire fleet with the power vented roof hatch kit would be approximately $3.5M requiring over 10,000 labor hours
- Due to the substantial labor and capital expense; after prioritizing mitigation strategies, the research team recommends the installation of additional fresh air makeup systems such as the power vented safety roof hatch kit, (**each hatch = additional 350 CFM, $750, and 2 hours to install**)
- The power vented roof hatch could be considered as a future requirement for next generations of buses.

Although beyond the scope of this project, it warrants mentioning that air quality is an important consideration for long term outside air exchanges on buses. The terms fresh air and outside air are used interchangeably in this report. However, the reality is that outside air may contain contaminants that are not desired inside the bus. Buses that are in the suburbs would potentially pull in far less atmospheric contaminants than those commuting through congested areas. Likewise, even bus type, such as diesel, may impact the outside air pollutant concentrations. A more detailed testing and monitoring effort may be warranted to verify that by drawing in more outside air, that exposure remains below required thresholds.

5.3.2 Filtration

Increasing the effectiveness of the air filters already being used within a bus's HVAC system can be an inexpensive and quick way to reduce airborne particles throughout the bus. These particles may contain viruses; including aerosolized or even larger sneeze droplets. The use of filtration in HVAC systems is recommended to be used as part of an overall risk mitigation strategy when it comes to the spread of COVID-19 by organizations such as The National Air Filtration Association (NAFA). They also do not regard HVAC air filtration as a solution by itself.[65]

Air filters used in conjunction with HVAC systems are given a Minimum Efficiency Reporting Value (MERV) rating to determine the filters effectiveness at filtering particles of different sizes. The higher the MERV rating of a filter, the higher the particle removal efficiency as illustrated in Table 7.

Table 7 Typical MERV Rating Chart[66]

Standard 52.5 Minimum Efficiency Reporting Value	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	< 0.30 pm particle size	Cleanrooms	≥99.999% eff. On .10-.20 pm Particles
19	n/a	n/a	Virus (unattached)	Radioactive Materials	Particles
18	n/a	n/a	Carbon Dust	Pharmaceutical Man.	Particulates
17	n/a	n/a	All Combustion smoke	Carcinogenetic Materials	≥99.97% eff. On .30 pm Particles
16	n/a	n/a	.30-1.0 pm Particle Size	General Surgery	**Bag Filter**- Nonsupported microfine fiberglass or synthetic media, 12-36 in. deep, 6-12 pockets
15	>95%	n/a	All Bacteria	Hospital Inpatient Care	
14	90-95%	>98%	Most Tobacco Smoke	Smoking Lounges	**Box Filter**- Rigid Style Cartridge Filters 6 to 12" deep m ay use lofted or paper media.
13	89-90%	>98%	Proplet Nuceli (Sneeze)	Superior Commercial Buildings	
12	70-75%	>95%	1.0-3.0 pm Particle Size Legionella	Superior Residential	**Bag Filter**- Nonsupported microfine fiberglass or synthetic media, 12-36 in. deep, 6-12 pockets
11	60-65%	>95%	Humidifier Dust Lead Dust	Better Commercial Buildings	
10	50-55%	>95%	Milled Flour Auto Emissions	Hospital Laboratories	**Box Filter**- Rigid Style Cartridge Filters 6 to 12" deep m ay use lofted or paper media.
9	40-45%	>90%	Welding Fumes		
8	30-35%	>90%	3.0-10.0 pm Particle Size Mold Spores	Commercial Buildings	**Pleated Filters**- Disposable, extended surface area, thick with cotton-polyester blend media, cardboard frame
7	25-30%	>90%	Hair Spray	Better Residential	**Cartridge Filters**- Graded density viscous coated cube or pocket filters, synthetic media
6	<20%	85-90%	Fabric Protector Dusting Aids	Industrial Workplace	**Throwaway**- Disposable synthetic panel filter.
5	<20%	80-85%	Cement Dust Pudding Mix	Paint Booth Inlet	
4	<20%	75-80%	>10.0 pm Particle Size Pollen	Minimal Filtration	**Throwaway**- Disposable fiberglass or synthetic panel filter.
3	<20%	70-75%	Dust Mites Sanding Dust	Residential	**Washable**- Aluminum Mesh
2	<20%	65-70%	Spray Paint Dust		**Electrostatic**- Self charging woven panel filter.
1	<20%	<65%	Textile Fibers Carpet Fibers	Window A/C Units	

As far as effectiveness of the filters when it comes to protection from COVID-19, NAFA states that “low-efficiency filters (e.g., **less than MERV-8** according to ASHRAE Standard 52.2 or less than *e*$PM_{2.5}$ 20% according to ISO 16890-1:2016) **are very unlikely to make a difference**”.[65] They also state that while properly installed higher efficiency filters can remove relevant sized particles based off of the filters’ efficiency, current information on COVID-19 virus does not allow for specific recommendations at this time.

As per the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) “SARS-CoV-2 virus is around 0.1 µm. However, the virus does not travel through the air by itself. Since it is human generated, the virus is trapped in respiratory droplets and droplet nuclei (dried respiratory droplets) that are predominantly 1 µm in size and larger.”[67] This aligns with guidance from WHO “Transmission of SARS-CoV-2 can occur through direct, indirect, or close contact with infected people through infected secretions such as saliva and respiratory secretions or their respiratory droplets, which are expelled when an infected person coughs, sneezes, talks or sings. Respiratory droplets are >5-10 µm in diameter whereas droplets <5µm in diameter are referred to as droplet nuclei or aerosols.”[50] Ultimately ASHRAE and the United States Department of Energy (DOE), both recommend installing filters with a minimum of MERV 13, with MERV 14 filters being even better, and High Efficiency Particulate Air (HEPA) filters being the preferred choice.[68] (find original source for this). **ASHRAE recommends improvement of the HVAC filter to MERV 13, or the highest compatible with the filter rack.**[69] This recommendation is general and although it applies to HVAC systems it’s probably more applicable for buildings than specific applications such as buses.

- Virus infected respiratory droplets are >5-10 µm[50] and droplet nuclei are <5µm[50] (dried respiratory droplets). In general, a 1 µm in size and larger threshold is commonly cited and used as a reference point for filtration requirements.
- MERV 8 filter, which is at least 20% efficient at capturing particles in 1 µm to 3 µm [67]
- MERV 13 filter, which is at least 85% efficient at capturing particles in 1 µm to 3 µm[67]
- MERV 14 filter, which is at least 90% efficient at capturing particles in 1 µm to 3 µm[67]
- HEPA filter, which is at least 99.97% efficient at capturing particles 0.3 µm or greater[70]

However, increasing the air filter to a higher MERV rating also increases the pressure drop within the HVAC system and can ultimately damage the system. HEPA type filters are regarded as being one of the most efficient filter types, with the ability to even filter out the smallest particles. Unfortunately, as filters approach HEPA level filtration they become impractical as a retrofit as these systems were never designed for the substantial decrease in airflow. The APTA whitepaper on disinfection generally suggested to use filters with MERV ratings no higher than MERV 10 - presumably without airflow testing. “It is not feasible in most cases to simply add higher-efficiency filtration to systems not originally designed for the associated pressure drop, as this can result in reduced performance and potential equipment damage. Ventilation and airflow testing of the vehicle or facility HVAC system is encouraged, to determine whether any increase in MERV rating can be accommodated."[10] Another potential disadvantage of increasing the MERV rating is that the filters may load with dust and particles more quickly, requiring more frequent filter changes.[65]

It should be noted that during this study, NFI Group Inc. began offering a MERV 12 filters, however as of August 2020 has since discontinued offering filters above MERV 8. Upon inquiry, no information was provided about the discontinuation of the higher-grade filters. The research team surmises that it's either due to lack of product availability or the improper match with most bus HVAC pressure/flow requirements.

In addition to traditional MERV rated filters, specialty antimicrobial filters can be added alongside the MERV filters. These thin antimicrobial layers in theory break down and inactivate viruses passing through them by using silver and copper embedded within the media which react with and sterilize the virus. Studies have also shown higher filtration efficiency and delayed deterioration of the filter.[71] Further investigation into the efficacy of these antimicrobial filters are currently being tested by transit agencies.[10] EPA guidelines must be met for the antimicrobial product to be used and the product must have data proving the claim. Copper is a well-established and is an EPA approved biocidal antimicrobial material. However, the specific efficacy as filter is unclear, it is suggested that copper and other chemical antimicrobial additives will inactivate the virus in hours instead of days.[72],[73] Nonetheless, it is unclear if the antimicrobial layer aids in disinfecting the air or if it simply prevents colonization on the filter media itself. The efficacy for specific products was not confirmed as part of this review. Although efficacy remains uncertain the research team does not have any health concerns at this time and recommends adopting antimicrobial filters. Since other techniques will take months to adopt and retrofit, given the rapid deployment, at a minimum the antimicrobial filter should help maintain the efficiency of the filter longer and have some virus reducing impact, even if it's only within the filter media. However, future testing to determine the efficacy is needed. Furthermore, given the sizeable year-over-year cost, reevaluation is needed as NJ TRANSIT adopts other technologies which may negate the benefit from the antimicrobial layer.

The NJ TRANSIT fleet is made up of approximately 1600 MCI, 1325 NABI, 85 Articulated, and 500 Minibuses. As shown in Figure 97; NFI has evaluated the flow rate for MCI buses and determined that "Flow-rate tested and approved for MCI brand. Coach applications - will not harm fan motor. No modifications needed - no need for filter frame reconstruction, can be cut and installed in existing filter assemblies"[74] NFI recommends a 3-month replacement schedule.

- MERV 7 filter: $57 for 90-ft roll (assume the current MERV 5 filters roughly the same cost as MERV 7)[75]

- MERV 8 filter: $200 for 90-ft roll
- Antimicrobial MERV 8 add-on: $800 for 90-ft roll

Therefore, the additional cost (above the existing filters) to upgrade the MCI portion of the fleet would be approximately an extra $102,688 per year MERV 8 or $670,578 per year with the MERV 8+ antimicrobial and would not require any additional labor if done with corresponding next filter replacement schedule. Although, the research team doesn't have enough performance data to recommend this filter for the rest of the fleet; if it were deployed across the entire fleet it would be approximately an extra $162k per year for MERV 8 or $1.1M per year for the MERV 8+ antimicrobial.

[1600 MCI *($200 - $57) *4 replacements per year * 10-ft per bus / 90-ft per roll = $101,688 per year EXTRA cost]

[1600 MCI *($200 + $800 - $57) *4 replacements per year * 10-ft per bus / 90-ft per roll = $670,578 per year EXTRA cost]

[1910 NABI + Artic + Mini-bus fleet *($200 - $57) *4 replacements per year * assumed average 5-ft per bus / 90-ft per roll = $60,695 per year EXTRA cost] reference only, known error regarding the filter length required

[1910 NABI + Artic + Mini-bus fleet *($200 + $800 - $57) *4 replacements per year * assumed average 5-ft per bus / 90-ft per roll = $400,251 per year EXTRA cost] reference only, known error regarding the filter length required

Figure 97 NFI MERV 8 filter with antimicrobial approved for MCI[74, xxii]

[xxii] Photo Credit: Photo by NFI Parts via https://www.nfi.parts/cleanandprotect/

It's clear that upgrading to a MERV 8 filter alone will help reduce exposure risk - but it's not sufficient to remove a majority of virus particles. Based on the consensus of several organizations' recommendations; the research team suggests that:

- If system performance permits that the HVAC should be upgraded to MERV 13 or better filter, or the highest compatible filter at a minimum MERV 8 or even MERV 8 with antimicrobial layer
- **More than likely - if the HVAC cannot be upgraded to MERV 13 or better either due to filter availability, lack of pressure testing data, or overall HVAC system inability; it's highly-recommended to further investigate and incorporate an in-duct system such as in-duct UVC system along with at a minimum MERV 8 filter.**
- At this time NFI has "Flow-rate tested and approved for MCI brand coach applications - will not harm fan motor" the MERV 8+antimicrobial; this would be an extra $670,578 per year beyond what NJ TRANSIT currently spends on filters. This retrofit would not require any additional labor if done with corresponding next filter replacement schedule.
- If it is possible to deploy MERV 8 uniformly across the entire fleet, the approximate added cost might be in the range of an extra $162k per year for MERV 8 or $1.1M per year for the MERV 8+ antimicrobial. (in addition to current filter costs and with known errors in the estimate mentioned above) Although the antimicrobial efficacy remains uncertain the research team does not have any health concerns at this time and recommends adopting antimicrobial filters. However, future testing to determine the efficacy is needed. Furthermore, given the sizeable year-over-year cost, reevaluation is needed as NJ TRANSIT adopts other technologies which may negate the benefit from the antimicrobial layer.
- If MERV 13 or better is achievable; an in-duct system would still add value but might be considered recommended or supplemental.
- It is recommended that future bus designs accommodate MERV 13 or better filters.

Some transit agencies such as SEPTA have already begun replacing HVAC filters in their transit vehicles with higher rated MERV filters. Many of their bus filters have already been upgraded to a MERV 8 rating with plans to evaluate air flow to upgrade to a MERV 14 in the future, while their rail vehicles have already been slated to be upgraded to a MERV 14 filter.

Removal and replacement of a used filter is also an important consideration as it's reasonable to assume that the filter will have some virus material present. Employees should exercise caution and follow established recommendations for replacement to manage health risks. ASHRAE has recommended that for each filter replacement the personnel changing them wear proper PPE while doing so. It is also recommended that spent filters be sealed in plastic bags for disposal.[69] The following ASHRAE guidelines highlight proper HVAC system maintenance and filter replacement during the COVID-19 pandemic:

- *For HVAC systems suspected to be contaminated with SARS-CoV-2, it is not necessary to suspend HVAC system maintenance, including filter changes, but additional safety precautions are warranted.*
- *The risks associated with handling filters contaminated with coronaviruses in ventilation systems under field-use conditions have not been evaluated.*
- *Workers performing maintenance and/or replacing filters on any ventilation system with the potential for viral contamination should wear appropriate personal protective equipment (PPE):*
- *A properly-fitted respirator (N95 or higher)*
- *Eye protection (safety glasses, goggles, or face shield)*
- *Disposable gloves*
- *Consider letting the filter load up further than usual to reduce frequency of filter changes.*
- *Don't let pressure drop increase enough to disrupt room pressure differentials.*
- *Confirm filters remain snug in their frames.*
- ***When feasible, filters can be disinfected with a 10% bleach solution or another appropriate disinfectant, approved for use against SARS-CoV-2, before removal. Filters (disinfected or not) can be bagged and disposed of in regular trash.***
- *When maintenance tasks are completed, maintenance personnel should immediately wash their hands with soap and water or use an alcohol-based hand sanitizer.*[76]

5.3.3 In-duct UVC Technologies

As discussed earlier in this report, UVC has been shown to kill viruses. Based on this principle, UVC has also been installed in HVAC systems. Conceptually UVC can be used to disinfect surfaces within the HVAC system such as coils, ducts, etc but also the air passing through the system. The low absorption coefficient of air allows for UVC light to deactivate viruses as well as kill other airborne pathogens.

