Dear Dr. Bonanno:

Following please find our review comments on the "In-Cabin Particulate Matter Quantification and Reduction Strategies Final Report" by Investigators at Rowan University, dated 12/8/2008. The review was conducted focusing on the six charge questions provided by New Jersey Department of Environmental Protection.

Our comments to the reviewers are in green Calibri font.

Charge Questions:

1. Based on your interpretation of the report, can you identify one or more technologies that would be effective in significantly reducing in-cabin $PM_{2.5}$, and /or Ultrafne Particulate Matter (UFPM)?

Based on data presented in the report, the efficiency of various retrofit technologies to reduce in-cabin $PM_{2.5}$ levels ranked as: DPF+CCVS>DPF>FTF+CCVS. All of these three technologies achieved over 250% $PM_{2.5}$ reduction from the baseline. Neither CCVS nor FTF produced significant reductions on $PM_{2.5}$.

For UFPs, a single CCVS or its combinations with DPF or TFT helped to reduce the in-cabin particle number concentrations. A single DPF or TFT did not contribute significantly to the reduction of UFPs.

For gaseous pollutants, two tailpipe retrofit technologies (DPF and TFT) showed significant reduction.

2. Are there major problems with the data analysis and/or interpretation that require correction before the results of the study are useable?

I have three major concerns about the study design, data analysis and interpretation, and the conclusions made in the study.

First, although the investigators took great care to make sure there was no other major PM source other than the bus own emissions when designed the study, sealing the rear door and windows may not reflect realistic driving conditions under which the bus is used to pick up and drop-off children. Using an over sealed bus also makes it difficult to draw any conclusions on retrofit technologies targeting on tailpipe emissions. In fact, the apparently high efficiency of CCVS and low efficiency of DPF for in-cabin pollutant concentration reduction may be due to the fact that DPF's effects, if any, were diminished by not allowing tailpipe emissions entering the school bus cabin.

Rowan:

We realize that New Jersey has one of the most restrictive inspection standards for school buses and with respect to the difficulty that an over sealed bus represents; the study was designed considering a school bus that had been inspected and accepted under the Motor Vehicle Commission (MVC) of New Jersey School Bus biannual inspection for school buses. MVC's School Bus Inspection Unit is responsible for inspecting all vehicles used for school transportation, including: school buses, small school vehicles, dual-purpose vehicles, summer camp vehicles registered in the state.

Vehicles registered for school transportation are inspected twice a year. Any vehicle used to transport school children must comply with the inspection requirements,for which the tested school bus for this study was inspected. Part of the inspection requirements include eliminating any leaks of the passenger cabin, for which the tested school bus was repaired at an experienced body shop in Maryland and then inspected by New Jersey Department of Motor Vehicles (NJDMV) personnel. More information can be found at:
http://www.state.nj.us/mvc/Inspections/SchoolBus.htm

Second, the crank system usually emits greater amount of larger particles than ultrafine particles, as the investigators mentioned in the report. Thus, a CCVS is expected to produce more benefits for larger particles, say $PM_{2.5}$, than ultrafines. However, the data reported in this study suggested that CCVS works better to reduce in-cabin ultrafine particles than $PM_{2.5.}$ This is confusing and needs better explanation.

Rowan: The results of this study for the final 19 runs showed that the CCVS works in reducing particulate matter PM2.5 when combined with a tailpipe retrofit. Using the nonparametric analysis shows that the use of the CCVS results in a statistically significant decrease in PM2.5 concentration compared to the baseline.

The particle size measurement range of the P-Trak is from 0.02 to 1µm diameter and the concentrations are reported as number of particles per cm^3 of gas. The DataRAM-4 is between 0.08µm to 2.5µm. From the study by Tatli and Clark et al.[1], they measured a significant number of particles originating from the crankcase that are less than 1 micron. The article from Donaldson[2] gives a mass based size distribution from 0.03 to 5.6 microns with a maximum at 1 micron. The P-Trak is only able to examine the number distribution of particles similar to that presented by Tatli and Clark and is not giving results based on a mass distribution. Therefore the CCVS is reducing the mass of particles being emitted from the vent tube, but it is not known what the effect is on the number concentration of particles. In addition the Tatli and Clark study has shows that the size distribution profiles and concentrations of crankcase particulate emissions differ greatly from one engine to another. This variation in emissions is based on both the design of the engine system as well as the formation process of aerosols.

