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Efficacy of Filter Improvements for Transit Vehicles to Combat the Spread of COVID-19 and Other Respiratory Infections

FINAL REPORT
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And
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And
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16. Abstract The COVID-19 pandemic has been a worldwide issue that transit agencies are still struggling to find cost-efficient solutions to. Upgrading the filters used on trains and buses to reduce the airborne transmission of the SARS-CoV-2 virus as well as other infectious viruses, such as influenza, may be an effective, cost-efficient way of containing the very small, hard-to-filter droplet and aerosol particles that these viruses may travel within. One way to improve transit vehicle air quality and safety is to upgrade the current MERV-rated filters to higher-rated ones such as a MERV 13 filter. This study will look at quantifying the upgraded filters' performance, focusing on their efficacy over time and comparing them to a MERV 8 filter. Filter performance was investigated using sodium chloride (NaCl) particles and Arizona Road Dust (ARD) particles to determine the filter collection efficiency. A Grimm MiniWras and Aerodynamic Particle Sizer was used to compare the number concentrations (#/L) of particles upstream and downstream of the filter. The filter testing data confirm that MERV-13 filters have better filtration efficiency compared to MERV-8 filters but the filter performance varies depending on the age of the filter (i.e., its loading), particle type, and particle properties (charged vs. neutralized).		
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Descriptions of Problem

The COVID-19 pandemic is a worldwide issue that transit agencies are still struggling to find cost-efficient solutions that will provide improved rider safety and restore rider confidence. Airborne transmission of the virus has been identified as one of the primary modes through which COVID-19 is spread. Thus, mitigating steps need to be taken to minimize the risk of airborne virus transmission. Transit agencies had used traditional air filters in their trains and buses to remove particulate matter from the air long before the pandemic began. Upgrading these filters may be an effective, cost-efficient way of containing the very small, hard-to-filter droplet and aerosol particles that the SARS-CoV-2 virus may travel within. The upgraded system will also have an extended benefit by combating the spread of other infectious viruses, such as influenza.

The Rutgers Center for Advanced Infrastructure and Transportation (CAIT) has been in contact with transit agencies across the U.S. while working with local transit operators and coordinating with other federal organizations to investigate different disinfection strategies to combat the spread of COVID-19. Throughout our many studies with these agencies, potential methods to improve transit vehicle air quality and safety were upgrading the current MERV-rated filters to higher-rated ones such as a MERV 13 filter. However, the efficacy of these filters changes over time, and their specific performance in a transit environment is unknown. This project seeks to quantify the upgraded filters' performance, focusing on their efficacy over time.

Rutgers CAIT, partnered with Rutgers Environmental and Occupational Health Sciences Institute (EOHSI), the Department of Environmental Sciences (DES), and NJ Transit (NJT), has the capability to test the real-world performance of these filters and other similar disinfection devices using both in lab specimens as well as specimens used in actual rail and bus vehicles.

Approach

The goal of this project was to test the performance of air filters (MERV 8 and MERV 13 ratings) in terms of their physical efficiency for particles sizes ranges similar to those specified by ASTM standard: E1 (0.3 to 1 µm), E2 (1 to 3 µm), and E3 (3 to 10 µm). The work was divided into three tasks.

<u>Task 1.</u> MERV 13 filter cutouts (pleated and flat disk) were tested, and the results were compared to those provided by a testing company when testing similar filters. The testing here was performed with used filters.

<u>Task 2.</u> MERV 13 filter cutout (flat disk) was tested with particles of two types: particles with their charge neutralized and particles with their charge not neutralized. Particles carrying electrostatic charge represent air pollution particles that have been freshly aerosolized (one can think of them as packaging peanuts that cling to surfaces due to charge); this phenomenon is simulated by aerosolizing the test particles but not removing the charge. As the particles spend time in the air, e.g., “age,” their charge levels decrease due neutralizing action of atmospheric ions. This phenomenon is simulated by aerosolizing particles and then passing them through a cloud of ions to remove the electrostatic charge. The testing in this task was performed with new filters.

<u>Task 3.</u> Cutouts from new and used MERV 8 filter (foam) were tested.

MERV 13 filters are able to filter 85% of particles from 1 µm to 3 µm in size, which is ideal for capturing respiratory droplets, which have been shown to be one of the most common modes of travel for the SARS-CoV-2 virus. Professional organizations such as The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have also recommended installing filters with a rating of MERV 13 or higher. Artificially infused electrostatic charge on such filters is one way in which a filter can achieve this MERV 13 rating, but they have the potential to lose their high filtration efficiency once the electrostatic charge has dissipated due to atmospheric ions. Still, the use of MERV-13 would be an improvement over their current MERV 8 foam filters being used in transit vehicles.