Although not practical for buses its worth mentioning that other than in-duct UVC there is also upper air UVC technology, where UVC light irradiates the air in the upper portions of a room. This form of UVC air disinfection follows that same concepts of in-duct UVC except that the UVC light fixtures are open to the upper portion of a high-ceiling room instead of hidden within the ductwork of the HVAC system. This allows for disinfection of air circulating through the room's upper ceiling area while shielding the lower areas of the room, eliminating exposure to the people below. This is probably not feasible for a bus due to low ceiling height.

While HVAC in-duct UVC lamps are more common in a building's HVAC system, smaller units using the same core concepts have also been designed for use with buses. Having the UVC light confined to only the space within the duct work of the vehicle's HVAC system allows for such lamps to disinfect the air while passengers are on-board. In order to ensure rider safety, in-duct UVC systems need to be carefully designed such that all light emitted from the bulbs are fully enclosed with no light bleed.

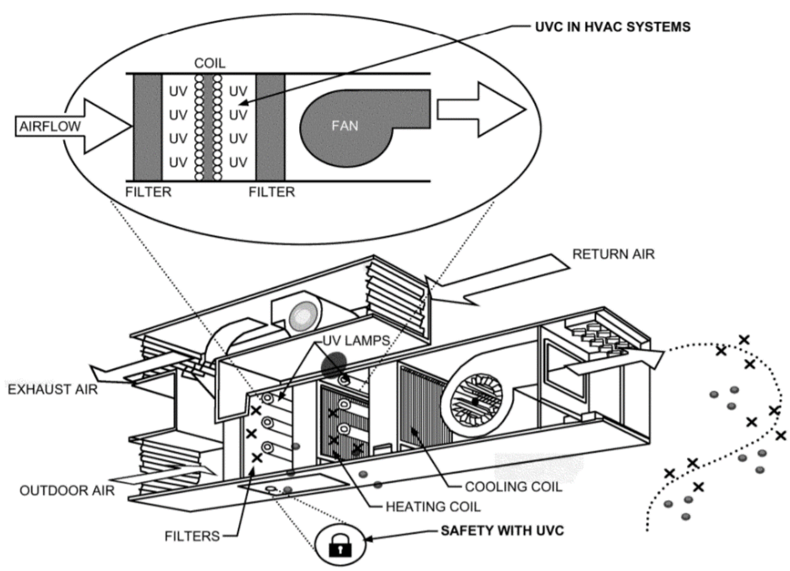

Figure 98 Example UVC air cleaning process within a building's HVAC system (ASHRAE).[77], [xxiii]

[xxiii] Photo Credit: Image by ASHRAE via https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_a19_ch62_uvairandsurfacetreatment.pdf

Placement of UVC lamps directly behind wet or damp areas inside the HVAC system such as the cooling coils and drain pans has been shown to significantly reduce the build-up of bacteria and mold-containing biofilms in these areas and is an ideal location for the lamps[78]. Outside of air disinfection, some installed UVC lamp systems within large buildings have been placed specifically to irradiate these coils with mold killing properties in mind. Ideally, bulb placement on a transit vehicle would be located in an area that could provide proper irradiation to the HVAC coils to prevent any biofilm buildup as well as sufficiently provide enough dwell time for any airborne particles to be treated while passing through the irradiated area.

When it comes to the effectiveness of in-duct UVC in the treatment and disinfection of moving air-streams, laboratory studies have concluded that this form of UVC technology is effective.[79] [80] The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development's National Homeland Security Research Center (NHSRC) funded a study of UVC for in-duct systems in 2006. "The objective of testing the device was to evaluate its bioaerosol inactivation efficiency as a heating, ventilation, and air-conditioning (HVAC) in-duct ultraviolet light system. [sic] The bioaerosol inactivation efficiencies calculated for the three organisms were 96% for B. atrophaeus, 99.96% for S. marcescens, and 99% for MS2."[81] It should be noted that these studies took place on a larger scale duct system such as one which would be more commonly found within a building and not on a smaller scale system similar to a bus.

While these studies show that the concept of using UVC to disinfect HVAC airstreams works, agencies such as ASHRAE are not currently making any recommendations for or against the use of UVC disinfection within air systems.[62] Other organizations such as the CDC have published studies which approve the use of UVC used in conjunction with proper filtration for the reduction of infectious diseases such as tuberculosis in a published guideline on the technology's application.[82] However, it should also be noted that these studies focused on "upper-room" UVC to disinfect the air-streams. **While in-duct UVC has been more widely used within building HVAC systems, their evaluation for use within bus HVAC systems is less documented.**

As per ASHRAE "In-duct air disinfection systems should be designed to have the desired single-pass inactivation level under worst-case conditions of air temperature and velocity in the irradiated zone."[77] Furthermore, ASHRAE recommends that in-duct systems should provide a minimum of 0.25 s of exposure in order to minimize system power consumption.[77] Based on compact size of a bus HVAC system and the air velocity it is highly unlikely that a 0.25s exposure time can be obtained nor an overall exposure time to achieve a single-pass inactivation. Therefore, the single-pass inactivation concept is likely the biggest argument against adopting in-duct UVC technology on a bus. Without a single-pass dosage being delivered, it is unknown how repeated dosages at different time intervals will impact the UVC kill-dosage required. This is likely why ASHRAE does not currently recommend using UVC light as a disinfecting agent within a transit vehicle's HVAC system due to concerns that pathogens passing through the system may not obtain proper exposure durations due to the UVC light's shorter dwell time in these smaller HVAC systems.[60] However, with an estimated rate of one air exchange per minute typically found on NJ TRANSIT buses, air passing through the irradiated area of the of the HVAC system will be treated with a dose of UVC light roughly once a minute. Depending on the intensity of the bulbs being used and the length of the irradiated area, the dwell time of the air passing through that area of the HVAC system can be calculated to determine how many Joules of energy are delivered on each pass. Even though there is an efficacy uncertainty, there has been support for in-duct UVC systems on buses[84], and some transit findings include:

- Dallas Area Rapid Transit (DART) had already installed internal HVAC UV systems on 70% of their buses prior to the COVID-19 epidemic.[9] The research team reached out to DART who confirmed that 77% of their buses have the SanUVaire product installed. DART has relied on the vendor claims and has not conducted efficacy testing. The vendor claims that it will reduce the requirement to clean the evaporator coil, and DART has observed that the coils are very clean. DART has also conducted fleet reliability studies and the HVAC systems are generally top performers; this implies that they are indeed effective in reducing maintenance costs.[83] In summary, DART has deployed in-duct UVC since 2013 with no major logistics concerns.
- A Federal Transit Administration (FTA) funded study by the Transportation Research Board (TRB) "Ultraviolet Germicidal Irradiation for Transit Buses" Transit IDEA project #53 of 14 Houston Metropolitan Transit Authority buses investigated the benefits of such UVC systems on transit buses.[84] The study ultimately found that the addition of an in-duct UVC system installed behind the heater coil would increase system efficiencies and reduce airborne pathogens. Depending on the age and model of the bus being evaluated, the UVC system was found to increase airflow by reducing mold and fungi built up around the evaporator anywhere from 23% to 31%, and increase temperature efficiencies by 9.4% to 19.4%, resulting in better cooling and lower maintenance costs for the bus's air conditioning system. The pathogen tests resulted in a 95% to 99% reduction in mold, fungi, and bacteria on the buses, and a 99% reduction in common viruses.[84] "to test the effectiveness of the UVGI System to improve the air quality in transit buses by reducing harmful pathogens, mold, fungi, bacteria and, viruses within the bus for passengers, drivers and employees. [sic] The tests conducted by Biological Consulting Services of North Florida, Inc. and Dr. James W. Kimbrough, Mycologist, University of Florida, **showed an effective reduction of 95% to 99% on mold, fungi, and bacteria on the buses tested. Testing showed a 99% reduction in common viruses. The use of UVGI Systems designed for transit buses was effective and produced positives results. These test results were very similar to other test results found in hospitals, schools, commercial buildings, food processing plants, and other stationary applications of UVGI Systems. EPA Office of Research and Development**, National Homeland Security Research Center testing for hospitals and commercial buildings titled

> "Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light Systems", June 2006, is consistent with testing results at Houston Metro for transit buses."[84]

Primary factors which determine the dosage of UVC light received include intensity of the bulb being used, cross-sectional area of the duct surrounding the UVC light air is passing through, the length of this cross-sectional area that will be irradiated by UVC light, and the velocity of the air travelling through this region.

Although in-duct UVC systems are well established for buildings with guidelines and recommendation, there is very little literature and technical data on the efficacy for buses. The research team contacted several vendors supplying in-duct UVC devices specifically for buses, but were unable to obtain efficacy data or only limited technical data.

One vendor, Mobile Climate Control (MCC), provided additional technical data on their in-duct UVC product estimating the feasibility of a typical in-duct UVC system placed just outside the coil. MCC stated that a typical roof mounted HVAC system commonly found on a 40 ft. long NABI bus would generate an airflow of 2400 CFM and an average air velocity of 357.9 ft/min (after typical duct losses) passing through the irradiated areas just outside each of the two coils. MCC also claimed a 99.96% kill rate after 6 air exchanges.[85] As a rudimentary check, the research team estimated an approximate dwell time for any particles passing through the HVAC system with an assumed 6" length of irradiated area, the estimate closely agreed with the 6 pass statement from MCC. However, this does not prove efficacy since it's unknown if cumulative UVC dosage is impacted by separate passes nor is it known if that same particle will flow through the cabin to pass through the air system subsequently to receive additional dosages. However, the science would suggest that some level of energy will be delivered and some virus weakening or even disinfection will occur with each pass. With the estimated one air exchange per minute, this implies positive support that particles would be subject to multiple doses in a relatively short period of time.

Although the efficacy of air disinfection is unknown, at a minimum it will kill mold and virus on the static objects within the area of the HVAC where the UVC is installed such as the coils. This may offer reduced maintenance costs, reduction of odors in the passenger cabin, and enhanced customer experience.

Depending on the UVC wavelength there is a potential for ozone generation. UVC bulbs generally have a coating to filter out the wavelengths that produce ozone, however with any UVC bulb there is ozone potential. MCC and SanUVAire have both stated that their units do not produce ozone, NFI provided a general statement that it "produces no pollution." Ozone can easily be measured and verified. Other in-duct technologies such as photocatalytic oxidizers and ion generators produce substances that will enter the occupied space, these substances have the added benefit of potentially disinfecting surfaces, which an in-duct UVC would not –

this can be viewed as both an advantage and disadvantage. Other than the potential for ozone - no chemical agents such as peroxides or reactive oxygen species would be introduced to the occupied cabin.

While investigating UVC HVAC air disinfection systems, the research team identified and contacted three vendors of in-duct UVC products designed for buses. All three prices were estimated to be within the $3,000 to $5,000 range. All three products ultimately use the same UVC technology to treat the air and HVAC coils. Although each vendor did have their own attributes nothing stood out as a unique functionality feature. Almost no information exists concerning operational costs, long term maintenance, or overall efficacy making it impossible to evaluate these products without further testing and evaluation. However, it's worth mentioning that:

- NFI Parts, has the advantage of being a subsidiary of the company which owns New Flyer, MCI, and NABI, all vehicle makes which NJ TRANSIT have in their bus fleet. However, the system is limited to **only MCI buses**. NFI's close relationship with the bus manufacture could be an asset when it comes to using their system and long-term device support. It may also be an advantage regarding uniformity of equipment, compatibility, and spare part inventory for future bus purchases as the fleet is replaced in coming years.
- SanUVAire has stated that they are capable of building <u>custom</u> in-duct UV systems for **any bus type**, which could prove beneficial for smaller HVAC systems such as those found on the NABI and mini-bus. This product has been **installed on 70% of DART buses**, however the research team has been unable to secure additional quantitative data concerning system performance. This information would be useful in assisting NJ TRANSIT with future decisions.
- Mobile Climate Control (MCC), is a global HVAC systems developer and has the advantage of designing and building the HVAC systems for both **NABI and MCI buses**. This relationship with MCI and NFI may also be an advantage if the product is widely adopted in the future. As discussed earlier, it could be an advantage regarding uniformity of equipment, compatibility, and spare part inventory for future bus purchases as the fleet is replaced in coming years. However, the MCC product is new and has only been **installed on a limited number of buses at this time**.

The following sections provide additional details for each product. Some products are more established while others are newer – some are custom while others are newer but have an established relationship with MCI/NABI. With the limited information available, no features on any of the products standout nor give any product a distinct advantage over the others.

Beyond the scope of this initial project, testing using real world techniques and measurements would be required to determine efficacy of an in-duct UVC system.

5.3.3.1 *Product 1 - NFI Parts - UV-C Lighting Kit*

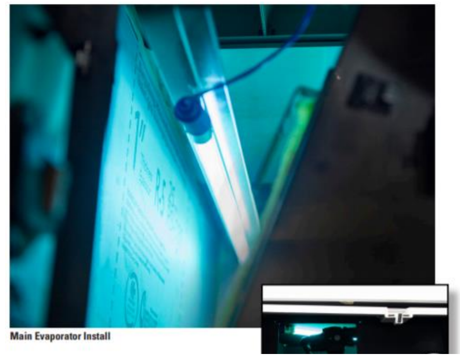

Figure 99 NFI Parts - UV-C Lighting Kit

- NFI Parts[xxiv]
- https://www.nfi.parts/cleanandprotect/prodlit/UV-CLights-PRI.pdf
- 800-665-2637
- 35 Cotters Ln # D, East Brunswick, NJ 08816
- Estimated Cost: $3,735 per bus

- MCI buses only
- "Simple installation into most main evaporator compartments
- UV-C lamp reduces viruses, bacteria, and mold in the air and on the HVAC coil by 99.9%
- Does not use harmful chemicals
- Produces no pollution"[86]
- Power Draw: The ballasts used in both systems (main evaporator and parcel rack evaporator) provide 55W max power to the bulbs. There are 3 total ballasts used in the complete system, each providing 55W of power at 110V AC.

