

MODAL ANALYSIS OF VEHICLE OPERATION AND PARTICULATE EMISSIONS FROM CONNECTICUT TRANSIT BUSES

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Eric D. Jackson, PhD
Research Engineer
Connecticut Transportation Institute
University of Connecticut
261 Glenbrook Road
Storrs, CT 06269
860 486 8426
e.jackson@engr.uconn.edu

Britt A. Holmén, PhD
Associate Professor
School of Engineering
University of Vermont
33 Colchester Avenue, Votey 213B
Burlington, VT 05405
(802) 656-8323
baholmen@cems.uvm.edu

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Abstract

Transit buses represent a significant source of particulate exhaust emissions, especially in urban areas, but few previous studies have quantified these emissions using real-world, onboard sampling while the vehicles operate in the transportation network. In this study, real-world particle number emissions for hybrid diesel-electric (HDE) and conventional diesel (CD) buses, are examined for various vehicle operating conditions and road types in the Hartford, CT region. The results presented in this paper are based on analysis of the unique second-by-second CT Transit on-road transit bus emissions and operations dataset collected between Jan-November, 2004 [13]. The results of this analysis indicate hybrid buses operate differently from conventional diesel buses. Although the distributions of vehicle specific power (kW) values were similar between the two bus types, the distributions of engine operation parameters (load and RPM) were different. Therefore, VSP alone cannot be used to distinguish between vehicle types when modeling engine operation (and possibly emissions) from hybrid and conventional vehicles. Furthermore, the modal analysis of ultrafine particle emissions indicates there are situations where the HDE buses do not outperform the CD, and may even produce higher emission rates than the CD buses tested. Thus, there are routes and conditions where transit authorities should avoid the use of HDE buses similar to those tested here when particle emissions are of concern.

Research Objective

This research aims to provide new understanding on time-resolved particle number emissions from conventional diesel (CD) transit buses and hybrid diesel-electric (HDE) buses. The first objective of this research was to investigate the differences in vehicle operation between the hybrid and conventional buses on a second-by-second basis. The second objective was to investigate particle number emissions to determine if there are significant differences between the two vehicle types.

Introduction

Transit buses are significant sources of particulate matter (PM) and oxides of nitrogen (NO_x) emissions in urban areas. Recent studies have shown that the number of airborne particles may be a *more* significant determinant of adverse respiratory and cardiovascular health effects than the total particle mass concentration (the basis for current state and federal ambient and emissions standards). Because ultrafine (diameter < 100 nm) particles have recently been linked to more adverse human health effects than larger particles of identical composition, future regulatory changes will likely target particle number instead of mass. The relationships between real-world transient vehicle operation and particle number emissions (which are chiefly due to ultrafine particles) are not well known, especially for alternative bus propulsion technologies.

This study is unique in that; (i) the electrical low pressure impactor (ELPI) instrument collected real-time particle number concentrations while the buses operated in the real-world road network; (ii) the ELPI data was collected at high temporal resolution (1-2 sec) which allowed for disaggregate modal emissions modeling; (iii) the on-board sampling included a Vansco USB scantool to collect engine and vehicle operating data at high temporal resolution; (iv) simultaneous operation of a Horiba gas exhaust analyzer system that monitored total exhaust flowrate allowed computation of particle number emission rates (PNER, #/sec) from raw ELPI particle number concentrations (#/cm³); and (v) the collection of road grade along the test route allows for real-world quantification of vehicle specific power (VSP).

Literature Review

Particle Number Emissions from Transit Buses

Diesel engines are known to be important sources of particulate matter and typically emit 10–100 times more total PM mass than spark ignition engines [1]. Diesel particulate matter is composed primarily of elemental carbon, organic carbon, sulfates and trace elements (Shi et al., 2000). The collection of particulate matter (PM) mass emissions is now a relatively mature science, while vehicle emissions research is currently focused on understanding particle number emissions. Current vehicle emissions models do not estimate the number of particles emitted, but as the regulatory environment shifts from mass to number, development of such number-based particle emissions models is warranted.

Research on particle number emissions remains limited and there have been only a handful of studies that focus on particle number emissions from transit buses. The general results of these studies are summarized in **Table 1**. Previous research efforts have investigated the impacts of fuel, engine type, aftertreatment devices, and engine load on particle number emissions (**Table 1**). Although the absolute magnitude of particle concentrations may depend on the dilution and sampling conditions, the relative effects of particle number emissions appear to

be similar between studies. For example, the use of a DPF appears to reduce particle number concentrations/emissions by two orders of magnitude (~99%) in all of the studies where DPF was evaluated [2-5].