An additional dimension of testing was the use of two instruments based on different principles of operation: 1) Grimm MiniWRAS (Grimm Technologies Inc., Douglasville, GA), which is a combination of electrical and optical measurements; the instrument has a range of 10 nm – 30 µm, 2) and APS 3321 (TSI Inc., Shoreview, MN), which sizes and counts particles based on their aerodynamic diameter. The instrument has a range of 0.53-20 µm. Particle aerodynamic diameter is an important parameter because it governs particle behavior in the air. Electrical and optical particle diameters measured by the Grimm MiniWRAS are derivative parameters that might differ from the aerodynamic diameter based on particle shape and density. However, electrical and optical measurement instruments have a wider range and are usually less expensive than APS. The APS is the only instrument on the market to measure aerodynamic particle diameter.

Tested filters

New and used MERV-13 filters, 16x20x2 inches shown below in **Figure 1** were tested. The used filters had been installed in N.J. Transit railroad car 6522 for 6 days.

Figure 1: MERV-13 filters, 16x20x2 inches

New and used MERV-8 foam filters, 15.25x19.25x1.75 inches shown in **Figure 2** below were also tested.

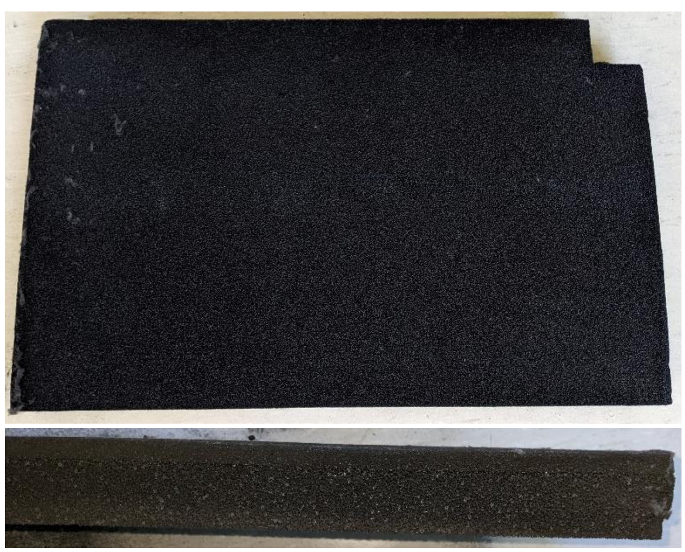

Figure 2: MERV-8 foam filters, 15.25x19.25x1.75 inches

Methodology

Experimental setup

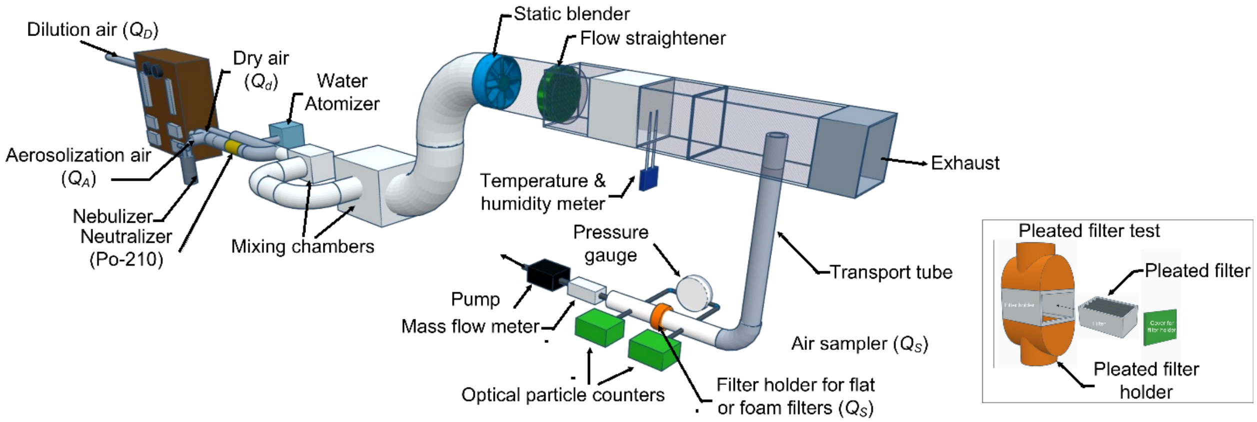

Figure 3: Experimental setup for aerosol generation and filter testing

The setup consisted of a flow control system, aerosol generation system, air humidity control system, air-particle mixing system, and particle monitoring system housed inside a Class II biosafety cabinet (Nuaire Inc., Plymouth, MN). A six-jet Collison nebulizer (Mesa Laboratories Inc, Butler, NJ) was used to aerosolize challenge particles from a liquid suspension at a flow rate (Q_{A}) of 5 L/min (pressure of 20 psi), and the aerosolized particles were mixed with a dry airflow, Q_d (5 L/min). A HEPA-filtered dilution airflow, Q_{D} (60 L/min), provided by an in-house compressor, was used to dilute the particle stream. The test chamber's relative humidity (RH) was controlled by adjusting a water atomizer's input into the air-particle mixing system. Combined air streams passed through a 2-mCi Po-210 charge neutralizer (Amstat Industries Inc, Glenview, IL) to reduce aerosolization-induced electrostatic particle charges to Boltzmann charge equilibrium. For some experiments, the neutralizer was removed, as noted in the text. The absence of the neutralizer allows us to investigate filter performance with particles carrying electrostatic charge.