5.3.3.2 *Product 2 – SanUVAire - Breathe-Safe System, Air Purification & Coil Disinfection*

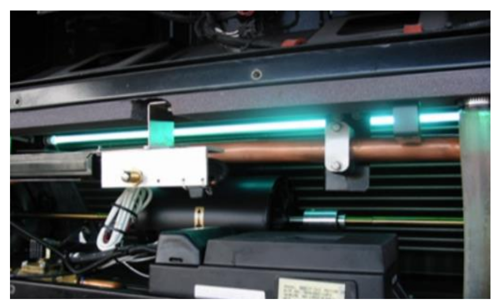

Figure 100 SanUVAire - Breathe-Safe System, Air Purification & Coil Disinfection

- SanUVAire[xxv]
- http://www.sanuvaire.com/products.html
- 888-611-6660
- Near Buffalo, NY (small business minority owned)
- Estimated Cost: $3,100 for rear mounted or $5,000 for rooftop mounted per bus

- "Longer HVAC Components life, Reduced Service Costs, Reduced Exposure to Airborne Diseases
- Coils are Disinfected and Remain Clean. HVAC System Uses Less energy
- Eliminate the Use of toxic chemicals for Cleaning Evaporators
- Reduce Maintenance Cost, Increased savings $2200/yr/Bus"[87]
- Power draw:
  - 12vdc ballast requires a 12vdc power input line and max Amp draw is up to 10amps depending on the lamp it is powering. It can drive up to a 110W lamp.
  - 24vdc ballast requires a 24vdc power input line and max Amp draw is up to 7.5amps depending on the lamp it is powering. It can drive up to a 160W lamp.

[xxiv] Photo Credit: Photo by NFI Parts via https://www.nfi.parts/cleanandprotect/
[xxv] Photo Credit: Photo by SanUVAire via http://www.sanuvaire.com/

5.3.3.3 *Product 4 - Mobile Climate Control (MCC) - Aire-Shield UVC*

- Mobile Climate Control[xxvi]
- www.mcc-hvac.com
- 717-309-0548
- 17103, State Road 4 East Goshen, Indiana 46528
- Estimated Cost: $3,000 per bus

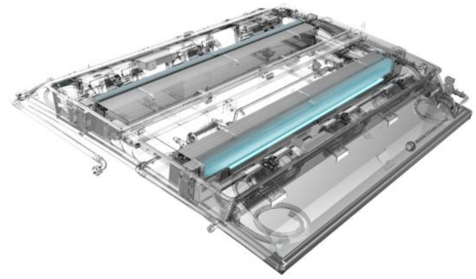

Figure 101 Mobile Climate Control (MCC) - Aire-Shield UVC

- "99.96% kill rate after 6 air changes*
- Sterilizes air as it passes by the evaporator
- Reduces evaporator maintenance
- Available for retrofit and new MCC systems
- Interlock switches prevent accidental exposure
- Sterilizes bus air volume up to once per minute
- Does not produce Ozone
- Teflon coating contains contents in case of breakage

  *Results based on modeling from Eco 353 systems, data from laboratory testing of existing coronaviruses, UVC bulb intensity after 9,000 hours of operation, and HVAC unit air flow. Without enough data on COVID- 19 (SARS CoV-2), UVC dosage values of other viruses in the SARS family are used for the novel coronavirus kill rate.

- 18,000-hour lamp life
- 46" & 60" Teflon coated lamps emit 17-25 UVC Watts
- Lamp emits 100% 254nm UVC light
- Power draw: 24VDC, 4A per UVC lamp"[85]

[xxvi] Photo Credit: Photo by MCC via www.mcc-hvac.com

5.3.4 In-duct Photocatalytic, Photohydroionization, and Ion technologies

In addition to UVC to disinfect air within a vehicle's HVAC system, there are other in-duct HVAC disinfecting systems using Ionization and Photocatalytic Oxidation to treat the air. The National Air Filtration Association (NAFA) – which admittedly might be biased toward filtration - has stated that ionizers, ozone generators, plasma, and other air cleaning technologies have not been proven to reduce infection in real buildings, even if they may show promise based off of tests performed in a laboratory under idealized settings.[65] However, ASHRAE, which would not appear, to have the same biases and is often cited and referred to by CDC, has summarized the technology efficacy as:

*"**Photocatalytic Oxidation (PCO)***

- *Consists of a pure or doped metal oxide semiconductor material*
    - *Most Common Photocatalyst is Ti02 (titanium dioxide)*
- *Activated by a UV light source*
    - *UV-A (400-315nm)*
    - *UV-C (280-200nm)*
    - *UV-V (under 200nm) Ozone can be formed at UV-V wavelengths*
- *Light mediated, redox reaction of gases and biological particles absorbed on the surface*
- *Some units claim disinfection from gaseous hydrogen peroxide.*
- *Possible by-products formed by incomplete oxidizing.*
- *Some air cleaners using PCO remove harmful contaminants to levels below limits for reducing health risks set by recognized cognizant authorities.*
- ***Some are ineffective in reducing concentrations significantly; manufacturer data should be considered carefully.**"[76]*

"Bipolar Ionization/Corona Discharge

- *High voltage electrodes create reactive ions in air that react with airborne contaminants, including viruses.*
- *The design of the corona discharge system can be modified to create mixtures of reactive oxygen species (ROS), ozone, hydroxyl radicals and super¬oxide anions.*
- *Systems are reported to range from ineffective to very effective in reducing airborne particulates and acute health symptoms.*
- ***Convincing scientifically-rigorous, peer-reviewed studies do not currently exist on this emerging technology; manufacturer data should be carefully considered.***
- *Systems may emit ozone, some at high levels. Manufacturers are likely to have ozone generation test data."[76]*

5.3.4.1 Ion (Plasma) Generator

With any disinfection technique that disperses disinfectant into the breathing zone of riders, it is difficult to maintain the safety of the rider or unprotected worker while simultaneously achieving the desired disinfection. Biological inactivation of the virus caused by the activity of the disinfecting agent is at best an irritant and at worst a potential health concern to those inhaling the agent. While application of disinfection techniques may be appropriate for filters within an air handling unit, the release of the disinfecting agent into breathing areas is generally either at a concentration too low to be effective yet safe to those without respiratory protection, or too high to be deemed safe.

There are multiple ways to generate a plasma, described as an ionized gas with roughly equal concentrations of positive and negative ions. Like a gas they have undefined shape but can be directed using electric or magnetic fields. It is often referred to as the 4th state of matter as it results from application of energy to a gas. Commercial devices have many applications including analytical chemistry, metal etching, television pictures, power generation and disinfection. Plasmas are easy to generate at low pressures but more difficult at atmospheric pressure. They are generated at atmospheric pressure by ionization of gasses that make up air or those introduced into a chamber at higher concentrations. They are generated using both DC and AC voltages to remove electrons from the gas and then exciting the electrons for further gas ionization. These plasmas are the principle means for generating the ions thought to be the driver of the disinfection or inactivation process.

Disinfection technologies that use ionization generate reactive ions within the space that they are created. Typically, two parallel plate capacitors are maintained with a voltage between them, high enough to remove the electrons from the water vapor in the air, generating reactive oxygen (and other) species.

One mechanism proposed for disinfection is that ions are added to the membrane of the cell of a bacteria spore or virus until the infecting species can no longer tolerate the surface charge and because the membrane ruptures, possibly due to columbic repulsion. In an uncontrolled environment there is no way to continue to force charges to continue to accumulate on a membrane until disruption of the membrane occurs.

One study demonstrated that currents of approximately 100uA for 90 seconds was required to achieve a disinfection of 10^6 CFU. The bus concentrations of ions were roughly 10^6 lower in air.

On June 2nd, CCT joined representatives of New Jersey Transit to identify optimal locations for the CCT24V-1 on the MCI bus and the CCT24V-D12 for the NABI bus. CCT used the Alphalabs AIC2 meter for testing the concentrations. One of these devices was employed in a bus under partially controlled conditions. It was not moving nor was it picking up passengers at multiple stops, but did record door opening and closing events. As per the vendor test and report, the concentration of ions measured fluctuated between zero and > 150,000 ions/cm3 during the study.

In general, the maximum and minimum ion concentrations can be measured within the breathing zone of a bus, but whether these concentrations are high enough for virus inactivation, or low enough not to present a human health risk, has yet to be determined. The reactivity of the ions that remain, as well as their concentration, will both help to determine the efficacy of ionization as a disinfection technique for air particulate.

Application and mounting of the device seems possible. However, which ions generated (including free radical plus electrons) and under what conditions, are questions that have yet to be fully characterized and quantified. Overall, the technique as it is applied to disinfection outside the duct cannot be evaluated thoroughly at this time.

The limitations of approach include no characterization of the ion types (their reactivity) was provided by the vendor other than Ozone concentrations. However, H20 has several hydroxyl combinations beyond ozone such as oxygen O2 but also O2- superoxide or oxide anion, as well as OH and OH-, and even H2O2 hydrogen peroxide. There has been little work on the characterization of the radical ions released by these devices that are essentially novel modifications of devices designed to work within a duct. While many of the more reactive species are expected to have short half-lives, the ions or ionic species that are longer lived have generally just been counted rather than characterized. They are proposed to be cluster ions (multiple atoms with an associated charge) but without further spectroscopic characterization within the larger environment of their release (i.e. bus cabin), the research team cannot confirm what they are or even how reactive. Furthermore, real-world uncontrolled factors such as relative humidity, surface composition and other air substituents (VOCs and chemical disinfectants), will all contribute to the composition to the actual ions that remain to inactivate virus.

The research team was unable to identify any scientific peer reviewed publications regarding the ion concentration required for efficacy within a breathing environment. The measured concentrations may be effective if the ionic species are highly reactive and mixed well within the breathing space but if they are highly reactive, they also represent a health risk to the passengers and especially the driver who would be exposed for a much greater duration of the day. As described above, the measured concentrations are orders of magnitudes lower than those founds in many bacteria disinfection studies where the plasmas generated were only a few centimeters above the active cultures that were neutralized. If the ions are less reactive and present little or no health risk, it is likely that disinfection times will be much longer than the resident time of a particle within the bus, possibly hours.

The overall conclusions are there are many unknowns and many possible pathways to negative health outcomes. Conversely, it's equally possible that it will or will not generated high enough ion concentrations in the bus to be effective or that it could be only marginally effective. However, this technology does have the potential to disinfect, especially in a closed environment within the duct. The research team is unable to confirm efficacy or fully assess health impacts without additional information.

5.3.4.2 Photocatalytic Oxidizer and Photohydroionization

Photocatalytic oxidation generates reactive oxygen species (ROS) that inactivate or kill the virus or bacteria. These include oxygen and O2 radicals, peroxide and others. It is an emerging technology used in HVAC systems, primarily to kill airborne bacteria, that uses a photoreaction accelerated by a catalyst (TiO2, WO3, ZnS, etc.). The ROS are formed on the catalytic surface when exposed to light of the appropriate wavelength. ROS are highly reactive and generally short lived because of their reactivity. They create free radicals that can reduce and oxidize compounds which are also present on the catalyst surface that undergo secondary reactions that generate biocides. They can also react to form aldehydes, ketones etc. that in turn present a secondary potential health risk to those exposed. Only a small percentage of the pathogens will be killed in a single pass system because those pathogens need to be absorbed to the catalytic surface and efficiency is also reduced by accumulation of a surface layer of pathogens already killed by the process. This is an emerging technology with varying efficacy claims for large scale air disinfection applications.

Its efficacy has not been demonstrated though inactivation or biocidal removal of the virus for application outside of an air duct. It may generate harmful byproducts. While there are no standardized test methods there are only a few studies to verify performance. According to RGF's oxidation test results the device in 6 hours achieves 99% inactivation of H1N1; and in approximately 2-3 hours achieves 99% inactivation of Avian Influenza.[88] At the very least it can aid in the overall disinfection of the air with the understanding that its efficiency is low or may take hours to have measurable results.

The limitations of the approach are they largely used for disinfection of water but has also been used for disinfection of air. There may not be any suitable devices to be used for general air disinfection. It may be more applicable to disinfection of air filtration devices because of the localized generation of reactive species.

The overall conclusions include that these devices are too new for complete air disinfection but may support or be used in conjunction with other technologies. Like the plasma generators, the species generated on the surface of the catalyst are at least irritants and at worst a potential health concern. The surface generation nature of the species, as well as the high reactivity/short lived nature of these species, means they present much less of a health risk than the plasma source, which is designed to push ions into the bus environment. Further identification and quantitation of the reactive species would need to be done before efficacy and possible health risks could be described in greater detail.