Third, greater variability of $PM_{2.5}$ levels from Run 7F to 19F, and UFPs levels throughout the study were observed, which may weaken the conclusions made in the report. This is especially true for UFPs analysis. Since the engine oil temperature is a major factor affecting UFP emissions, extrapolating the data out of the measured temperature range to draw conclusions is risky. It is better to control the engine oil temperature and reduce its variation before compare the in-cabin pollutant concentrations.

Rowan: This study was designed to eliminate as many confounding effects that contribute to in-cabin particulate matter concentrations. The protocol for this study was to warm the engine to a minimum engine oil temperature and then start the testing. Based on the current data it would be desirable to revise the testing protocol to obtain a more constant engine oil temperature, since it has been shown in this study and in other recent studies to affect the concentration of particulates emitted from the engine. Alternatively to control the engine oil temperature within a small temperature range, would require an external heat exchanger. This would require a modification in the engine of the school bus which is not permitted in this study.

3. On pages 93-95, the investigators perform an ANOVA on the $PM_{2.5}$ and UFPM in-cabin concentrations with and without retrofit devices.

3a. Is this an appropriate statistical test for this data?

ANOVA is a statistical method to analyze if the mean of variables are different. It is an appropriate statistical test for the type of data reported in the current study. However, to use ANOVA, several assumptions should be satisfied: (1) normality of the data (2) variances are equal, and (3) independence of the data points. If more than one of these assumptions is violated, transformation is needed or non-parametric test has to be used. So in this report the assumptions should be checked and stated before using ANOVA.

Rowan: Taking the average values from the data presented in that section, the normal distribution was obtained, however we realized that we needed to take the complete set of values (6 points for each retrofit configuration) in which there was not normality in the distribution. We corrected the analysis using nonparametric statistics.

3b. If yes, are the investigators' conclusions based on the results of this test appropriate? See Conclusion #5, i.e., that the crankcase ventilation system (CCVS) alone does not reduce $PM_{2.5}$ based on the results of the ANOVA analysis

As mentioned in 3a, although ANOVA is appropriate for this type of data analysis, it is important to check for the three assumptions that ANOVA requires. It is not clear from the report whether these assumptions hold for the data used in achieving the conclusions regarding CCVS reducing $PM_{2.5}$ levels.

Rowan: The assumptions for normality were checked and are now use a non-parametric analysis.

RE: High Ambient $PM_{2.5}$ Measurements: see Figure 47, page 77
4a. During runs 7F-19F, is it reasonable that the ambient measurements were higher than the in-bus measurements?

This may be due to the over sealed study design. When there is no significant PM sources penetrate into the school bus cabin, the PM concentrations inside the bus could decay due to particle deposition onto interior surfaces. Thus, for a well-sealed bus, it is possible for in-bus concentrations to be lower than the ambient concentrations.

Rowan: This is an interesting theory on particle deposition on clean surfaces of the interior of the bus. Using this theory, then passengers in the bus with clean clothes and hair would present a much higher surface area for particle deposition. Calculations would be needed to verify is this theory is reasonable. A quick estimate of the diffusive deposition of particles based on laminar flow in a cylinder gives a 5 to 10% reduction.[3]

4b. In your opinion, does this reflect actual conditions or to what extent do you think that this may reflect inaccuracies in data handling or in the measurement of either the ambient particulates or the in-bus particulates?

This may not reflect actual conditions when a regular (not sealed) bus was driven on roadways. It has little to do with inaccuracies in data handling or in the measurement of either the ambient or in-bus particulates. Instead, it came from a study design issue where a usually leaky bus was over sealed.