The air with challenge particles entered two separate mixing chambers to ensure uniform distribution of particles across the plenum. A well-mixed flow stream then passes through a flow-straightener (honeycomb). The air temperature and R.H. were monitored downstream of the flow-straightener using a probe (Cooper-Atkins Corp, Middlefield, CT).

Airborne test particles were then pulled into a vertical transport tube and subsequent horizontal transport tube. The tube contained a filter holder with the filter to be tested. The particle concentrations upstream and downstream of the filter were measured by an employed instrument described above. The pressure drop across the filter was measured by a pressure gauge (Dwyer Instrument Inc., Michigan City, IN). The air flowrates across the tested filters varied depending on the shape of the test filters (pleated or flat, or foam filter), and they were provided by a vacuum pump (SKC Inc., Eight Four, PA) and monitored by a mass flowmeter (TSI Inc., Shoreview, MN).

Filter performance was investigated using sodium chloride (NaCl) particles and Arizona Road Dust (ARD) particles - both substances produced polydisperse test particles, i.e., particles with a wide size distribution. The filter collection efficiency was determined by comparing the number concentrations (#/L) of particles *upstream and downstream of the filter* using Grimm MiniWras (Grimm Technologies Inc., Douglasville, GA) and Aerodynamic Particle Sizer (APS, Model 3321, TSI Inc., Shoreview, MN) and it was reported at a size range of 0.3 µm to 10 µm. In addition, we calculated efficiencies for particles sizes ranges similar to that specified by ANSI/ASHRAE standard 52.2: E1 (0.3 to 1 µm), E2 (1 to 3 µm), and E3 (3 to 10 µm). Measurements for each particle were repeated at least three times for 30 sec upstream and downstream.

Preparation of the filters

Due to limited test chamber size, tests were conducted with filter cutouts. The flow rate through the tested filter was adjusted so that the air velocity through the filter approximates air velocity during its use, e.g., when installed in an N.J. Transit vehicle.

The test specimens were cut from MERV-13 pleated filters (Camfil Aeropleat, 16x20x2 inches) and MERV-8 foam filters (15.25x19.25x1.75 inches). Two cutouts from MERV-13 were tested: 47 mm flattened disk and 4.0x2.47x1.75 inch cutout. For the MERV-8 filter, a 50.8 mm diameter disk was used.

Test conditions

The study was conducted with three tasks to evaluate MERV-13 and MERV-8 filters with NaCl or ARD particles. When available, the data were compared with that provided by other parties. Table 1 summarizes the experimental conditions for the Task 1 used filters.

Table 1: Test conditions for Task 1.

Test location	#	Specific filter	Type	Nominal size, inch	Face velocity m/s
Camfil facility	1	Car 6522 - A-End Middle	Pleated-Panel	20x16x2	0.82
Camfil facility	2	Car 6522 - A-End Left	Pleated-Panel	20x16x2	0.80
Camfil facility	3	Car 6522 - A-End Right	Pleated-Panel	20x16x2	0.80
Camfil facility	4	Car 6522 - B-End Middle	Pleated-Panel	20x16x2	0.80
Camfil facility	5	Car 6522 - B-End Left	Pleated-Panel	20x16x2	0.80
Camfil facility	6	Car 6522 - B-End Right	Pleated-Panel	20x16x2	0.80
Camfil facility	7			24x24x2	2.54
Rutgers	1		Pleated-Panel	4.0x2.47x1.75	0.88
Rutgers	2		Flat-disk	1.85	0.21

For Task 2, the filter cutout (47 mm in diameter) of the MERV-13 filter was tested at 0.21 m/s face velocity with NaCl and ARD particles and with or without a 2-mCi Po-210 charge neutralizer. The neutralizer reduces aerosolization-induced particle charges to Boltzmann equilibrium.

For Task 3, the filter cutouts of the MERV-8 foam filter were tested and compared at 0.9 m/s face velocity when testing with NaCl: new versus two used filters. The latter had been used in railroad car numbers 6040 Middle and 7640-B-end.

Findings

Task 1

Figure 4 compares collection efficiencies between MERV-13 filters measured by Camfil's ASHRAE testing facility (Riverdale, NJ) and new filters (flat disk and pleated filters) tested at Rutgers. Here, testing was performed with 2% NaCl solution at 0.21 m/s face velocity (for the flat filter) and 0.88 m/s face velocity (for the pleated filter). The filter's performance for each of the 41 size bins (10 nm to 35 µm) was determined using Grimm MiniWras (Grimm Technologies Inc.).