5.3.4.3 CCT 24V-1 Ion Generator

- Climate Comfort Technologies (CCT)[xxvii]
- http://climatecomforttechnology.com/
- 303-287-3113
- 6897 E 49th Avenue, Commerce City, CO 80022
- Estimated Cost: $2,000 per bus

Figure 102 Climate Comfort Technologies CCT 24V-1

- "Ionic technology has allowed commercial building designers to save energy costs by controlling various air contaminants (ASHRAE 62.1 IAQ procedure).
- It has been used to address smoke, body odors, jet and diesel fuel odors, airborne microbiological particles, dust particles and more.
- There are several goals of the elevated (ion) concentrations:
    1. Help remove small particles from breathing space.
    2. Help treat aerosolized microbiological contaminants
    3. Reduce odors through gas disassociation.
    4. Dust particles bind together and increase weight which helps to make them settle rather than cycle continuously through the HVAC system."[89]
- "Power draw: 24VDC 1 amp
- average reading was 20,000 ions with peaks over 60,000 ions
- MCI Coach buses: average reading was 20,000 ions with peaks over 60,000 ions
- NABI Bus #5637: 100K ions/cc in localized spots with readings consistently in the 30-60K ions/cc range"[90]

5.3.4.4 United Safety RGF PHI Cell Technology Photocatalytic Oxidizer

- RGF Environmental Group, Inc.[xxviii]
- https://www.rgf.com/air-purification/
- 1-800-842-7771
- 1101 W 13th St., Riviera Beach, FL 33404
- Estimated Cost: $3000 to $3500 per bus

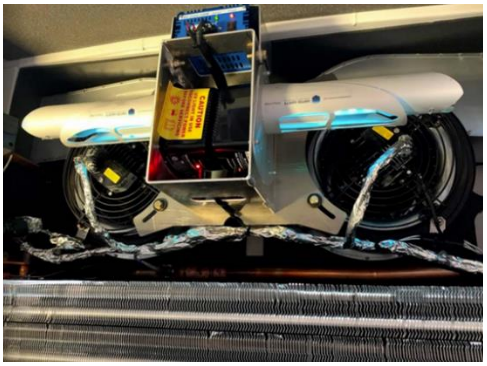

Figure 103 United Safety RGF PHI Cell Technology Photocatalytic Oxidizer

- "Sanitation using low dose hydrogen peroxide (H2O2) generated through UV oxidation
- Airborne (H2O2) distributed throughout the vehicle through HVAC airflow

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[xxvii] Photo Credit: Photo by CCT via email and http://climatecomforttechnology.com/
[xxviii] Photo Credit: Photo by RGF via email and https://www.rgf.com/air-purification/

- PHI (Photohydroionization®) Cell produces continuous low dose airborne hydrogen peroxide (H202) generated via UV catalytic advanced oxidation technology
- Active technology, no touch (requires no operator or application) sanitation of the occupied space
- Proven efficiency on microbes (test data on H1N1, Avian Flu, sneeze test and many other 3rd party test results). Kills up to 99% of bacteria and viruses in the air and on surfaces
- Proven impact on odor reduction (test data available)
- Low level H202 effective in air and on surfaces
- Zero impact to current product performance (plastics, etc.)
- Potential for major operational cost savings
- Scheduled maintenance: 1-year lamp replacement”[91]
- 2 PHI cells
- 24V DC-AC inverter
- Power draw: Dual cell 0.7 Amps, 45 Watts
- 2,000 – 13,000 CFM capability
- Weight: 10 lbs.
- Package space: 28” x 10.625” x 13.25”
- Maintenance: Cell Replacement after 1 year
- Remote mounted LED in operator’s area confirming functionality
    - Displays functionality of 24 VAC supply to cells
    - End user choice of placement (maintenance staff only, operator only, or operator and passengers – with signage)

5.3.4.5 Luminator - Grignard Pure

- Grignard Company and Luminator Technology Group[xxix]
- https://grignardpure.com/
- 732-340-1111
- 505 Capobianco Plaza, Rahway, NJ 07065
- Estimated Cost: unknown

Figure 104 Luminator - Grignard Pure

- Air treatment that continuously treats indoor spaces
- “Inactivates more than 99% of the airborne virus particles in 1-3 minutes. The tested virus is considered harder to kill than the SARS-CoV-2 virus, indicating that Grignard Pure’s inactivation (or kill) rate may be even greater” [92]

[xxix] Photo Credit: Image by Grignard Pure via https://grignardpure.com/

- Intrinsik Toxicology Risk Assessment – United States: “Based on available data, Grignard Pure MEETS the requirements for classification as not toxic (acute/chronic), corrosive, a skin/eye irritant, or a strong sensitizer as defined in 16 CFR 1500.3, when used as intended or under circumstances involving reasonable foreseeable misuse. In addition, the ingredients in the product are not included in the list of banned hazardous substances cited in 16 CFR 1500.17.”[92]
- “NIOSH concluded that air treatment products did not affect people with asthma. The EPA has said that the active ingredient in Grignard Pure does not cause harm when inhaled. Locations where Grignard Pure is in use to provide protection against airborne microbes will have the “Protected by Grignard Pure” logo prominently displayed at major entrances, to advise people who might have questions about their own health and to give them the clear option not to enter the facility should they not feel comfortable.”[92]
- Currently under review for an emergency exemption from the United States Environmental Protection Agency (EPA) and several state-level regulatory programs[93]

5.3.4.6 In-duct Photocatalytic and Ion Follow-up

The research team contacted several vendors supplying in-duct Ion and Photocatalytic devices specifically for buses. The pricing on all three of these systems is likely similar although pricing for the Grignard Pure unit has not yet been released.

- Climate Comfort Technologies (CCT) performed a demonstration for NJ TRANSIT highlighting system operation on June 2, 2020. The unit operates by generating ions and hydroxyl radicals and introducing them via the HVAC system into the occupied space of the bus. Ion concentrations were measured by CCT and a CCT report was supplied to NJ TRANSIT. Rutgers followed up with CCT on July 14, 2020 in which a number of concerns were discussed. The interview mainly focused on 1) is the device emitting things into the air that are unhealthy to breath? Such as reactive oxygen species and radical hydroxyls and 2) if not then do you have enough time to kill in the air stream? Other topics included biological testing, disinfection concertation for surfaces versus air, right concentration to kill on surfaces within the air stream, discussion about use while occupied, and other items.
    - CCT responded on July 30, 2020 with a 3-page memo responding to the potential concerns raised during the earlier discussion ultimately stating “Our products are producing positive and negative ions which when they surround microorganisms, they bond and create hydroxyls with a life span of 50-100 milliseconds. The chemistry has demonstrated ionization and the working mechanism of hydroxyls is effective and the toxicology side (Odorox GLP study) demonstrated hydroxyls are harmless to people animals and plants. I hope to find other studies to support our position, but at this point I have not found any to say otherwise, but I would welcome any information you feel relevant.”[94]

  - According to CCT they started in 2014 mainly for odor control. The systems have been installed by a number of agencies including Broward County, Hampton Roads, Pace Chicago and DART.
- United Safety RGF PHI Cell Technology Photocatalytic Oxidizer is current demonstrating their technology with MTA and SEPTA. The product produces low levels ozone and hydrogen peroxide and introduces these chemicals via the HVAC system into the occupied space of the bus. The vendor has supplied presentations and other materials which were reviewed by the Rutgers Team. The ozone and hydrogen peroxide produced by the device as reported by the vendor and confirmed by MTA would appear to be below the OSHA action levels. However, according to RGF's oxidation test results the device in 6 hours achieves 99% inactivation of H1N1, and in approximately 2-3 hours achieves 99% inactivation of Avian Influenza.[88] At the very least it can aid in the overall disinfection of the air with the understanding that its efficiency is low or may take hours to have measurable results.
- Grignard Pure system is assumed to have a similar technology as the RGF photocatalytic oxidizer, no specific information published by the manufacturer was found that details the mechanism behind the device's disinfecting claims. While the company states a similar system has been used in buildings previously, the system's application towards buses is still fairly new and is currently under review for an emergency exemption from the United States Environmental Protection Agency (EPA).[92] It is unclear what the chemical "agent" or "active ingredient" is although they do indicate that it's not banned and "hundreds of millions of people have been exposed to a product with properties identical to Grignard Pure over the past 20 years."[95] In one video they indicate that it's closely related to their lighting effects from the entertainment industry, which may imply that it is related to a photocatalytic device. Ultimately it's a new product and there is uncertainty in the agents and efficacy.

All these devices introduce a disinfection agent via the HVAC systems into the occupied space of the bus while in service. This may or may not be a concern for Transit. For example, the devices that produce hydrogen peroxide - although the exposure may be below the OSHA exposure limit - as per NJ Department of Health "All contact with this chemical should be reduced to the lowest possible level. [sic] Hydrogen Peroxide can irritate the lungs. Repeated exposure may cause bronchitis to develop with coughing, phlegm, and/or shortness of breath."[96] Ultimately these products are eligible to be considered but should be considered within the agencies internal review process when introducing any chemical agent or substance into the occupied space. The research team is unable to confirm efficacy or fully assess health impacts without additional information.

5.3.5 Emerging Techniques using HVAC

Additional emerging disinfection and virus removal methods involving the use of a vehicle's HVAC system have also been searched with the intent of providing as much guidance to NJ TRANSIT as possible. Two potential techniques to reduce the spread of COVID-19 use heat as well as air pressure differentials. However, unlike the previously discussed in-duct systems that have an established basis in buildings, heat and air pressure are used for specialty applications such as clean rooms and are not widely used in buildings, let alone for transit applications.

Very little information was found on these techniques. However, both are mentioned as "ideas" for preventing the spread of COVID-19 rather than well-established technologies ready for vehicle deployment.

5.3.5.1 Disinfection by using Vehicle HVAC to Increase Interior Temperature

The Ohio State University department of microbiology performed a study with Ford Motor Company that indicated that "exposing coronaviruses to temperatures of 56 degrees Celsius, or 132.8 degrees Fahrenheit, for 15 minutes reduces the viral concentration by greater than 99 percent on interior surfaces and materials used inside Police Interceptor Utility vehicles".[97] Increasing temperatures inside police vehicles above the aforementioned temperatures would not require labor resources and allow for a simple and chemical free disinfection of the vehicle.

Figure 105 Ford Explorer police cruiser undergoing studies on heat increase application[xxx]

The exact process in which this technique works is described below:

- "A driver activates the system and then gets out of the vehicle.
- The vehicle's hazard lights will flash.

[xxx] Photo Credit: Photo by Ford via https://media.ford.com/content/fordmedia/fna/us/en/news/2020/05/27/ford-heated-sanitization-software-police-vehicles-coronavirus.html

- The speedometer will increase to around 100mph, marking the beginning of the process. The increase in speed also increases RPMs to around 1800 or more. This is around the same RPM experienced when driving on a highway. Experiencing this RPM while parked allows the vehicle to put the extra effort towards generating more heat.
- Coolant, which cools the engine, helps harvest the heat and sends it to the heater. Normally, if a heater gets dangerously hot in a car, the coolant flap will close so that no more heat will get through. With the new software, this safety feature has been taken away in order to deliver the extra heat needed for sterilization.
- Once the process is complete (around the 15-minute mark), the speedometer slows to zero and the brake lights will come on."[98]

This process is achieved through a software update that can be installed on newer police cruiser models. **New York City** has begun implementation of these software updates on some of their vehicles already. [98]

A high-performance vehicle like a police cruiser may be suitable for the extra strain of racing the engine while the coolant is disabled. However, the research team has significant concerns about the extra strain on a bus engine. Furthermore, a bus has a large physical volume of air, significant internal mass, and surface area; it may not be able to achieve the 132-degrees – let alone reach this temperature evenly throughout the bus in the middle of the cold winter months.

Nevertheless, if the technology proves effective on the paratransit vehicles (mini-bus, minivan, and sedan), disinfection could be performed intermittently throughout the day or at the end of a shift once back at the garage. However, one potential drawback is that according to one news report the whole procedure (heat up, disinfect, and cool down) will take 45-minutes to one hour to complete the entire process.[99] This is a considerable time commitment while having the engine revising at such a high RPM. Adding portable heaters to the bus to elevate the temperature would create the same difficulties as the UV disinfection approach and would require a longer disinfection time.

Similar techniques could be considered for use on NJ TRANSIT vehicles in the future. Additional wear and tear on the vehicle's engine should be considered when considering modifying a vehicle for this technique.

As a final thought, there might also be a required cool down period. This might be a typical temperature achieved in a parked car on a hot summers day, but there could be the potential for burns. Paratransit serves people with disabilities who are unable to use the local bus service. Due to the special needs of paratransit customers including non-verbal communicators it's critical that a proper procedures be developed to ensure safe and comfortable temperatures afterwards if this technique were to be used. Thereby prevent any potential burns or other temperature related concerns and meeting NJ TRANSIT’s mission to help safely serve these customers.

5.3.5.2 Modifying Vehicle Airflow to Increase Driver Safety

Another HVAC related modification manipulates the air flow between the passenger and driver zones within a vehicle to help protect drivers. The City of Detroit worked with engineers at Honda on a system that would modify the HVAC systems on their Honda Odyssey minivans, which are used to transport healthcare workers as well as potentially infected passengers.

Figure 106 Modified Honda Odyssey with view of interior polycarbonate barrier[xxxi]

The modification involves two parts to the process. In the first step, as shown in Figure 106 a sealed polycarbonate barrier would be installed between the front seat compartment and rear seating area (as shown in the figure above). The second half of this process involved modification of the ventilation system to provide a more positive pressure zone in the front driver area and a more negative air pressure to the passenger zone. This modification to the ventilation system would reduce potential for droplet infection migration by creating an air pressure differential which would allow the air passing through the vehicle to exhaust out the vents in the rear of the vehicle without ever be recycled back to the driver zone. [100]

[xxxi] Photo Credit: Photo by Honda via prnewire.com

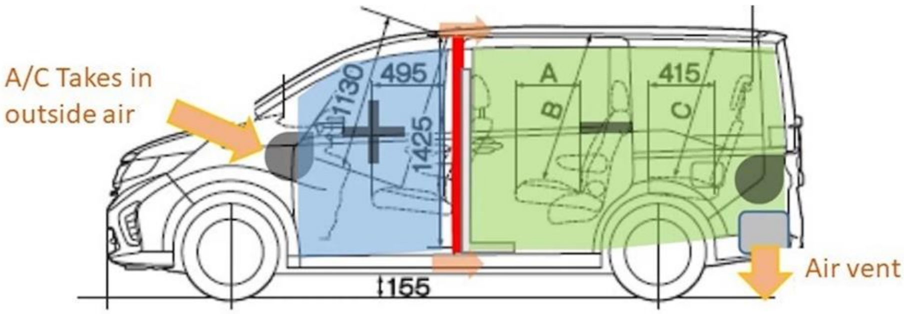


Figure 107 Pressure differentials shown within the vehicle[xxxii]

As shown in Figure 107 “Up front, the driver and front passenger sit in a pressurized area, where the air conditioning unit draws in air from the outside and gets filtered for that section of the vehicle only. To separate the two zones, Honda engineers added a partition to seal off airflow between the front and rear. The rear portion of the vehicle is pressurized to a lower level, which creates airflow from the front to the rear of the van. Air reaches the rear area through channels in the floor and in the headliner. Then, a new vent was added near the rear bumper to remove air from the vehicle without it recirculating through the cabin like it would on a normal van.”[101]

While the HVAC systems on full sized buses is likely to be too complex to emulate the effectives of this modification, smaller paratransit vehicles such as sedans and minivans with similar ventilation to Honda Odyssey vehicles may benefit from the upgrade.