Rowan: We obtained data from an ambient monitoring station from the Maryland Department of Environmental Protection at Fairhill which is near Aberdeen. On the 3 June 08 (Run 7F) the values from the BAMM instrument varied from 11 to 16 and then back to 8 $\mu g/m^3$. Assuming that the values of the DataRam 4 read 1.8 times high, then these would correspond to DataRAM equivalent values from 20 to a maximum of 30 down to 14. The DataRAM values on that day started at 35.7 and ended at 16.5 $\mu g/m^3$. This is reasonable agreement with our data and would indicate that the DataRAM ambient values are reasonable. No comparison could be made for the runs 10F trough 12F, because the BAMM was not recording that day.

4c. Additionally, since runs 7F, 11F and 12F had extremely high ambient measurements resulting in large negative values for in-bus particulates when the ambient values are subtracted out, would this be justification to not use those runs in analysis/conclusions?

Data from these runs should be eliminated in any analysis regarding retrofit technology efficiency. As mentioned above, this phenomenon is likely due to particle deposition inside the bus under well-sealed conditions not a benefit from retrofit technologies.

Rowan: The decision to test on the days that runs 7F, 11F and 12F were performed was based on a PM forecast with a cutoff of 40μg/m^3 that is given in the testing protocol. Run #12F had the highest ambient concentration of 41.3μg/m^3 and was obtained at the end of the day after two previous runs. This value is within 5% of 40μg/m^3 value. Another interesting aspect of these runs was that the interior values were lower than the ambient. One would presume that if the high concentrated PM containing ambient air leaked into the bus, then the levels of PM in the bus would be significantly higher than what was measured.

4d. In your opinion, is it appropriate to conclude that a technology (or combination of technologies) was more effective because that condition produced a more negative value when the high ambient value was subtracted out?

It depends. If all the runs were conduced under the same ambient condition, following the same protocol, then such conclusion can be made. However, the data suggest a huge variability in both ambient and in-bus particulate concentration levels. Thus, making conclusions simply based on more negative values is risky.

Rowan: The design of the study, and most on-road school bus studies, is to use an ambient measurement to obtain a net particle concentration within the cabin of the bus. This is done either with a stationary ambient, a lead car or both. The experiments show that the DPF and CCVS show the greatest difference from ambient. This has been observed in at least 2 other school bus studies that were previously mentioned and have been added (In the CATF study[4] and Rim et al. (2008)[5]).

5. Is it reasonable that while the DPF alone did not impact ultrafine particulate matter (UFPM) and possibly increased them, and the CCVS reduced UFPM somewhat, that the combination of DPF and CCVS almost completely eliminates UFPM?

It is reasonable that the efficiency of DPF+CCVS was much higher than any single one if the following assumptions are met:

(1) There were much more large size particles than small size particles emitted from the crankcase vent.

Rowan: As figures 53 and 54 show, there are larger particles emitted from the crankcase vent without any controls.

(2) The crankcase emission is the major source of in-cabin UFPs.

Rowan: As the results showed, the CCVS reduced the UFPs indicating that the crankcase accounts for the major in-cabin UFPs.

(3) CCVS only worked to remove large size particles and turn them into smaller size particle.

Rowan: This seems reasonable based on the filter removing the large particles and passing smaller particles. .

(4) DPF only worked to remove smaller size particles.

If all above assumptions were met, we could explain the result as follow:

(1) Since the in-cabin UFPs mainly came from the crankcase emission, the tailpipe retrofit technology did not work efficiently to reduce UFPs. However, due to the over sealed study design; it is difficulty to make any conclusions on the tailpipe retrofit technology based on data collected in this study.
Rowan: We agree that making sure that the back door of the bus and other joints that are inspected by NJDMV is a very effective method to control in-cabin particulate matter.
(2) CCVS removes large size particles so that the result of single CCVS application showed some efficiency.
(3) Since large size particles were more than small size in crankcase emission and CCVS turned them into smaller size, most of the particulate matters became smaller size particles which could be removed by DPF.
Rowan: This is logical based on the filtration technology of both of these devices.
(4) The small size particles in the tailpipes were removed efficiently by DPF.