Figure 4 shows the resulting size-resolved collection efficiency measured for the MERV-13 filter for particle sizes 0.3 µm to 10 µm. Collection efficacy is represented by 0.0 filtering none of the particles and 1.0 filtering all particles. This figure shows results for the 7 filters with Camfil-reported values and the 2 filters with Rutgers-tested values. Overall, as could be expected, when particle size increased, the collection efficiency increased. However, there was a difference depending on a particular used filter among those tested by Camfill. Filters tested at Rutgers showed a higher collection efficiency at smaller particle sizes. The efficiencies matched well for particles 4 µm and larger.

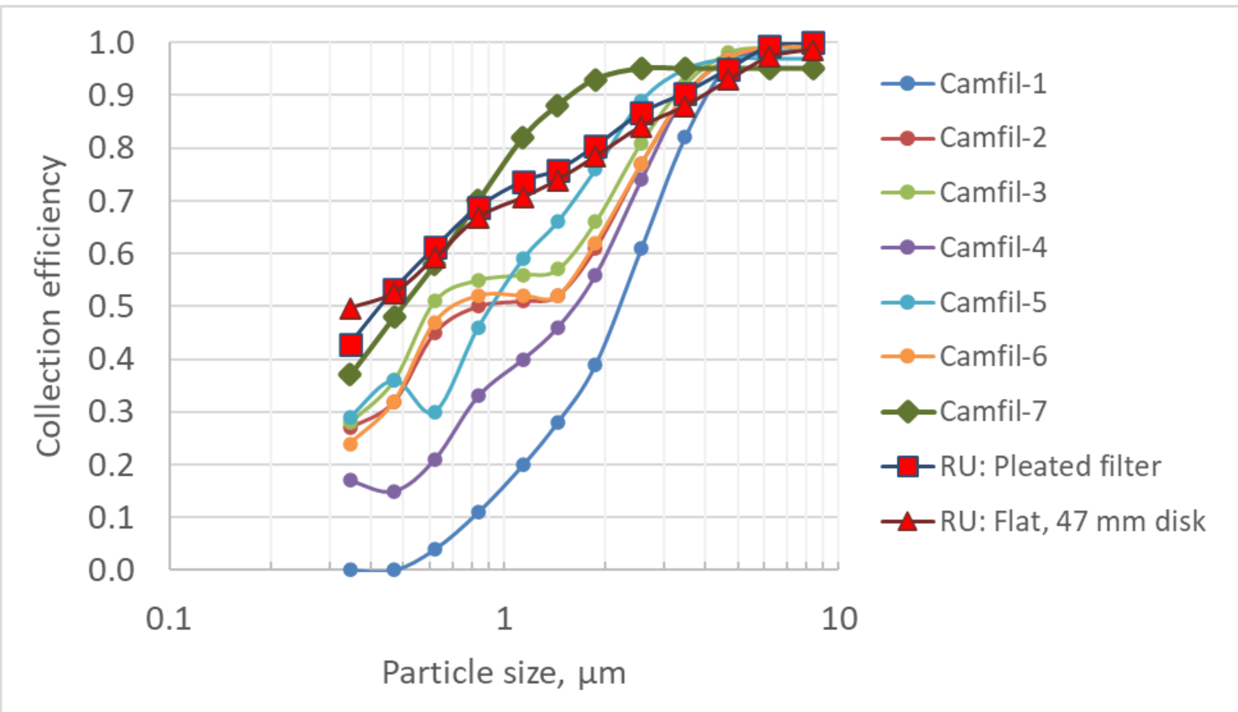

Figure 4: Collection efficiency of MERV-13 filter as a function of particle size at 0.21 or 0.88m/s face velocity measured by Grimm MiniWRAS when testing 2% NaCl particles

The **Figure 4** shows collection efficiency of a MERV-13 filter as a function of particle size at 0.21 or 0.88m/s face velocity measured by Grimm MiniWRAS when testing 2% NaCl particles. A flat filter (47 mm in diameter) and a pleated filter (4x2.47 inches) are used.

In addition to collection efficiency curves presented in Figure 4, we also calculated efficiency ranges similar to those specified by the ASHRAE 52.2 standard: E1 (which is 0.3 to 0.94 µm), E2 (which is 1.11 to 2.98 µm), and E3 (which is 3.52 to 9.43 µm). E1, E2, and E3 values defined according to ASHRAE 52.2 are summarized in **Table 2**.

Table 2 below shows a comparison of E1, E2, and E3 efficiencies: the filters tested at the Camfil facility using KCl particles and measured by TSI OPS, and the filters tested at Rutgers with NaCl particles and measurement with Grimm MiniWras.