There have been no vendors outside of Honda’s engineers that were identified to perform this modification, although the overall modification would appear simplistic enough that NJ TRANSIT could implement a similar strategy. The overall effectiveness is unknown; though the use of pressure environments is well established for clean room environments. Therefore, the science implies this may be a beneficial and practical retrofit though the exact vehicle modification is unclear.

There are no major concerns regarding this technique.

5.3.5.3 Experimental HVAC Modifications Summary

- Though probably not practical for most Transit vehicles; disinfection can potentially be performed by modifying a vehicle’s current HVAC to increase interior temperatures above 130 degrees Fahrenheit for 15 minutes. However, one potential drawback the whole procedure (heat up, disinfect, and cool down) will take 45-minutes to one hour to

[xxxii] Photo Credit: Photo by Honda via thedrive.com

complete. Additional wear and tear on the engine as well as allowing for proper cooling of the vehicle should be considered.

- Modifying the airflow in a vehicle using polycarbonate barriers alongside modification of the air pressure differentials within the driver and passenger zones can help move potentially contaminated air from passengers away from the driver.
- These airflow modifications have only been performed on Honda Odyssey minivans used in Detroit to transport passengers, but could potentially be emulated on other transit sedans and minivans outside of the Odyssey car model as well.

5.3.6 Cost Summary for In-Duct Disinfection of Air

The NJ TRANSIT fleet is made up of approximately 1600 MCI, 1325 NABI, 85 Articulated, and 500 Minibuses. It is unlikely the minivans and sedans can be retrofitted with an in-duct device and have been omitted from the capital cost estimate. However, for full fleet wide deployment as an initial estimate of the in-duct UVC might cost between $10.5M-16.3M, in duct plasma $7M, and in-duct PHI $12.3M.

[3010 MCI + NABI + Artic fleet * $5000 for in-duct UVC device (split rooftop system) + ($2500 single bulb UVC * 500 Mini-bus) = $16.3M capital cost]

[3510 MCI + NABI + Artic + Mini-bus fleet * $3000 for in-duct UVC device (lower end of range) = $10.5M capital cost]

[3510 MCI + NABI + Artic + Mini-bus fleet * $2000 for in-duct plasma device = $7M capital cost]

[3510 MCI + NABI + Artic + Mini-bus fleet * $3500 for in-duct PHI device = $12.3M capital cost]

As per the previously discussed Federal Transit Administration (FTA) funded study by the Transportation Research Board (TRB) “Ultraviolet Germicidal Irradiation for Transit Buses” Transit IDEA project #53 of 14 Houston Metropolitan Transit Authority buses

- “The UVGI System in combination with the Reusable Electrostatic Air Filters allowed for a new labor saving method of cleaning evaporators without chemicals, merely by using a vacuum. Evaporator cleaning was reduced to 10 minutes labor time.
- By using the UVGI System and Reusable Electrostatic Air Filters, maintenance cost savings identified are estimated to be approximately $129,000 per year, per 100 buses. [i.e. $1,290 per bus per year] At an estimated cost of $2,100 per UVGI system, that would provide a return on investment in about 18 months.”[84]

It’s likely the return on investment (ROI) may be longer than stated for the NABI due to the split rooftop configuration requiring “two” UVC devices. However, based on the FTA report the ROI would still likely be less than 4 years. As confirmation, the research team also discussed one in-duct UVC vendors claim of $2,200 savings per year.[102] The majority of the vendors estimated savings was from 6.25 gallons of diesel fuel saved per day for 200 days resulting in $1,250 saved per bus per year. The balance of the estimate consisted of $250 for 1-day drive absenteeism, $350 for 1-day driver replacement (time and a half overtime pay), $300 coil cleaning labor, and $40 coil cleaning solution.[102]

The vendor approach differs significantly from the TRB Transit 53 study – specifically 1-day driver absenteeism/replacement versus 1-day bus out-of-service time respectively. Furthermore, the FTA study only estimated 0.4 gallons instead of 6.25 gallons of fuel saved per day. Though the evaporator coil cleaning and solution were roughly in agreement at $400 and $40 respectively per bus. By taking the most conservative estimate of 0.4 gallons of diesel per day at $2.29/gallon and removing evaporator coil labor this results in a $334 savings per year.

[(0.4 gallons * $2.29 per gallon of diesel) * 365 operating days per year = $334 saved per year]

- As per the previously discussed Federal Transit Administration (FTA) funded study the ROI for an in-duct UVC device is estimated at $1,290 annually
- Estimated $334 saving per year per in-duct UVC device is likely on the low end of the actual savings but still represents a measurable and significant ROI.

5.3.6.1 Bulb Replacement and Life-Cycle Cost

If NJ TRANSIT were to adopt an in-duct UVC device further investigation is needed to fully understand the life cycle costs. After the initial purchase, the most substantial life cycle cost beyond device replacement would be bulb replacement.

In-duct UVC devices are generally designed to be “on” when the bus is running. However, since the coils is where moisture condenses it’s a prime location for mold and biofilm to form, there is an argument to keep the UVC device on even when the bus is off to minimize growth. However, for the purposes of this analysis it is assumed that the UVC devices will by synced with the bus and will therefore run for 2 shifts at 16-hours per day.

As per Phillips website, a typical UVC Mercury bulb has a 9000 hour useful operational life.[103] However, one manufacturer 8000-10,000 hour (consistent with Phillips data) as well as 16,000 hour bulb.[104] Based on these two bulb lives where they are in use for 365 operating days per year for 16-hours per day the bulbs should last between 1.7 to 2.7 years.

[10,000 hours / 16 hours per day / 365 days per year = 1.7 years between each bulb replacement]

[16,000 hours / 16 hours per day / 365 days per year = 2.7 years between each bulb replacement]

Most buses will Replacement bulbs are estimated at approximately $150 per bulb. The total cost to replace all of the bulbs is approximately $978k every 1.7 to 2.7 years.

[3010 MCI + NABI + Artic fleet * 2 bulbs * $150 for in-duct UVC device (split rooftop system) + ($150 single bulb UVC * 500 Mini-bus) = $978k replacement cost]

Therefore, the annual average bulb replacement cost is approximately $469k per on average fleet wide.

[($978k/ 1.7 years + $978 / 2.7 years) / 2 = $575k + $362k per year / 2 = 469k per year on average]

With a $16.3M initial capital expenditure and an estimated $469k annual bulb replacement cost compared to the FTA Transit #53 report's estimated $1,290 annual maintenance savings per year the ROI breakeven point is 4 years. Using the research teams more conservative estimate of $334 annual saving per bus the ROI breakeven point is 23 years. Whether it's 4 years based on the FTA report or 23 years based on a more conservative estimate there is a measurable and overall positive ROI.

[$16,300,000 capital cost / ($469,000 annualize bulb replacement cost – ($1,290 annual maintenance savings per year *3510 bus fleet)) = 4 years ROI breakeven point]

[$16,300,000 capital cost / ($469,000 annualize bulb replacement cost – ($334 annual fuel/maintenance savings per year *3510 bus fleet)) = 23 years ROI breakeven point]

- In-duct UVC bulbs should last between 1.7 to 2.7 years
- Approximately $469k will be required on average per year to replace all in-duct UVC bulbs
- Estimated 4 years ROI based on the FTA report or 23 years ROI based on the more conservative estimate; there is a measurable and overall positive ROI.

6 CONCLUSIONS

The surface disinfection efforts of this research project were largely based on small portable UVC source characteristics - independent of a specific vendor. It's important to note that each product will have significantly different performance and size. For example, each UVC device may have different sized bulbs or may require 3, 4 or even 8 bulbs – therefore the conclusions do not represent "absolutes" but instead are intended to provide broad guidance that can be used to help guide decision makers. As such, the quantifiable values presented in the conclusions are based on a two "representative" UVC sources – one Mercury and one pulsed Xenon. As such the exact coverages, costs, labor etc. will vary however the overall intent of the finding remain unchanged.

A Summary of the Findings for Mercury Source UVC Disinfection of Surfaces Includes:

- The 40-ft bus four Mercury UVC sources model showed that 65.61% of visible surfaces would receive a direct line of sight dosage. The measured values demonstrate the models are very conservative as they do not estimate contribution from reflected light.
- The mini-bus three Mercury UVC sources model showed that 70.88% of visible surfaces would receive a direct line of sight dosage.
- Shadowed areas, which could still receive some "indirect" light such as reflected dosage, were field measured. Results imply that the true percentage of the bus receiving a kill dosage is much higher than the model prediction.
- All except three (3) test mini-bus locations (back of the last row of seats, back of wheelchair seatbelt, and the strap storage bag) received dosages in excess of the established 25 uW/cm2 threshold required to achieve a 10.6 mJ/cm2 kill dosage in less than seven minutes.
- All except six (6) test NABI locations received dosages in excess of the established 25 uW/cm2 threshold required to achieve a 10.6 mJ/cm2 kill dosage in less than seven minutes.
- However, any gap in coverage of a critical or high touch surfaces like a seatbelt raises overall efficacy concerns for UVC disinfection of surfaces.
- No light leakage was detected in the target wavelength (200-300 nm) for any transparent surfaces (i.e. windows) during operation of the UVC sources.

A Summary of the Findings for Pulsed Xenon Source UVC Disinfection of Surfaces Includes:

- The model showed for three pulsed Xenon UVC sources the 40-ft bus that 53.72% of visible surfaces would receive a direct line of sight dosage.
- The model showed for two pulsed Xenon UVC sources the mini-bus that 59.11% of visible surfaces would receive a direct line of sight dosage.

- Overall, the pulsed unit produces a wider spectrum but is far less intense in the 254 nm wavelength. The pulsed Xenon delivers a 60 ms dose roughly every 6 seconds which is much less exposure time than the Mercury "continuous" wave source. However, the wider range spectrum of the pulsed Xenon should be an advantage. Therefore, the research team can't calculate a direct efficacy comparison. That being said, the 254 nm wavelength at 8-ft a 3.65 uW/cm2 per pulse dose was also measured with a 35 ms integration time. With pulses occurring once every 6 seconds, that would be 1.1 mJ/cm2 delivered in 30 minutes versus the required 10.6 mJ/cm2 to achieve disinfection. Where the 10.6 mJ/cm2 was identified earlier in this report as a reasonable yet conservative dosage required to achieve kill.
- At least at the 254 wavelength a kill dosage does not appear to have been achieved. As previously stated, the broader spectrum should contribute to the yet to be determined efficacy impacts.
- Light leakage was observed in the 300-400 nm range creating a very small but measurable potential risk to those around the bus, during a disinfection cycle. Furthermore, peak intensities in the visible spectrum which can certainly be a visual distraction for the NJ TRANSIT garage environment and a strobe distraction for bus drivers in the garage.

General Observations for UVC Devices for Surface Disinfection:

- Different UVC disinfection devices basically use the same irradiance mechanisms but with varying intensities and device characteristics. Some products have additional features such as motion/occupancy sensors, timers, remote controls, UV sensors, onboard computers/processors, etc.
- Many UVC devices identified weighed more than 100lbs. Although equipped with wheels, the weight would limit usability and maneuverability while positioning and carrying onto and off a bus, especially for buses with stairs, including the bi-level trains.
- Many portable units were identified that can likely be used in an inverted position - that illuminate from above - simplify light distribution throughout the cabin and help ensure broader coverage on surfaces.
- Only two vendors were identified that use pulsed Xenon technology. There are conflicting claims regarding the efficacy of pulsed Xenon in comparison to constant on Mercury UV bulbs.
- Handhelds may still be appropriate for smaller vehicles such as Sedans or for operator/driver areas on the buses. A more detailed review and testing effort for handhelds may be warranted to expand those tools for TRANSIT.
- A significant amount of literature exists regarding UV degradation of plastics. However, a majority of past research focuses on wavelengths found in sunlight and not UVC. UV

over time will cause many plastics to chalk, become brittle, discolor, and crack as well as cause loss of strength in fibers/fabrics.

- The biggest expectation of damage is discoloration. The discoloration represents the first stage of micro-damage; not functional damage which will occur in the future, well after the initial color change is observed.
- Prior to becoming so damaged that it's brittle, plastic is more likely to experience several of the micro-damages including an increased surface roughness. The roughness may increase the cleaning difficulty and theoretically the effectiveness of disinfectants.
- If UVC were to be applied daily, there would be some level of damage to the plastics. However, without accelerated UVC testing the research team cannot predict the decrease in useful life of the interior finishes but it is highly likely that any damage will be minor and cosmetic.
- Since the garage has electrical power as well as access to gasoline, using a generator or even ceiling mounted cable reels would be practical and simplistic.

Cost Comparison of Chemical Application (Spray and air-dry), Mercury UVC, and Pulsed Xenon UVC Observations:

- It's estimated that for placement, operation, and removal of Mercury UVC sources it will take:
  - Mini-bus = setup 5 minutes + disinfection 7 minutes + take down 3 minutes and
  - NABI = setup 7 minutes + disinfection 7 minutes + take down 5 minutes.
- It's estimated that for placement, operation, and removal of pulsed Xenon UVC sources it will take:
  - Mini-bus = setup 3 minutes + disinfection 30 minutes + cool down 15 minutes (can include take down and next bus setup)
  - NABI = setup 5 minutes + disinfection 30 minutes + cool down 15 minutes (can include take down 3 minutes and next bus setup)
- Fleet wide chemical disinfection cost scenario = 48 dedicated disinfection staff
- Fleet wide Mercury UVC disinfection cost scenario = 96 dedicated disinfection staff + 768 UVC sources (estimated at $3.4M)
- Fleet wide Pulsed Xenon UVC disinfection scenario = 80 dedicated disinfection staff + 1,680 UVC sources at an estimated at $11M
- Approximately $215k will be required every six years to replace all Mercury bulbs at 9,000 hours useful life per bulb
- Equipment cost for UVC far exceeds hand or backpack sprayers
- PPE supplies and other consumables assumed to be roughly comparable to similar items from other scenarios

- The research team acknowledges that there would be some variability in the setup and take down times from the field tests. However, this same variability would exist with the chemical disinfectant application too.
- The spray and air-dry method is compliant with the manufacturer instructions, but NJ TRANSIT may consider a weekly spray and wipe cleaning to perform a more thorough cleaning and to remove any build-up.
- The research team was not able to identify any permanently retrofit efforts by other agencies or companies at this time. However, permanently mounted built in UVC disinfection is something that should be considered as a future requirement for next generations of buses.