If any of the assumptions could not be satisfied, it will be not reasonable to expect such high reduction of UFPs from CCVS+DPF, while either single technology did not work very well.

Rowan: The Tatli and Clark study shows that the concentration of UFP from the crankcase vent decreases with engine oil temperature. Donaldson's data shows that the CCVS removes particles with diameters of dp> 0.25μm, but this appears to be a mass based measurement and not a number based measurement. From the Tatli and Clark data it would be reasonable that the CCVS filtered particles smaller than 0.25μm. There would be a decreasing particle removal efficiency with decreasing particle size. Since our data shows that the CCVS is effective in reducing the concentration of UFP's in the cabin of the bus, then the CCVS is effective in reducing particle sizes in the range of the P-Trak measurements (0.02 to 1μm). If the back door had leaks or other leaks were present, then the tailpipe retrofit would become more important in reducing these particulates.

6. The study claims that the use of a CCVS alone reduces UFPM and not $PM_{2.5}$. Is that reasonable in your opinion?

As mentioned in question No. 2, one of my major concerns is the conclusion on CCVS on reducing UFPM but not $PM_{2.5}$. UFPM tested in this study is the number concentration of ultrafine particles whose diameters range from 0.02 μm ~ 1 μm. $PM_{2.5}$ is the mass concentration of fine particles with diameters less than 2.5 μm. For vehicular emitted particles, over 90% by number was in the UFP size range, but their mass concentrations were quite low because of the small size. UFPM number concentrations and PM2.5 mass concentrations usually don't correlate. This, it is possible for one technology to remove a large amount of UFPs but not reduce the mass concentration of $PM_{2.5}$. However, it is well-know, as the investigators also mentioned in the report, that the crank system usually emits greater amount of larger particles than UFPM. Thus, a CCVS is expected to produce more benefits for larger particles, say $PM_{2.5}$, than ultrafines. However, the data reported in this study suggested that CCVS works better to reduce in-cabin UFPM than $PM_{2.5.}$ In addition, the investigators stated that the sizes of the particles in the bus equipped with CCVS were smaller than the baseline (page 91), and concluded that CCVS had greatly reduced the fraction of larger particles from the crankcase vent, rather than small size particles. Overall, the investigators' conclusions on CCVS are confusing and needs better explanation.

Rowan: We have revised the conclusion of the report to improve the clarity. The new non-parametric analysis helps to explain this difference.

From another peer reviewer:

I find the experimental measurements disappointing. The instruments chosen are not the most accurate and precise that could have been used. They could have used batteries and an inverter to power a much better quality CPC and a nephelometer that had better response below 0.1 μm. If they had been on a bus with people riding on it or where making personal measurements, their choice of measurement systems would make sense, but given the nature of the study, the lack of best practice instruments is disappointing. They have missed an opportunity to make a real contribution to the problem. Since diesel has a peak around 70 nm, they are underestimating the PM2.5 mass with the DataRAM. Since 70 nm particles deposit much more effectively than 0.25 μm particles, lack of data in this size range is a significant deficiency. An instrument like an FMPS would have proven much more useful because they could get high time resolution measurements from 5.6 to 560 nm.

Rowan: All previous studies were done with this equipment. This proposal was based on using this equipment and funds were not available for higher grade instrumentation. Also, these instruments take an extreme level of abuse in actual measurements on a bus driven on roadway. We are not aware of studies that use advanced instrumentation under these extreme conditions.