Table 2: Comparison of E1, E2, and E3 efficiencies: Camfil facility using KCl particles measured by TSI OPS, and at Rutgers with NaCl particles measued with Grimm MiniWras

	Camfil-1	Camfil-2	Camfil-3	Camfil-4	Camfil-5	Camfil-6	Camfil-7	RU-1	RU-2
E1	0.04	0.39	0.43	0.22	0.35	0.39	0.53	0.57	0.57
E2	0.37	0.60	0.65	0.54	0.73	0.61	0.90	0.79	0.77
E3	0.94	0.96	0.97	0.97	0.97	0.96	0.95	0.96	0.94
AVG	0.45	0.65	0.68	0.57	0.68	0.65	0.79	0.77	0.76

Task 2.

In this task, the efficiency of a new MERV-13 filter was tested with NaCl and ARD particles that were either charge-neutralized or non-neutralized particles (Figure 5). The results are also presented in Table 3 for the collection efficiency ranges specified by the ASHRAE 52.2 standard. For ultrafine particles (< 0.1 µm), the average collection efficiencies were 69% (NaCl) versus 93% (ARD) without a neutralizer and 48% (NaCl) versus 40% (ARD) with a neutralizer. It is obvious that the charge and particle type play a big role in the filter's performance, especially for particles <0.5 in size, where electrostatic phenomena dominate the collection process. The collection of larger particles is dominated by inertia-based phenomena.

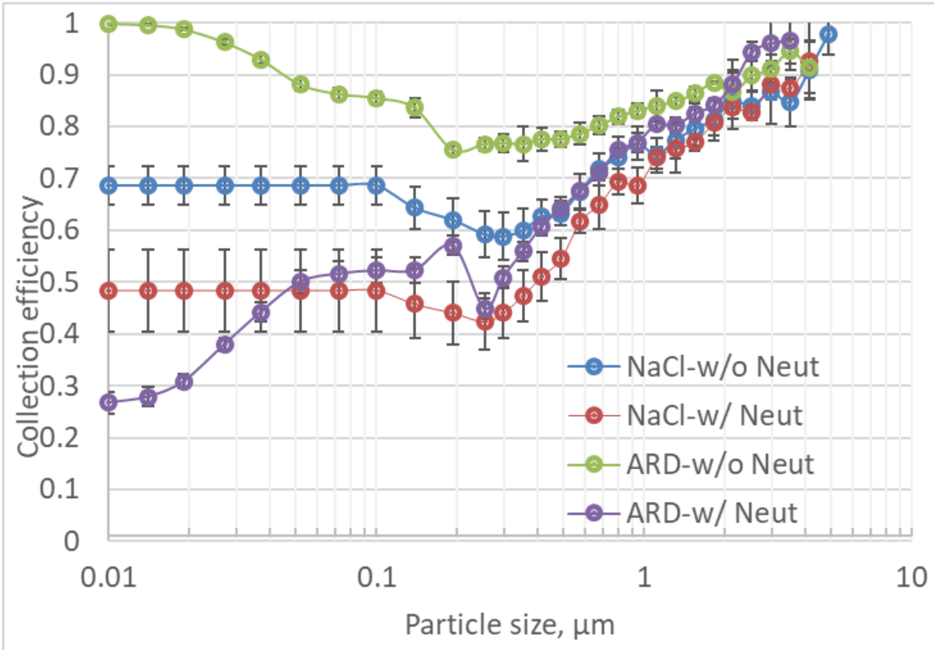

Figure 5: Collection efficiency of MERV-13 filter as a function of particle size at 0.22 m/s face velocity with Grimm MiniWRAS when testing with NaCl and ARD particles

Figure 5 shows a collection efficiency of MERV-13 filter as a function of particle size at 0.22 m/s face velocity with Grimm MiniWRAS when testing with NaCl and ARD particles. The size of the tested filters is 47 mm in diameter. According to Table 3, efficiencies in E ranges were higher with ARD particles than NaCl particles for all ranges and conditions. It could have to do with ARD's dielectric properties and different shape compared to NaCl particles.

Table 3 shows a comparison of E1, E2, and E3 efficiencies of MERV-13 when testing with NaCl and ARD particles that were charge neutralized and non-neutralized. The measurements were performed with a MiniWRAS electrical/optical instrument.

Table 3: Comparison of E1, E2, and E3 efficiencies of MERV-13 when testing with NaCl and ARD particles that were charge neutralized and non-neutralized with a MiniWRAS electrical/optical instrument

	Charge non-neutralized		Charge-neutralized	
	NaCl	ARD	NaCl	ARD
E1	0.67	0.79	0.58	0.65
E2	0.81	0.87	0.80	0.87
E3	0.91	0.94	0.88	0.97

While data in **Figure 4** were obtained with a MiniWRAS device, the experiments were repeated with the APS device, which measures aerodynamic particle size (Figure 6). For PM 2.5 (< 2.5 µm), the average collection efficiencies were 68% (NaCl) versus 80% (ARD) without a neutralizer and 65% (NaCl) versus 71% (ARD) with a neutralizer. E1, E2, and E3 efficiencies are summarized in Table 4. Average E efficiencies for ARD particles were higher than efficiencies with NaCl particles for all size ranges and test conditions.