Previous research efforts have investigated the impacts of vehicle type, fuel and operation on particle emissions. The results of these studies indicate that vehicle type can cause mean PN emissions rates to vary by a factor of 10 [6]. Furthermore, because vehicle age and engine model can contribute to differences in PN emissions [7], the two bus types tested within this study were similar in model year and engine type. With the use of a catalyst, previous studies indicate an overall negligible reduction in PN emissions with fuel type [3, 8]. The buses in this study used No. 1 diesel and ultralow sulfur diesel (ULSD) but, for this analysis the two fuel types were analyzed as one. Finally PN emissions have been shown to be highly dependent on engine operation [1, 9, 10]. Studies are conflicting on whether free-flow conditions or stop-and-go driving causes higher PN emissions [11, 12]. Other studies indicate acceleration and cruise events generate larger PN emissions than decelerating and idling modes [4]. This work investigates differences in engine operation and PN emissions rates over multiple operating conditions.

Data Collection

Test Route and Nomenclature

Data were collected for this research on a predefined test route which incorporated multiple road types and a wide range of driving conditions. The route was comprised of three Connecticut Transit (Hartford, CT) bus routes run sequentially during each testing day. Detailed route information can be found in Holmén et al. [13]. The first bus route, Enfield, travels along I-91 north and south. The second bus route travels along an urban arterial with stop-and-go driving (Farmington Ave) in downtown Hartford. The third and final route travels along a rural arterial over Avon Mountain. The three routes will be analyzed separately due to the distinctly different driving conditions encountered on each route and the routes are distinguished by route name: Enfield, Farmington and Avon. Furthermore, direction traveled along the route will be distinguished by designating the route north (for northbound), west (for westbound)...etc. Finally the Avon Bus route has sections with steep up and down grades (up to 9%). Data collected on these sections were labeled as 'Up' or 'Down'. Therefore, Avon West Up indicates traveling on the Avon route, in the westbound direction, on a steep uphill grade.

Vehicles

A total of four transit buses from the in-service Connecticut Transit (CT Transit) fleet were tested between Jan-Nov, 2004. Two conventional diesel (CD) buses equipped with model year 2002 Detroit Diesel Corporation Series 40 engines and two HDE buses with 2003 Cummins ISL 280 engines and the Allison E^p 40 electric drive parallel hybrid transmission. For this analysis over 213,000 seconds of data were collected over 22 days. The HDE buses accounted for 10 days of testing and 105,198 seconds of the total dataset, while the CD buses accounted for 12 days of testing and 180,258 seconds of data.

Emissions Instrumentation

Particle number (PN) concentrations ($\#/cm^3$) were measured using a Dekati, Ltd. (Finland) Electrical Low Pressure Impactor (ELPI) operating at 30 Lpm and outfitted with an

electrical filter stage. Prior to entering the ELPI, bus exhaust was diluted with a Dekati ejector-diluter single-stage mini-dilution system operating at nominal dilution ratios of 22 to 35, (mean = 27). Under field sampling conditions, the flow rates of sample exhaust and dilution air were continuously recorded to compute dilution ratios. A Horiba OBS-1000 gas emission analyzer unit was employed to measure the second-by-second gaseous exhaust emissions. As described below, the exhaust flow rate from the Horiba system's pitot tube measurements were used to compute particle number emissions rate (#/s).

Engine Diagnostic Scan Tool

All vehicle diagnostic data for the study was collected using three separate types of scan tools. For the HDE buses, Cummins "InSite" software was used to download data directly from the vehicle's diagnostic port using a Cummins INLINE I Data Link Adapter (DLA) communicating under the SAE J1708/J1587 protocols. Additionally, a prototype USB scantool, the Vansco USB Data Link Adapter, was connected to the bus's second network port to transmit both transmission and engine information. The Vansco DLA was used on both the hybrid and diesel bus types. Engine values, for example engine speed (RPM), engine load (%), and vehicle speed (MPH), were collected on a second-by-second basis for both bus types.

Database Development

Where an instrument recorded data at a sub-second rate, the raw data were first averaged into a mean for each second to achieve a 1-Hz observation rate. Conversely, the ELPI had instances where the particle concentrations were recorded every two seconds (or more). To fill one-second gaps in the ELPI particle count data the average of the previous and next particle concentration was used. For gaps larger than 1 second, the concentrations were left as missing values (< 0.5% of the data).