Efficacy being assumed to be roughly equivalent - the research team only envisions one circumstance where the labor component would be less than chemical disinfection via spray and air-dry procedures for fleet wide deployment- if the bus were to have permanently mounted UVC disinfection installed. This is probably not practical as a retrofit. The research team was unable to identify any permanent retrofit efforts for UV surface disinfection by other agencies or companies at this time. However, this is something that could be considered as a future requirement for the next generation of buses. In that scenario, more lights can be built-in and evenly distribute irradiance throughout the cabin and even cover more shadowed areas. The source may very well be small UVC LEDs throughout the bus shell, ceiling, and floor area. The increased capital expense may even be recouped by labor savings.

Although UVC for surface disinfection is highly effective, there are a number pragmatic considerations too. In comparison to chemical disinfection via spray and air-dry procedures, using a portable UVC source does not appear to save labor time or cost. Nevertheless, portable UVC can still be invaluable to supplement chemical disinfection for particular applications. For example, UVC disinfection might be used to further minimize risk as a redundant safety procedure, such as when its known that a bodily fluid was discharged (i.e. blood, vomit) or if an employee is confirmed COVID-19 positive. Ultimately, in comparison to the simplicity and speed of spraying an EPA List N approved chemical disinfectant, the time and logistics of portable UVC deployment may not be practical for fleet wide deployment for surface disinfection but it can still be a valuable tool. However, consideration may be given to including UVC lamps as built-in features of future bus purchases.

A Summary of the Findings for HVAC Air and Filters for Disinfection of Airborne Materials Include:

- Avoid using recirculation mode on HVAC system,
- Ensure HVAC dampers are set to maximize fresh air intake as conditions permit
- Approximate cost to upgrade the entire fleet with the power vented roof hatch kit would be approximately $3.5M requiring over 10,000 labor hours
- Due to the substantial labor and capital expense; after prioritizing other mitigation strategies and <u>contingent upon air flow tests,</u> the research team recommends the installation of additional fresh air makeup systems such as the power vented safety roof hatch kit, (each hatch = additional 350 CFM, $750, and 2 hours to install)
- The power vented roof hatch could be considered as a future requirement for next generations of buses.
- If system performance permits, the HVAC filter should be upgraded to MERV 13 or better, or the highest compatible filter at a minimum MERV 8, or even MERV 8 with antimicrobial
- More than likely, if the HVAC cannot be upgraded to MERV 13 or better either due to filter availability, lack of pressure testing data, or overall HVAC system inability; it's highly-recommended to further investigate and incorporate an in-duct system such as in-duct UVC system along with at a minimum MERV 8 filter.
- At this time NFI has "Flow-rate tested and approved for MCI brand coach applications - will not harm fan motor" the MERV 8+antimicrobial; this would be an extra $670,578 per year beyond what NJ TRANSIT currently spends on filters. This retrofit would not require any additional labor if done with corresponding next filter replacement schedule.
- If possible to deploy MERV 8 uniformly across entire fleet the approximately might be in the range of an extra $162k per year for MERV 8 or $1.1M per year for the MERV 8+antimicrobial (in addition to current filter costs and with known errors in the estimate mentioned above). Although the antimicrobial efficacy remains uncertain the research team does not have any health concerns at this time and recommends adopting antimicrobial filters. However, future testing to determine the efficacy is needed. Furthermore, given the sizeable year-over-year cost, reevaluation is needed as NJ TRANSIT adopts other technologies which may negate the benefit from these antimicrobial layers.
- If MERV 13 or better is achievable, an in-duct system would still add value but might be considered recommended or supplemental.
- It is recommended that future bus designs accommodate MERV 13 or better filters.

A Summary of the Findings for HVAC In-Duct Disinfection Include:

- For in-duct UVC - without a single-pass kill dosage being delivered, it is unknown how repeated dosages of airborne materials at different time intervals will impact the UVC kill-dosage required. However, the science would suggest that some level of energy will be delivered and some virus weakening or even disinfection will occur with each pass. With the estimated one air exchange per minute, this implies positive support that particles would be subject to multiple doses in a relatively short period of time. Even though there is an efficacy uncertainty, there has been support for in-duct UVC systems on buses.

- Some in-duct UVC products are more established while others are newer – some are custom while others are newer but have an established relationship with MCI/NABI. With the limited information available, no features on any of the products standout nor give any product a distinct advantage over the others.
- For Ion (plasma) generators there are many unknowns and many possible pathways to negative health outcomes. Conversely, it's equally possible that it will or will not generated high enough ion concentrations in the bus to be effective, or that it could be only marginally effective. However, this technology does have the potential to disinfect, especially in a closed environment within the duct. The research team is unable to confirm efficacy or fully assess health impacts without additional information.
- Photocatalytic Oxidizer (PCO) and similar technologies are too new for complete air disinfection but may support or be used in conjunction with other technologies. The surface generation nature of the species and the high reactivity/short lived nature of these species means they present much less a health risk than the plasma source which is designed to push ions into the bus environment. Further identification and quantitation of the reactive species would need to be done before efficacy and possible health risks could be described in greater detail.

A Summary of the Findings for HVAC In-Duct Costs Include:

- Full fleet wide deployment might cost between $10.5M-16.3M for in-duct UVC, in duct plasma $7M, and in-duct PHI $12.3M.
- As per the previously discussed Federal Transit Administration (FTA) funded study the return on investment for an in-duct UVC device is estimated at $1,290 annually
- Estimated $334 saving per year per in-duct UVC device is likely on the low end of the actual savings but still represents a measurable and significant return on investment.
- In-duct UVC bulbs should last between 1.7 to 2.7 years
- Approximately $469k will be required on average per year to replace all in-duct UVC bulbs
- Estimated 4 years ROI based on the FTA report or 23 years ROI based on the more conservative estimate; there is a measurable and overall positive return on investment.

Emerging Technologies Observations Include:

- Though probably not practical for most Transit vehicles, disinfection can potentially be performed by modifying a vehicle's current HVAC to increase interior temperatures above 130 degrees Fahrenheit for 15 minutes. Additional wear and tear on the engine as well as allowing for proper cooling of the vehicle should be considered.

- Modifying the airflow in a vehicle using polycarbonate barriers alongside modification of the air pressure differentials within the driver and passenger zones can help move potentially contaminated air from passengers away from the driver.
- These airflow modifications have only been performed on Honda Odyssey minivans used in Detroit to transport passengers, but could potentially be emulated on other transit sedans and minivans outside of the Odyssey car model as well.

The use of in-duct disinfection technology while the bus is occupied, and in-service is very appealing to help protect passengers from contracting SARS-CoV-2 (COVID-19) from a passenger that is exhaling virus particles. Such systems may offer continuous disinfection activity. This is a different problem and solution set than surface disinfection systems discussed in prior sections of this report that are only effective well after a virus particle is introduced to the vehicle by customer or operator.

However, each in-duct technology discussed in the previous sections of this report has an efficacy or health concern that remains unclear. The research team believes that some products are indeed effective in killing viruses. However, it's uncertain how long it will take or how many exposures to reduce concentrations significantly – i.e. minutes or even hours. Furthermore, there is conflicting information on some technologies as well as lack of peer-reviewed studies for these products in the NJ TRANSIT operating environment. Ultimately, disinfection that occurs in the occupied space remains a challenge. The general rule that remains true is that if a concentration is high enough to kill viruses it may also be harmful to occupants. On the other hand, concentrations that don't harm occupants may not be effective in killing the viruses in a reasonable time to be effective.

While each air treatment technology has its own merits as a stand-alone system, certain technologies will potentially work better in conjunction with each other or will be more effective on specific vehicle types. For example, proper filtration is recommended in conjunction with in-duct UVC bulbs in order to reduce an accumulation of dust and debris which may build up over time and reduce the effectiveness of the UVC lamp output. A minimum MERV 8 filter is recommended by ASHRAE to be used alongside in-duct UVC systems for dust control.[105] Technology readiness and the labor time to install some of these devices fleet wide may take a year or more. Economics aside the practicality and speed unfortunately becomes a driving consideration too; retrofit labor plans may become quickly obsolete if the vehicle is to be retired in the near future.

The in-duct systems will cost between $7M-$16.3M for fleet wide deployment, representing a substantial capital cost. Beyond COVID-19, filtration has a track record of removing particles from the air which is beneficial for everyday dust irritants as well as harmful viruses. Likewise, UVC has a proven track record of killing viruses and bacteria so the benefit extends beyond the immediate pandemic. UVC is a well-established technology where the health exposure concerns are well defined and can be measured and mitigated. Furthermore, DART has deployed in-duct UVC since 2013 with no major logistics concerns. This is further supported by recommendation from a 2009 Federal Transit Administration (FTA) funded study by the Transportation Research Board (TRB) "Ultraviolet Germicidal Irradiation for Transit Buses" Transit IDEA project #53. Furthermore, based on the FTA report the return on investment dues to maintenance savings would likely be between 2 to 4 years depending on bus type. Estimated 4 years ROI based on the FTA report or 23 years ROI based on the more conservative estimate; there is a measurable and overall positive return on investment. Whereas other in-duct technologies have many unknowns and many possible pathways to negative health outcomes; further identification and quantitation of the reactive species would need to be done before efficacy and possible health risks could be described in greater detail. In-duct UVC is not the cheapest option at approximately $16.3M but has a favorable potential breakeven ROI. Nor is it without its own drawbacks but given the other technologies health and efficacy uncertainty the research team recommends the in-duct UVC. With that said, the research team recommends immediately focusing efforts to upgrade the filtration as well as conducting a pilot for in-duct UVC systems with the intention of near-term fleet wide adoption would appear to be a prudent, reasonable, and conservative approach.

6.1 Implementation and Next Steps

All Vehicles: Continue using an EPA List N approved chemical disinfectant following the manufacturer instructions. In comparison to chemical disinfection via **spray and air-dry procedures**, using portable UVC sources fleet wide does not appear to save labor time or cost.

All Vehicles: Consider adopting a weekly **spray and wipe** cleaning to achieve a more thorough cleaning and to remove any residue build-up. Develop a nightly rotation schedule to minimize labor requirement throughout the week.

All Vehicles: Review HVAC systems to ensure that **recirculation mode on HVAC system is turned off** and that **HVAC dampers are set to maximize fresh air intake** as conditions permit.

All Vehicles but likely more appropriate for buses: Review filters and **upgrade filters as appropriate**, will need to conduct air flow testing to ensure the system is within design specification. The goal is to upgrade to MERV 13 or better, but MERV 8 or even MERV 8 with antimicrobial would add value. NFI antimicrobial product has been flow tested for MCI Coach buses. The cost will likely exceed $1.1M above what NJ TRANSIT is currently spending on filters.

> All Vehicles: NJ TRANSIT should review the original design specification for the vehicles and **identify the original HVAC air flow design requirements**. This information will be needed to develop an air flow testing plan for the filter upgrades.

Bus Vehicles (NABI, MCI, and Mini-bus): Consider soliciting **in-duct UVC** vendors with a Request for Information (RFI) and/or conduct pilot testing on a few buses. The parent company of New Flyer (NABI) and MCI is NFI Group which has a product for MCI Coach buses. SanUVaire has a product that has been deployed by DART on NABI buses since 2013. There may be additional vendors and other factors to consider which is why the RFI process and pilot is recommended to develop the full approach, light leakage measurements, retrofit time, maintenance costs, and overall cost estimate.

> All Vehicles: Alternatively, if a vehicle is nearing retirement given the capital investment, though less ideal, NJ TRANSIT may elect to forego the in-duct UVC retrofit and attempt to reduce exposure through **mitigation controls**. For example, strategies may include physical distancing, reduced vehicle capacity limits, mask requirements, route changes, additional disinfection throughout the day, and others.

Paratransit vehicles specifically sedan and minivan: Consider **emerging technologies**, such as reprograming HVAC system in the sedan for heat disinfection as well the airflow modification (barrier and extra vents) to create positive pressure environment in the minivans.

Future Vehicles: NJ TRANSIT could **develop a working group** to review and provide recommendation and design review for future vehicles. Testing, modeling, and vetting vendor claims may be required.

7 FUTURE WORK

In-duct UVC systems show promise. The research team recommends a pilot study be performed on select in-duct UVC systems. This study could be as simple as installation and demonstration i.e. working through the logistics for specific buses and fully documenting the retrofit requirements and installation process. However, it could also be a robust efficacy evaluation involving surrogates. For the latter, a testing plan would need to be developed and conducted to determine efficacy of the system. This effort could be laboratory or on-vehicle but a testing plan likely with Institution Biosafety Review Board review and approval would be required. Swab type testing could be used, but to quantify a reduction the environment would have to be controlled start to finish. This would certainly provide a higher level of confidence regarding energy delivered by the UVC in-duct system with each pass.

As part of the in-duct UVC pilot testing plan, the research team would also recommend testing for UV light leakage into the passenger area and confirm that no ozone is produced. No significant levels of ozone are expected based on the emitted wavelength of light these lamps, this would simply be an extra precautionary measure. Additionally, light leakage is not expected to be an issue with these systems. However, there is a potential for small amounts of light to leak from around the filter frame, through the filter media, air vents, and other areas depending on lamp placement. The visible blue light emitted is not UVC, UVC is invisible, the research team would need to verify light leakage through the use of a spectrometer.