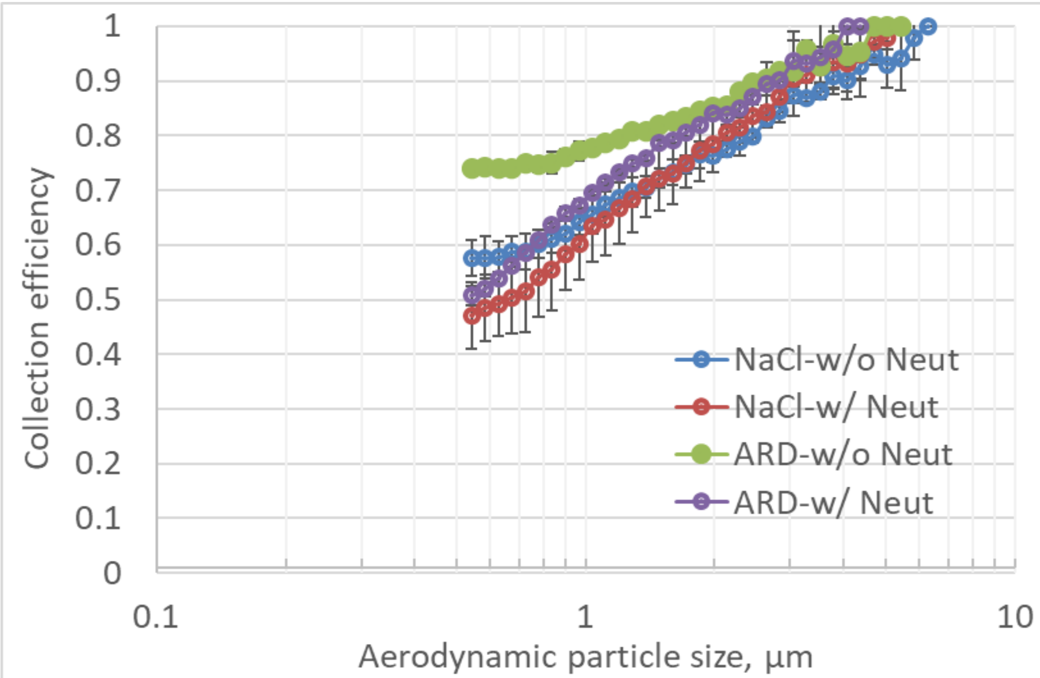

Figure 6: Collection efficiency of MERV-13 filter as a function of particle size at 0.22 m/s face velocity when tested with TSI APS and NaCl and ARD particles

Figure 6 shows a collection efficiency of MERV-13 filter as a function of particle size at 0.22 m/s face velocity when tested with TSI APS and NaCl and ARD particles. The tested filter cutout was 47 mm in diameter.

Table 4: Comparison of E1, E2, and E3 efficiencies of MERV-13 filter when testing with NaCl and ARD that were charge neutralized and non-neutralized with an aerodynamic particle sizer APS

	Charge non-neutralized		Charge-neutralized	
	NaCl	ARD	NaCl	ARD
E1	0.60	0.75	0.53	0.59
E2	0.75	0.84	0.75	0.80
E3	0.92	0.96	0.94	0.96

Table 4 above shows the comparison of E1, E2, and E3 efficiencies of MERV-13 filter when testing with NaCl and ARD that were charge neutralized and non-neutralized. The measurements were performed with the aerodynamic particle sizer APS.

The data in **Figure 5** and **Figure 6** show different collection efficiency by MERV-13 the filter when the measurements were performed with the MiniWRAS and APS. The difference in observed filter performance was likely due to the different principles in the device operation. In the overlapping size range of the two instruments, the MiniWRAS used an optical measurement technique, i.e., it measures the optical particle diameter while the APS measures the aerodynamic particle diameter. When the particles are spherical and have a density of 1 g/cm^3, their optical and aerodynamic sizes overlap. Therefore, we applied a correction factor based on the square root of particle density. As can be seen in **Figure 7**, there is a strong agreement between the efficiency data yielded by the two instruments. For comparison, the data provided by Camfill were obtained with an Optical Particle Sizer, another device based on optical measurements.