To account for time lags in the exhaust and dilution system, a cross correlation method was used to determine the lag between the instantaneously obtained RPM (from the Scantool), exhaust flowrate (from the Horiba) and an increase in PN at engine start (from the ELPI). The corresponding lags were then checked manually and the data were temporally adjusted to align operations, engine and emissions data.

Emissions Rate Calculation

The following equation was used to calculate the emissions rate (PNER, in number of particles per second) from concentrations reported by the ELPI.

$$\text{Emissions_Rate} = \text{PNER} = P * Q * DR \quad [\text{Equation 1}]$$

P = ELPI particle number concentration (#/cm³)

Q = Flow rate (cm³/s calculated from Horiba pitot tube data)

DR = Dilution ratio = $[V_{\text{dil}} + V_{\text{exh}}]/[V_{\text{exh}}]$

Where V_{dil} is the measured volume of dilution air and V_{exh} is the measured exhaust sample volume.

Road Type and Road Grade

Using the GPS data collected by the Horiba unit, road grade was assigned to each second of the dataset. Grade data were collected along the exact test route by the Connecticut Department of Transportation's Automatic Road Analyzer (ARAN) Photologging Van. ConnDOT's ARAN van is a highly modified vehicle, instrumented with an extensive set of

sensors (including accelerometers, GPS, gyroscopes, laser reflectometers and high definition video vision systems) and computers. ConnDOT uses ARAN vehicles annually to document and obtain road geometrics for all state roads. The ARAN van was able to provide road grade (in %, at survey level accuracy) every 10 meters along the test route. Using ArcGIS, the ARAN road grade were overlaid and spatially joined to the data. Spatial alignment of the data were checked manually in several locations within the route to ensure the bus data and grade data were overlaid correctly before the join was executed.

Vehicle Specific Power

The addition of second-by-second grade observation allows for a level of detailed modal emissions analysis that was previously not available. Vehicle Specific Power (VSP) is a measure of engine power demand that is calculated from velocity, acceleration and road grade. The joining of second-by-second road grade to the dataset allows for a detailed calculation of VSP where previous efforts had to ignore or estimate grade for the calculation of VSP. Previous research on vehicle emissions suggests VSP is highly correlated to increased concentrations of gas-phase exhaust emissions [15-18]. VSP for each second of data were calculated (see Equation 2) using an expression derived from the United States Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) manual [19]. The equation for VSP (kW) used here was tailored to a heavy-duty vehicle using coefficients outlined on pages 55-58 of [19]. The resulting VSP equation would be the same expression as the one used in MOVES to model modal emissions from "buses and motor homes".

$$\text{VSP}_{\text{bus}} = v * [a * g * \sin(u) + 0.064] + [0.000265 * v^3] \quad [\text{Equation 2}]$$

a = vehicle acceleration (meters/s²)
u = road grade (as decimal fraction, *not* percent)
g = acceleration due to gravity, 9.81 m/s²
v = vehicle velocity (meters/s)

Note that the scantool of the HDE collected engine parameters only for the onboard diesel engine and did not collect data pertaining to the electric motor. Therefore, calculating VSP for the HDE bus indicates how hard the **vehicle** is working but **not** how hard the **diesel engine** of the HDE vehicle is working. Since the diesel engine produces the exhaust for the HDE VSP which is based on vehicle operation and not engine operation may not be the best predictor for PN emissions. Modifications to the VSP coefficients and calculation may be necessary to develop a HDE VSP. However, for this research, equation 2 was used for both the HDE and CD buses.

Data Analysis

Vehicle Operation by Bus Technology

The first objective of this research was to investigate the differences in vehicle operation between the hybrid and conventional buses. Figure 1 contains histograms for vehicle specific power (VSP), by route and bus type. The Avon and Farmington Routes have similar VSP distributions, although the Avon route has a larger VSP standard deviation. The Enfield route, has a different distribution of VSP values due to the high speed cruising nature of travel on I-91. Overall, VSP distributions across bus types are very similar. This is expected because speed, acceleration and road grade should be nearly identical regardless of bus type. Because VSP is

calculated from the vehicle speed, acceleration and road grade, the plots in Figure 1 imply that **vehicle** behavior did not differ greatly between the testing dates for the two bus types.