They also substantially underestimate the ultrafine particles (<20nm) with the PTrak. They state "This study illustrates that the P-Trak is a good instrument for measuring particulates that have aged." Rowan: This statement has been removed. However, their set-up is such that the particles have not had time to age and thus, they are missing the large number of 10 to 20 nm particles. Even the 3022 that was used in comparison in the quoted study is an old design instrument. I would have looked at a 3781 with a 50% cut point of 6 nm to properly characterize the ultrafine particle number concentrations.
I have never used the DataRAM-4 monitors. These are the next generation monitors after the DataRAM 2000s. We have the personal DataRAM 1000 and 1200s, which are meant to be worn. The DataRAM-4 is a portable but not a personal monitor. Regardless, I expect that some of the same limitations will hold. The investigators did a decent job characterizing the instruments before the initial study at different concentrations using a

like source of particles. However, you see that the coefficient of variation (Tables 3 and 4) is fairly high, especially for low concentrations. Also, there appears to be a predictable bias among the monitors (e.g., Fig 22 and calibration curves).

Rowan: The calibration curves were used as a comparative study, and we have removed the title of "calibration" in the report to comparative study of the particulate matter instrumentation.

As far as I can tell from the report, the calibration curves that were developed were not used to correct the data from the monitors, even though the slopes and intercepts are not close to 1 and 0, respectively. Also, the monitors were recalibrated before the final study so the calibration curves would not be applicable. No collocation experiment was conducted following the recalibration, unless I missed something. Therefore, the reported results likely have a monitor bias. This could be why the ambient monitor is higher than the monitors in the bus. However, there is also the issue of pollutants building up in the vicinity of the track from the exhaust and resuspended dust (a bigger issue for the initial study where the ambient measurement was in the center of the track).

I did not see calibration curves for the gaseous species using the SEMTECH-D gas analyzer. We have no information on its accuracy and precision.

Rowan: Information of the accuracy and precision for each gas analyzer of the SEMTECH-D has been added to the report. The instrument was calibrated before and after each run versus calibrated gas bottles. There are no calibration curves given because the software of the SEMTECH-D moves the zero every time the instrument has been re-zeroed in order to maintain its accuracy.

The work they did to seal the leaks may make the bus they used unrepresentative of the bus fleet. Are most buses really sealed properly? Thus, in actual practice, the exposure would be much higher.

I found the beginning of the report hard to read since they outlined the experimental design with the names of the instruments before defining the nature of the instruments. I knew what they were, but I suspect that many less versed in particle measurements will have a tough time with that section. Rowan: This order has been fixed in the report.

I am not sure why they made runs with the windows open. One would have expected dilution and infiltration of the ambient aerosol. Why seal the doors and then open the windows? Those runs could have been used more profitably.

They have evaluated the technology on a bus. However, I wonder how well the retrofits are installed on a fleet and how well they are maintained. Such information was beyond the scope of this study, but clearly there is a need to look at how these technologies work in real applications and over time.

A reference they should review is

Title: Predicting airborne particle levels aboard Washington State school buses
Author(s): Adar SD, Davey M, Sullivan JR, et al.
Source: ATMOSPHERIC ENVIRONMENT Volume: 42 Issue: 33 Pages: 7590-7599
Published: OCT 2008

Rowan: This reference has been added.

[1] Tatli, E. and N. N. Clark, (2008) "Crankcase Particulate Emissions from Diesel Engines, SAE World Congress 2008, paper number 2008-01-1751, 2008.

[2] Hou, Jason and Julian Imes, "A Sure Way to Cut Emissions from In-Use Diesel Vehicles - A Retrofit System from Donaldson," Donaldson Publication, April 2003. http://www.donaldson.com/en/exhaust/support/datalibrary/003570.pdf

[3] Hesketh, H. E., "Fine Particles in Gaseous Media," Ann Arbor Science, Ann Arbor, MI 1979.

[4]Hill L.B., Zimmerman N.J., Gooch J., (2005); A Multi-City Investigation of the Effectiveness of Retrofit Emissions Controls in Reducing Exposures to Particulate Matter in School Buses; Clean Air Task Force, January 2005.

[5] Rim D., et al., (2008); "Characteristics of cabin air quality in school buses in central Texas"; Atmospheric Environment 42, pp. 6453-6464.