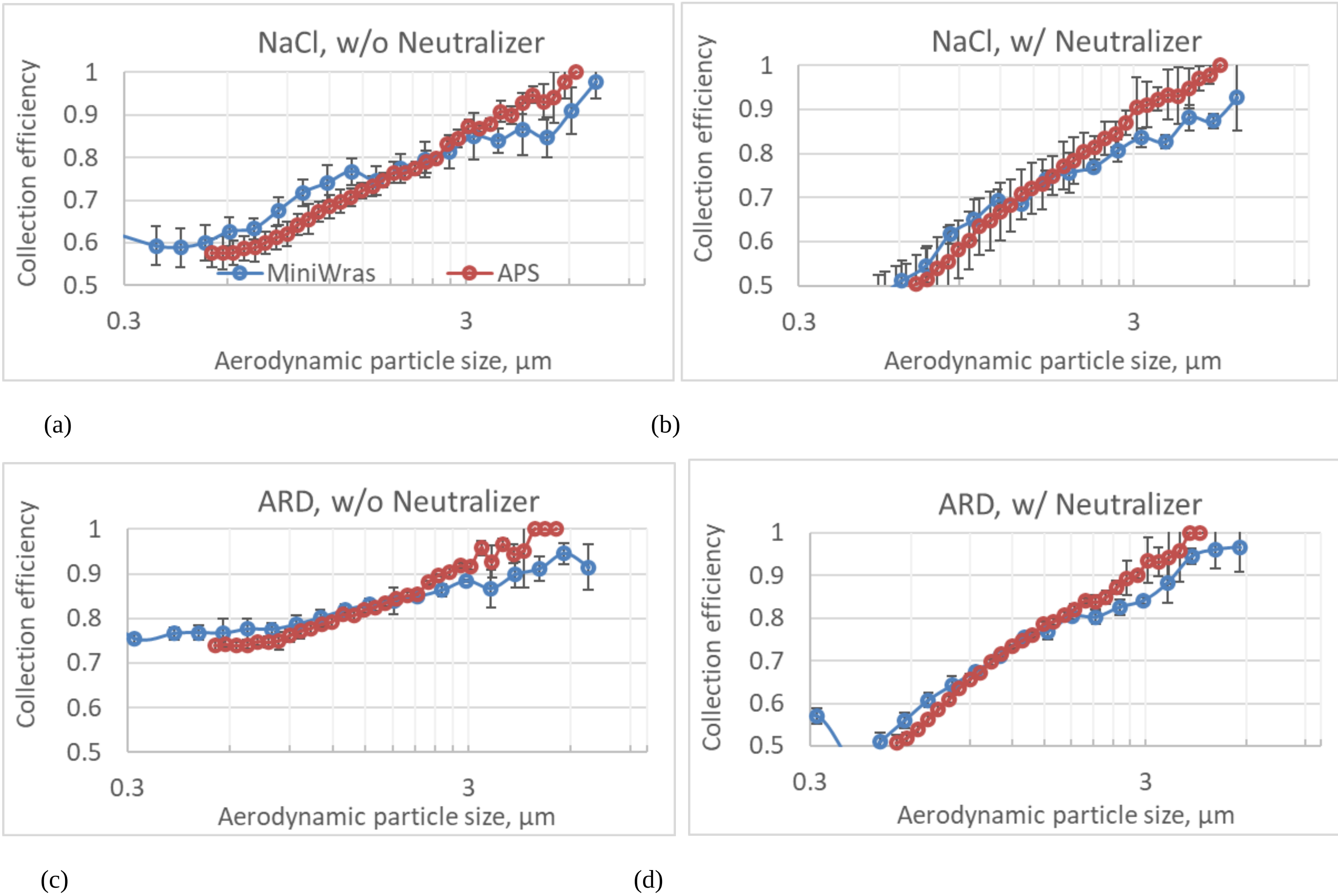

Figure 7: Comparison of collection efficiency as a function of aerodynamic particle size when testing with NaCl and ARD particles w/ or w/o a neutralizer. The concentration was measured by Grimm MiniWras and TSI APS

Task 3.

Particle collection efficiencies of MERV-8 foam filters (one new and two used (6040 Middle and 7640-B-end)) were determined using charge-neutralized NaCl particles and MiniWras device. The flow rates of the air passing through the filter were set at 27.3 L/min, resulting in a face velocity of 0.9 m/s. The new filter reached 50% collection or better for particles of 3.5 µm and larger – substantially poorer performance than the MERV-13 filter. The two used filters reached 50% collection or better for particles of 2.5 µm and larger – a better performance than the new filter, most likely due to the loading of used filters with particles. All three filters had collection efficiencies below 20% for particles < 0.3 µm.

As shown in **Table 5**, efficiencies of the new filter at E1 (0.3 to 1 µm) and E2 (1 to 3 µm) were 2x and 0.54x lower than those of the used filters, respectively. However, the efficiencies were the same for the E3 range, representing larger particles. We also measured pressured drop across the filter, and the used filters showed about 3.1% higher pressure drop (1.65 inch H_2O)than the new filter (1.60 inch H_2O).