Engine operating parameters were analyzed to determine if there were differences in diesel **engine** operation (note: HDE has electric motor to assist). The first parameter investigated was engine speed (RPM) (Figure 2). Similar to the VSP plots, the Avon and Farmington routes have similar distributions but the Avon route has a larger standard deviation. For these two routes, both vehicle types have a similar distribution of RPM with peak frequencies occurring around 700-800 RPM, 1200-1300 RPM and 2000 RPM. The 700-800 RPM peak represents idle operation for both bus types and, occurs less frequently on the divided highway route, Enfield. The HDE RPM data shows a much more defined peak at 1200 RPM that is not as apparent in the CD data. The narrow, well-defined peak at 1200 RPM in the HDE data on the Avon and Farmington routes appears as a small peak at the same location in the Enfield data. This peak in frequency could be associated with the transition from the electric motor to diesel-only power operation. This transition between engines has the potential to generate a very high emissions spike due to a sudden increase in power demand on the diesel engine.

Histograms of engine load (Figure 3) were also examined. For engine load the Enfield and Avon routes have similar engine load distributions, while the Farmington route has a different distribution. Furthermore, when comparing the two bus types, the HDE bus had a much different load distribution than the CD bus on the Farmington route. On the Farmington route, the mean and median engine load for the HDE was much lower than for the CD bus type, while the standard deviations were similar. For the Enfield route the mean, median and standard deviation were all similar for both bus types because high-speed highway operating power is derived solely from the hybrid's diesel engine. The similar engine load patterns on Enfield confirm that the diesel engines on the two different bus types performed in a similar manner under high speed, high load operation. On the Avon route, there were major differences in median load between the two bus types; with the HDE buses have much lower median (25 vs. 45 for CD bus type). Figure 3 also indicates, for the Farmington route, the diesel engine of the HDE vehicles did not have to work as hard as the CD bus diesel engines. This is expected since the electric motor of the hybrid drive should provide the needed power assistance under the stop-and-go conditions. The lower frequency of high load operation for the hybrid buses on the Farmington route also suggests that the hybrids should have lower exhaust emissions than conventional diesel vehicles for this route.

The plots of vehicle operation over the test route indicate that VSP distributions are very similar between the two bus types. This is expected since VSP is comprised of speed, acceleration and grade and both buses were driven under similar traffic conditions by one driver. However, the distributions of engine load and engine speed suggest there may be significant differences in how the diesel engines operate between the two bus types; these differences in engine operation can be expected to affect the number of particles emitted. **Keeping in mind that the VSP histograms (Figure 1) were similar between vehicle types, these differences in both RPM and engine load between bus types and route suggest that VSP alone cannot be used to model or compare engine operation (and possibly emissions) from hybrid and conventional vehicles.**

Bus Operation by Route

Enfield Route Operation

Speed/acceleration histograms for the data collected on the Enfield section of the test route (top row of plots in Figure 4) have similar patterns which are dominated by high-speed cruise. With the exception of the data occurring at high acceleration rate ($< 3\text{ mph/s}$) at low speed ($< 25\text{ mph}$), these plots indicate there were no major differences in vehicle operation between testing days for different bus types on the Enfield route. While the percentage of time spent in each speed-acceleration combination varied slightly between the two bus types, this is hypothesized to be caused by the binning definitions chosen and not as an indication of a significant difference in vehicle operation.

Note the CD bus type showed no operation at acceleration rates greater than 3 mph/s , whereas the HDE bus type had some operation at these relatively high acceleration rates, even on the Enfield route. Because the rationale of using the hybrid design is to relieve the diesel engine of those operating regimes where it is least efficient, it is likely these high-acceleration events occurred during acceleration of the bus from stops (highway ramps on the Enfield route).

The middle row in Figure 4 shows speed-acceleration plots where the vertical axis is the average engine load. The two vehicle types are similar in the distribution of corresponding engine load over speed-acceleration, except for the low speed deceleration bins. The CD diesel engine experienced larger average loads than the HDE bus (40% vs. 20%), in agreement with Figure 3, which indicated the conventional diesel had a larger frequency of loads in the 40 to 55% range. The HDE bus type also had a series of high engine load events during low speed (5 - 20 mph) moderate acceleration (3 - 5 mph/s) operation that were not experienced by the CD bus type.

The bottom row Figure 4 plots show mean engine speed (RPM). The HDE bus data contains a series of elevated RPM values at higher vehicle speeds ($> 30\text{ mph}$) and rapid decelerations ($< -5\text{ mph/s}$) that is not present in the CD data (Figure 4). Also, for the HDE buses, as acceleration or deceleration increased there was an increase in RPM not seen in the CD data. This indicates the HDE's diesel engine speed is more sensitive to acceleration and deceleration events, which could correspond to larger variations in tailpipe emissions for the HDE bus on the Enfield route.