The research team recommended the adoption of antimicrobial filters. Although efficacy remains uncertain the research team does not have any health concerns at this time. However, future testing to determine the efficacy would be prudent to fully justify the expenditure. Furthermore, given the sizeable year-over-year cost of approximately $940k just for the antimicrobial layer, reevaluation is needed as NJ TRANSIT adopts other technologies i.e. in-duct UVC which may negate the overall benefit from these antimicrobial filters.

Many in-duct air treatment systems, such as ionization and photocatalytic oxidation, may warrant further investigation. Development of a testing plan to provide guidance on how to properly evaluate each of these technologies for efficacy, characterization of species, as well as health safety is needed. This is a larger time consuming undertaking, therefore NJ TRANSIT may elect to forego this effort in order to expedite other well established and more readily deployable technologies. For the ion generator type devices, the research team recommends further testing to identify and quantify ions of the reactive species to resolve the uncertainty regarding possible health risks as well as testing to confirm the efficacy.

Upgrading air filters to a more efficient MERV ratings is a potential strategy when it comes to treating the air circulating through HVAC systems. Though, pressure drop and airflow restrictions in the HVAC system can damage systems and may prevent higher MERV rated filters from being used. Furthermore, filter performance changes over use i.e. clean filters perform differently than clogged filters. The research team recommends airflow testing before adopting a higher rated MERV filter.

Many technologies mentioned throughout this report can be used for light rail, commuter rail, facilities, and buildings. However, since this project focused on buses there might be other approaches for light rail and commuter rail. Furthermore, there are many more devices not included herein that can be used for buildings. For example, other disinfection technologies such as upper-room UVC are more common in buildings but just not practical for a bus. A deeper look into how these technologies could be used alongside similar systems already researched thoroughly in this report would be beneficial. The knowledge gained throughout this study would provide a starting point for future research. The research team recommends identifying additional technologies and to develop a detailed plan to effectively deploy disinfection technologies for NJ TRANSIT light rail, commuter rail, and facilities.

Air quality is an important consideration for long term outside air exchanges on buses. The terms fresh air and outside air are used interchangeably in this report. However, the reality is that outside air may contain contaminants that are not desired inside the bus. Buses that are in the suburbs would potentially pull in far less atmospheric contaminants than those commuting through congested areas. If NJ TRANSIT adopts the power vent roof hatch, the research team recommends a more detailed testing and monitoring effort may be warranted to verify that by drawing in more outside air, that exposure remains below required thresholds.

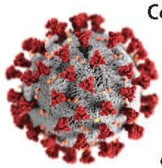
NJ TRANSIT will most certainly be looking to go through an extensive design review for future vehicles. The research team recommends developing a working group to review and provide recommendations. Furthermore, efforts may include testing and modeling to help validate vendor claims and recommendations. This group can also serve to provide ongoing support, quick commentary on new products, interpretation of news stories, and general engineering and public health guidance as the need arises. The specification may include:

- MERV 13 or better filters or even HEPA filtration
- Coupling technologies such as filters and UVC lights to increase contact time of particles which would also require a significantly different filter placement deeper in the system where UVC can illuminate without potential exposure
- Power vent roof hatch to increase ventilation
- Positive pressure environments or even possibly heat disinfection
- Built in permanently mounted UVC. Simple to use and could evenly distribute irradiance throughout the cabin and even cover more shadowed areas. The source may very well be small UVC LEDs throughout the bus shell, ceiling, and floor area. The increased capital expense may even be recouped by labor savings.
- Safety interlocks, occupancy sensors, and other safety devices
- Other new technologies

What Transit Workers Need to Know about COVID-19

BUS TRANSIT OPERATORS

Accessible version: https://www.cdc.gov/coronavirus/2019-ncov/community/organizations/bus-transit-operator.html



Coronavirus disease 2019 (COVID-19) is a respiratory illness caused by a virus called SARS-CoV-2. Symptoms often include a fever, cough, or shortness of breath. Our understanding of how the virus spreads is evolving as we learn more about it, so check the **CDC website** (https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html) for the latest information.

The virus is thought to spread mainly from person-to-person:

Between people who are in close contact with one another (within about 6 feet).

Through respiratory droplets produced when an infected person coughs, sneezes, or talks.

Recent studies indicate that the virus can be spread by people before they develop symptoms (pre-symptomatic) or who never develop symptoms (asymptomatic). It also may be possible that a person can get COVID-19 by touching a surface or object that has the virus on it and then touching their own mouth, nose, or possibly their eyes. However, this is not thought to be the main way the virus spreads. Older adults and people of any age who have serious underlying medical conditions may be at **higher risk for more serious complications** (https://www.cdc.gov/coronavirus/2019-ncov/need-extra-precautions/people-at-higher-risk.html) from COVID-19.

CDC recommends wearing cloth face coverings (https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/diy-cloth-face-coverings.html) in public settings where other social distancing measures are difficult to maintain, especially in areas of significant community-based transmission. Cloth face coverings may prevent people who don't know they have the virus from transmitting it to others. These face coverings are not surgical masks or respirators and are not appropriate substitutes for them in workplaces where masks or respirators are recommended or required.

As a bus transit operator, how can I protect myself?

For bus transit operators, potential sources of exposure include having close contact with a bus passenger with COVID-19, by contacting surfaces touched or handled by a person with COVID-19, or by touching your mouth, nose, or eyes.

- Limit close contact with others by maintaining a distance of at least 6 feet, when possible.
- Consider asking bus passengers to enter and exit the bus through rear entry doors.
- Request passengers avoid standing or sitting within 6 feet of the bus driver.
- Avoid touching surfaces often touched by bus passengers.
- Use gloves if required to touch surfaces contaminated by body fluids.
- Practice routine cleaning and disinfection of frequently touched surfaces, including surfaces in the driver cockpit commonly touched by the operator.
- Proper **hand hygiene** (https://www.cdc.gov/handwashing/index.html) is an important infection control measure. Wash your hands regularly with soap and water for at least 20 seconds. If soap and water are not readily available, use an alcohol-based hand sanitizer containing at least 60% alcohol.
- Key times to clean hands in general include:
    - Before, during, and after preparing food
    - Before eating food
    - After using the toilet
    - After blowing your nose, coughing, or sneezing
- Additional times to clean hands on the job include:
    - Before and after work shifts
    - Before and after work breaks
    - After touching frequently touched surfaces, such as fareboxes and handrails
    - After putting on, touching, or removing cloth face coverings
- Avoid touching your eyes, nose, or mouth.

cdc.gov/coronavirus

CS 316403-B 04/23/2020

What steps should my employer take?

Employers of bus transit operators should develop a COVID-19 health and safety plan to protect employees according to **CDC Business Guidance** (https://www.cdc.gov/coronavirus/2019-ncov/community/guidance-business-response.html). This plan should be shared with you and your coworkers. Your employer should:

- Institute measures to physically separate or force distance greater than 6 feet between bus transit operators and passengers. These may include use of physical partitions or visual cues (e.g., floor decals, colored tape, or signs to indicate to passengers where they should not sit or stand near the bus operator).
- **Take steps to help prevent the spread of COVID-19 if an employee is sick** (https://www.cdc.gov/coronavirus/2019-ncov/if-you-are-sick/steps-when-sick.html). Actively encourage sick employees to stay home. Sick employees should not return to work until **the criteria to discontinue home isolation are met** (https://www.cdc.gov/coronavirus/2019-ncov/hcp/disposition-in-home-patients.html), in consultation with healthcare providers and state and local health departments.
- Provide information on who to contact if employees become sick.
- Implement flexible sick leave and supportive policies and practices. Consider drafting non-punitive emergency sick leave policies if sick leave is not offered to some or all employees.
- Designate someone to be responsible for responding to COVID-19 concerns. Employees should know who this person is and how to contact them.
- Provide employees with correct information about COVID-19, how it spreads, and risk of exposure.
- Conduct worksite assessments to identify COVID-19 prevention strategies.
- Provide employees training on proper **hand washing** (https://www.cdc.gov/handwashing/index.html) practices and other routine infection control precautions. This will help prevent the spread of many diseases, including COVID-19.
- Provide employees access to soap, clean running water, and drying materials, or alcohol-based hand sanitizers containing at least 60% alcohol at their worksite.
- Provide employees with appropriate gloves when necessary and provide training on properly using them.
- Provide disposable disinfectant wipes so that surfaces commonly touched by the bus operator can be wiped down. To disinfect, use **products that meet EPA's criteria for use against SARS-CoV-2** (https://www.epa.gov/pesticide-registration/list-n-disinfectants-use-against-sars-cov-2), diluted household bleach solutions, or alcohol solutions with at least 70% alcohol, and are appropriate for the surface. Provide employees training on manufacturer's directions for use.
- Provide tissues and no-touch disposal receptacles for use by employees.
- Place posters that encourage **staying home when sick** (https://www.cdc.gov/nonpharmaceutical-interventions/tools-resources/educational-materials.html)**, covering coughs and sneezes** (https://www.cdc.gov/healthywater/hygiene/etiquette/coughing_sneezing.html) and **washing hands often** (https://www.cdc.gov/handwashing/materials.html) at the entrance to the workplace and in other workplace areas where they are likely to be seen.
- Reach out to local public health officials to establish ongoing communications to facilitate access to relevant information before and during a local outbreak.
- Follow all applicable federal regulations and public health agency guidelines.

Where can I get more information?

Stay informed. Talk to your employer, supervisor, union representative, or agency personnel who are responsible for responding to COVID-19 concerns. See these sources for more information on worker exposures to COVID-19:

CDC Interim Guidance for Businesses and Employers to Plan and Respond to Coronavirus Disease 2019 (COVID-19) website: https://www.cdc.gov/coronavirus/2019-ncov/community/guidance-business-response.html

NIOSH Workplace Safety and Health Topic website: www.cdc.gov/niosh/emres/2019_ncov.html

CDC COVID-19 website: www.cdc.gov/coronavirus/2019-ncov/

OSHA COVID-19 website: www.osha.gov/SLTC/covid-19/controlprevention.html

CDCINFO: 1-800-CDC-INFO (1-800-232-4636) | TTY: 1-888-232-6348 | website: https://wwwn.cdc.gov/dcs/ContactUs/Form

cdc.gov/coronavirus

Centers for Disease Control and Prevention

Coronavirus Disease 2019 (COVID-19)

Protect Yourself When Using Transportation

Public transit, rideshares and taxis, micro-mobility devices, and personal vehicles

As schools, businesses, and community organizations begin providing services, consider ways that you can protect yourself and slow the spread of COVID-19 when using transportation. When you consider the following options, think about what is feasible, practical, and acceptable to you and meets your needs. Also see CDC's tips for how to stay safe while running errands.

For all types of transportation

When using any type of transportation, follow these general principles:

Practice hand hygiene and respiratory etiquette.

- Before you leave, wash your hands with soap and water for at least 20 seconds or use hand sanitizer with at least 60% alcohol.
- Once you reach your destination, wash your hands again with soap and water for at least 20 seconds or use hand sanitizer with at least 60% alcohol as soon as possible upon arrival.
- Avoid touching your eyes, nose, and mouth with unwashed hands.
- Cover your coughs and sneezes with a tissue or use the inside of your elbow. Throw used tissues in the trash and wash your hands immediately with soap and water for at least 20 seconds or use hand sanitizer with at least 60% alcohol.

Practice social distancing.

- During travel, try to keep at least 6 feet (2 meters) from people who are not in your household — for example, when you are waiting at a bus station or selecting seats on a train.

Wear cloth face coverings.

- Wear a cloth face covering when physical distancing is difficult.
    - Note: Cloth face coverings should **not** be placed on:
        - Babies and children younger than 2 years old
        - Anyone who has trouble breathing or is unconscious
        - Anyone who is incapacitated or otherwise unable to remove the cloth face covering without assistance
- Cloth face coverings are meant to protect other people in case the wearer is unknowingly infected but does not have symptoms.

Stay home when appropriate.

- People who are sick or have recently had a close contact (closer than 6 feet for at least 15 minutes) to a person with COVID-19 should not use public transportation and should stay home except to seek medical care.

Have adequate supplies.

- Before traveling, pack sanitizing wipes and hand sanitizer with at least 60% alcohol (in case you are unable to wash your hands at your destination). Bring your cloth face covering to wear at times when physical distancing is difficult—

for example, while riding on a train or bus, waiting at a rest stop, or riding in a car with people outside your household.

Protect people at risk for severe illness from COVID-19.

- Individuals who are at higher risk of severe illness from COVID-19, such as older adults, people with disabilities, and people of any age who have serious underlying medical conditions, should limit their travel.
- If you need special accommodations or assistance while traveling (for example, help with a wheelchair lift or with carrying bags), if possible, take a transportation "buddy" with you (preferably from your household) to help you during travel.

Public transit

Follow the general principles listed above, plus the following. . . . .

Stay up-to-date.

- Check with local transit authorities for the latest information on changes to services and procedures, especially if you might need additional assistance.

Avoid touching surfaces.

- Limit touching frequently touched surfaces such as kiosks, digital interfaces such as touchscreens and fingerprint scanners, ticket machines, turnstiles, handrails, restroom surfaces, elevator buttons, and benches as much as possible.
  - If you must touch these surfaces, as soon as you can, wash your hands for 20 seconds with soap and water or rub your hands with sanitizer containing 60% alcohol.
- Use touchless payment and no-touch trash cans and doors when available. Exchange cash or credit cards by placing them in a receipt tray or on the counter rather than by hand, if possible.

Practice social distancing.

- When possible, consider traveling during non-peak hours when there are likely to be fewer people.
- Follow social distancing guidelines by staying at least 6 feet (2 meters) from people who are not from your household. For example:
  - Avoid gathering in groups, and stay out of crowded spaces when possible, especially at transit stations and stops.
  - Consider skipping a row of seats between yourself and other riders if possible.
  - Enter and exit buses through rear entry doors if possible.
  - Look for social distancing instructions or physical guides offered by transit authorities (for example, floor decals or signs indicating where to stand or sit to remain at least 6 feet apart from others).

Practice hand hygiene.

- After you leave the transit station or stop, use hand sanitizer containing at least 60% alcohol.
- When you arrive at your destination, wash your hands with soap and water for at least 20 seconds.

Rideshare, taxi, limo for-hire vehicle passengers

Follow the general principles listed above, plus the following. . .

Avoid touching surfaces.