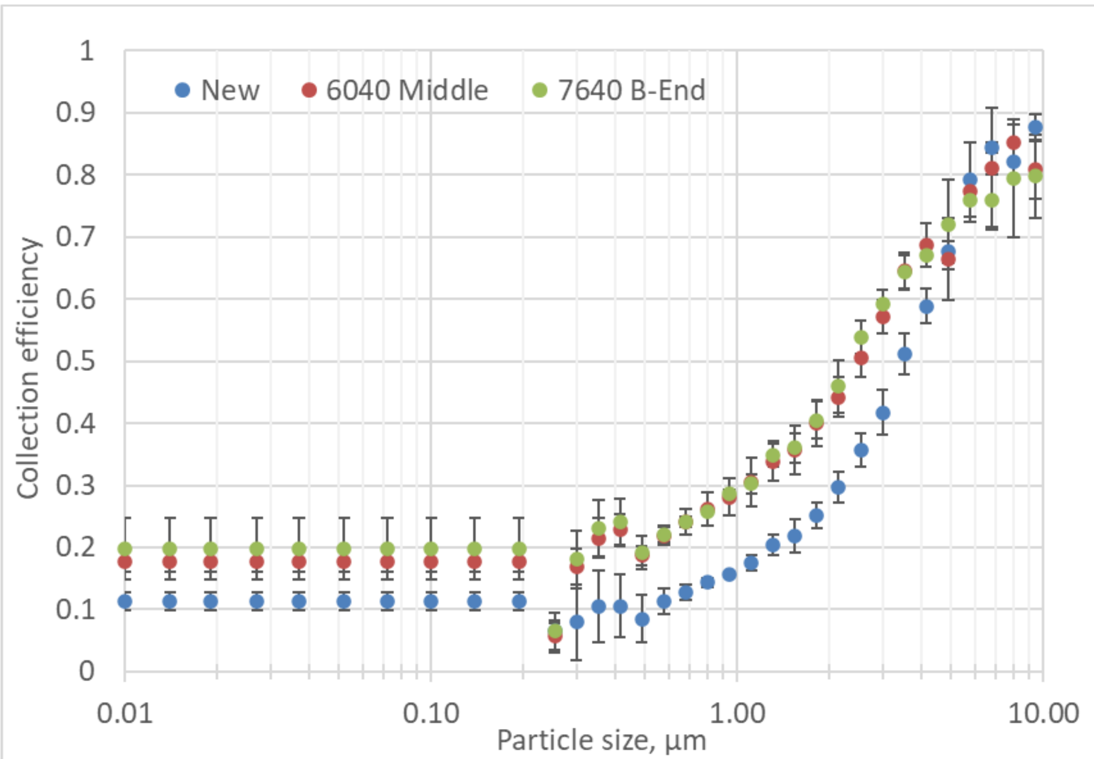

Figure 8: Collection efficiency of MERV-8 foam filters as a function of particle size when testing with charge-neutralized NaCl particles. The particle concentration was measured by Grimm MiniWras.

Table 5: Comparison of E1, E2, and E3 efficiencies of MERV-8 filters

	New	Used filter	
		6040 middle	7640 B-End
E1	0.11	0.23	0.23
E2	0.27	0.42	0.43
E3	0.73	0.75	0.74

Conclusions

The filter testing data confirm that MERV-13 filters have better filtration efficiency compared to MERV-8 filters.

The filter performance varies depending on the age of the filter (i.e., its loading), particle type, and particle properties (charged vs. neutralized).

Enhanced filter performance due to its embedded charge dissipates over its use and offers a relatively small performance enhancement for charge-neutralized (i.e., aged) particles.

Foam MERV-8 filters offer much lower collection efficiency than MERV-13 filters, especially for submicron particles, although their performance improves a little due to loading.

Recommendations

Whenever technically feasible, transport agencies should upgrade filtration systems in their vehicles to MERV-13 or better systems. Upgrading filters is an effective, cost-efficient way of containing small air pollutant particles, including those that might carry the SARS-CoV-2 virus or other infectious and detrimental airborne agents. The upgraded system will also have an extended benefit of combating the spread of infectious viruses, such as influenza, as well as offer general health protection for each agencies ridership.

When assessing the performance of selected filter systems, it is important to examine the data showing the performance of charge-neutralized filters against charge-neutralized test particles. This is a worst-case (or conservative) performance scenario for filters. For example, enhanced filter performance due to charge infusion wanes over time, and initial performance data might be valid only during the initial utilization period.

The current testing by commercial companies and testing performed at Rutgers investigated the efficiency of filter material but not the performance of the filtration system installed in transit vehicles. The latter could be affected by the quality of installation, the actual airflow velocity, particle sources on the vehicles, and other factors. It is recommended to conduct actual filter performance studies on representative transit vehicles.