- Avoid contact with surfaces frequently touched by passengers or drivers, such as the door frame and handles, windows, and other vehicle parts. In circumstances where such contact is unavoidable, use a hand sanitizer containing at least 60% alcohol as soon as possible afterwards.
- Avoid accepting offers of free water bottles and avoid touching magazines or other items that may be provided for free to passengers.
- Use touchless payment when available.

Practice social distancing.

- Limit the number of passengers in the vehicle to only those necessary.
- Avoid pooled rides or rides where multiple passengers are picked up who are not in the same household.
- Sit in the back seat in larger vehicles such as vans and buses so you can remain at least six feet away from the driver.

Improve ventilation.

- Ask the driver to improve the ventilation in the vehicle if possible — for example, by opening the windows or setting the air ventilation/air conditioning on non-recirculation mode.

Practice hand hygiene.

- After leaving the vehicle, use hand sanitizer containing at least 60% alcohol.
- When you arrive at your destination, wash your hands with soap and water for at least 20 seconds.

Shared bikes, scooters, skateboards, and other micro-mobility devices

Follow the general principles listed above, plus the following. . .

Clean and disinfect surfaces.

- **Clean and disinfect** frequently touched surfaces on the device (e.g., handlebars, gears, braking handles, locks etc.) or shared equipment before you use it. Use disinfecting wipes, if available.

Avoid touching surfaces.

- Use touchless payment when available and if applicable.

Practice hand hygiene.

- After completing your trip, wash your hands with soap and water for at least 20 seconds or use a hand sanitizer containing at least 60% alcohol.

Personal vehicles

Follow the general principles listed above, plus the following. . .

Clean and disinfect surfaces.

- **Clean and disinfect** frequently touched surfaces regularly (for example, the steering wheel, gear shift, door frame/handles, windows, radio/temperature dials, and seatbelt buckles).
- When using parking meters and pay stations, consider using alcohol wipes to disinfect surfaces or use hand sanitizer containing at least 60% alcohol after use. Wash hands with soap and water for at least 20 seconds as soon as it is possible.

Practice social distancing.

- Consider limiting the number of passengers in the vehicle to only those necessary (for example, choose one or two family members who are not at higher risk for severe illness to run the essential errands).

Improve ventilation.

- Improve the ventilation in the vehicle if possible (for example, open the windows or set the air ventilation/air conditioning on non-recirculation mode).

People with transportation-related jobs

If transportation is part of your job, see these additional resources on how to protect yourself from COVID-19 at work.

- Information for bus transit operators, rail transit operators, transit maintenance workers, and transit station workers
- Information for food and grocery pick-up and delivery drivers
- Information for mail and parcel delivery drivers
- Information for rideshare, taxi, limo and other passenger drivers-for-hire
- Information for long-haul truck drivers

Page last reviewed: May 26, 2020

9 APPENDIX – EPA CFL Cleanup and Disposal Guidance

U.S. Environmental Protection Agency April 7, 2014

What to Do if a Compact Fluorescent Light (CFL) Bulb or Fluorescent Tube Light Bulb Breaks in Your Home[1]

Fluorescent light bulbs contain a small amount of mercury sealed within the glass tubing. When a fluorescent bulb breaks in your home, some of this mercury is released as mercury vapor. The broken bulb can continue to release mercury vapor until it is cleaned up and removed from the residence.

To minimize exposure to mercury vapor, EPA recommends that residents follow the cleanup and disposal steps described below. This cleanup guidance represents the minimum actions recommended to clean up a broken CFL, and will be updated as EPA identifies more effective cleanup practices.

CLEANUP AND DISPOSAL OVERVIEW

The most important steps to reduce exposure to mercury vapor from a broken bulb are:

1. **Before cleanup**
   a. Have people and pets leave the room.
   b. Air out the room for 5-10 minutes by opening a window or door to the outdoor environment.
   c. Shut off the central forced air heating/air-conditioning system, if you have one.
   d. Collect materials needed to clean up broken bulb:
      - stiff paper or cardboard;
      - sticky tape;
      - damp paper towels or disposable wet wipes (for hard surfaces); and
      - a glass jar with a metal lid or a sealable plastic bag.

2. **During cleanup**
   a. DO NOT VACUUM. Vacuuming is not recommended unless broken glass remains after all other cleanup steps have been taken. Vacuuming could spread mercury-containing powder or mercury vapor.
   b. Be thorough in collecting broken glass and visible powder.
   c. Place cleanup materials in a sealable container.

3. **After cleanup**
   a. Promptly place all bulb debris and cleanup materials outdoors in a trash container or protected area until materials can be disposed of. Avoid leaving any bulb fragments or cleanup materials indoors.
   b. Next, check with your local government about disposal requirements in your area, because some localities require fluorescent bulbs (broken or unbroken) be taken to a local recycling center. If there is no such requirement in your area, you can dispose of the materials with your household trash.
   c. If practical, continue to air out the room where the bulb was broken and leave the heating/air conditioning system shut off for several hours.

Before Cleanup

- Have people and pets leave the room, and avoid the breakage area on the way out.
- Open a window or door to the outdoors and leave the room for 5-10 minutes.
- Shut off the central forced-air heating/air conditioning (H&AC) system, if you have one.
- Collect materials you will need to clean up the broken bulb:
    - Stiff paper or cardboard
    - Sticky tape (e.g., duct tape)
    - Damp paper towels or disposable wet wipes (for hard surfaces)
    - Glass jar with a metal lid (such as a canning jar) or a sealable plastic bag(s)

Cleanup Steps for Hard Surfaces

- Carefully scoop up glass fragments and powder using stiff paper or cardboard and place debris and paper/cardboard in a glass jar with a metal lid. If a glass jar is not available, use a sealable plastic bag. (NOTE: Since a plastic bag will not prevent the mercury vapor from escaping, remove the plastic bag(s) from the home after cleanup.)
- Use sticky tape, such as duct tape, to pick up any remaining small glass fragments and powder. Place the used tape in the glass jar or plastic bag.
- Wipe the area clean with damp paper towels or disposable wet wipes. Place the towels in the glass jar or plastic bag.
- Vacuuming of hard surfaces during cleanup is not recommended unless broken glass remains after all other cleanup steps have been taken. [NOTE: It is possible that vacuuming could spread mercury-containing powder or mercury vapor, although available information on this problem is limited.] If vacuuming is needed to ensure removal of all broken glass, keep the following tips in mind:
    - Keep a window or door to the outdoors open;
    - Vacuum the area where the bulb was broken using the vacuum hose, if available; and
    - Remove the vacuum bag (or empty and wipe the canister) and seal the bag/vacuum debris, and any materials used to clean the vacuum, in a plastic bag.
- Promptly place all bulb debris and cleanup materials, including vacuum cleaner bags, outdoors in a trash container or protected area until materials can be disposed of. Avoid leaving any bulb fragments or cleanup materials indoors.
- Next, check with your local government about disposal requirements in your area, because some localities require fluorescent bulbs (broken or unbroken) be taken to a local recycling center. If there is no such requirement in your area, you can dispose of the materials with your household trash.
- Wash your hands with soap and water after disposing of the jars or plastic bags containing bulb debris and cleanup materials.
- Continue to air out the room where the bulb was broken and leave the H&AC system shut off, as practical, for several hours.

Cleanup Steps for Carpeting or Rugs

- Carefully scoop up glass fragments and powder using stiff paper or cardboard and place debris and paper/cardboard in a glass jar with a metal lid. If a glass jar is not available, use a sealable plastic bag. (NOTE: Since a plastic bag will not prevent the mercury vapor from escaping, remove the plastic bag(s) from the home after cleanup.)

- Use sticky tape, such as duct tape, to pick up any remaining small glass fragments and powder. Place the used tape in the glass jar or plastic bag.
- Vacuuming of carpeting or rugs during cleanup is not recommended unless broken glass remains after all other cleanup steps have been taken. [NOTE: It is possible that vacuuming could spread mercury-containing powder or mercury vapor, although available information on this problem is limited.] If vacuuming is needed to ensure removal of all broken glass, keep the following tips in mind:
    - Keep a window or door to the outdoors open;
    - Vacuum the area where the bulb was broken using the vacuum hose, if available, and
    - Remove the vacuum bag (or empty and wipe the canister) and seal the bag/vacuum debris, and any materials used to clean the vacuum, in a plastic bag.
- Promptly place all bulb debris and cleanup materials, including vacuum cleaner bags, outdoors in a trash container or protected area until materials can be disposed of. Avoid leaving any bulb fragments or cleanup materials indoors.
- Next, check with your local government about disposal requirements in your area, because some localities require fluorescent bulbs (broken or unbroken) be taken to a local recycling center. If there is no such requirement in your area, you can dispose of the materials with your household trash.
- Wash your hands with soap and water after disposing of the jars or plastic bags containing bulb debris and cleanup materials.
- Continue to air out the room where the bulb was broken and leave the H&AC system shut off, as practical, for several hours.

Future Cleaning of Carpeting or Rugs: Air Out the Room During and After Vacuuming

- The next several times you vacuum the rug or carpet, shut off the H&AC system if you have one, close the doors to other rooms, and open a window or door to the outside before vacuuming. Change the vacuum bag after each use in this area.
- After vacuuming is completed, keep the H&AC system shut off and the window or door to the outside open, as practical, for several hours.

Actions You Can Take to Prevent Broken Compact Fluorescent Light Bulbs

Fluorescent bulbs are made of glass and can break if dropped or roughly handled. To avoid breaking a bulb, follow these general practices:

- You can switch off and allow a working CFL bulb to cool before handling.
- You can handle CFL bulbs carefully to avoid breakage.
    - If possible, screw/unscrew the CFL by holding the plastic or ceramic base, not the glass tubing.
    - Gently screw in the CFL until snug. Do not over-tighten.
    - Never forcefully twist the glass tubing.
- You can choose not to install CFLs in table lamps and floor lamps that can be easily knocked over, in unprotected light fixtures, or in locations where they can easily be broken, such as play spaces.
    - Other available options for these areas: LEDs (super-efficient, with very low energy costs; pricey, although prices are dropping rapidly), and halogens (inexpensive, more efficient than incandescents, but not as efficient as CFLs or LEDs).
- You can purchase CFL bulbs that have a glass or plastic cover over the spiral or folded glass tube, if available. These types of bulbs look more like incandescent bulbs and may be more durable if dropped.

- You can consider using a drop cloth (e.g., plastic sheet or beach towel) when changing a fluorescent light bulb in case a breakage should occur. The drop cloth will help prevent mercury contamination of nearby surfaces and can be bundled with the bulb debris for disposal.

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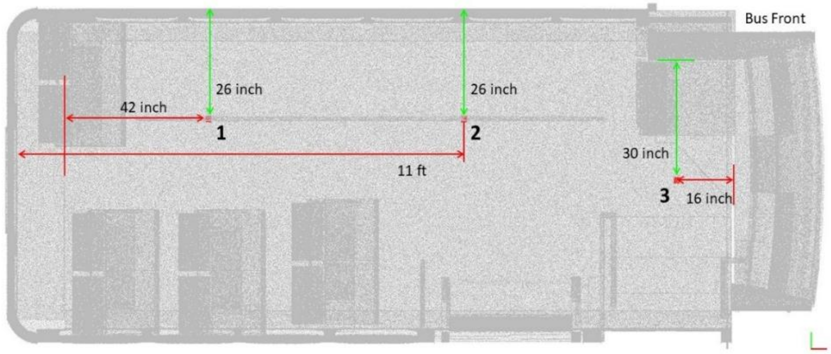
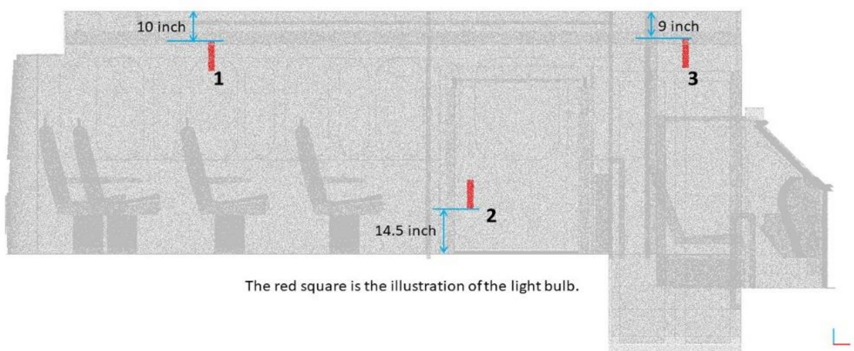
[1] This document contains information designed to be useful to the general public. This document does not impose legally binding requirements, nor does it confer legal rights, impose legal obligations, or implement any statutory or regulatory provisions. This document does not change or substitute for any statutory or regulatory provisions. This document presents technical information based on EPA's current understanding of the potential hazards posed by breakage of mercury-containing fluorescent lamps (light bulbs) in a typical household setting. Finally, this is a living document and may be revised periodically without public notice. EPA welcomes comments on this document at any time and will consider those comments in any future revisions of this document.

10 APPENDIX – Reference Locations for Portable Mercury UVC

TOP VIEW

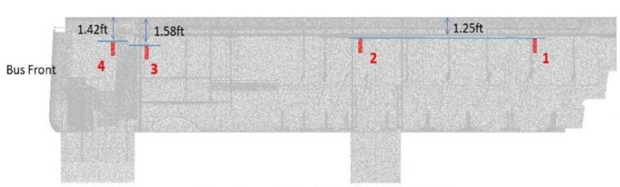


SIDE VIEW



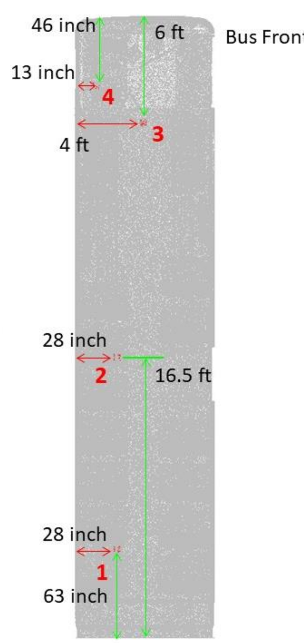
The red square is the illustration of the light bulb.

SIDE VIEW



The red square is the illustration of the light bulb.

TOP VIEW



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