Avon Route Operation

Speed/acceleration histograms for the data collected on the Avon section of the test route (top row of plots in Figure 5) have similar patterns indicating vehicle operation was generally consistent between bus types. However, there are some notable differences. First, the HDE vehicle type had several instances of high acceleration rates ($> 5\text{ mph/s}$) at low speed that were not experienced by the CD buses on the Avon route. Second, the CD bus sat idle at intersections or simulated bus stops longer on this route than the HDE bus. This is seen in the larger percent of zero MPH observations.

The speed-acceleration-average engine load plots for the Avon route (middle row of Figure 5) are similar to the plots seen for the Enfield route where the conventional diesel had larger mean loads at lower speeds/deceleration bins and the HDE bus type had high loads at very high acceleration under low vehicle speed, operating conditions that were not experienced by the CD buses. Engine loads for both vehicles increased as acceleration rate increased.

The bottom row of Figure 5 displays speed acceleration plots of mean engine speed (RPM) for the two bus types and show differences in how RPM is distributed over the speed-acceleration bins on the Avon route. The HDE vehicle data appears to be a mirror image of the

CD data: the CD data had larger RPM values at high **acceleration** rates, but the diesel engine on the HDE bus type had larger RPM values at larger **deceleration** rates.

Farmington Route Operation

The speed/acceleration histograms for the data collected on the Farmington section of the test route (top row of Figure 6) have similar patterns indicating vehicle operation was consistent between bus types. There is a large portion of the data concentrated around zero speed and zero acceleration due to the stop-and-go nature of the urban arterial and the simulated bus stops along this route. Similar to the Avon route, the HDE data had acceleration events of larger magnitude (> 5 mph/s) that were not seen in the CD.

The Farmington route engine load plots for the CD and HDE bus types (middle row of Figure 6) are similar to the plots seen for the Enfield and Avon routes. However, for the Farmington route, high acceleration, low speed instances are associated with relatively high engine load compared to the other two routes. Furthermore, the operation of the HDE bus on the Farmington route had the largest frequency of high acceleration events (>4 mph/s) at low speeds (<25 mph). The engine loads in this speed/acceleration region were also the largest of all the bus types and route combinations.

Farmington route speed-acceleration, RPM plots (bottom row of Figure 6) indicate differences in how RPM is distributed over the speed-acceleration combinations for each bus type. The CD bus type had larger RPM values at high acceleration rates and low speeds compared to the HDE bus type. However, the CD buses had relatively consistent RPM values once speeds were above 10 mph on the Farmington route. The HDE bus type had moderate RPM in the higher acceleration rate/ low speed bins where the electric motor provided power assist.

Bus Operation Summary

The speed-acceleration 3D plots suggest there are differences in vehicle operation based on route and vehicle type. With the exception of the low vehicle speed (< 20 mph), high acceleration (>4 mph/s) operation observed for the HDE bus type, but not experienced for the CD bus type, the speed acceleration frequency plot patterns differ between routes but are similar when comparing bus types for a single route. This indicates that the way the vehicle was driven on each of the test sections was consistent (note: the same driver was used for all data runs). However, when comparing the engine operating parameters (load and RPM) between the two bus types, there were notable differences in operation distributions over the speed-acceleration profiles. This indicates that *bus type is significant and that HDE bus operation should **not** be modeled using the same equations as CD buses.*

Particle Number Emissions Rate

The second objective of this research was to investigate particle emissions from the conventional and hybrid buses and determine if there were significant differences between the two. The previous section indicated that vehicle operating parameters were different based on route and vehicle type.

Histograms of PNER by vehicle type indicate the data are not normally distributed. Therefore, the PNER data were transformed using a natural log transformation ($\ln(\text{PNER})$). The histograms for the transformed data (Figure 7) indicate noticeable differences in the distribution of emissions rates between the two vehicle types. These differences become more pronounced as the data are analyzed even further by route. From these plots and the summary statistics in Table 2, there do not appear to be major differences in the range of particle number emissions rates between the two bus types when data from all test dates are considered together.

The median emissions rates for the HDE bus type were slightly lower than for the CD vehicle. Conversely, the HDE bus type had a mean emission rate that was larger than that for the CD buses. When the mean and median are compared for the HDE bus type, there is more than an order of magnitude difference. This discrepancy between the mean and median suggests there are outliers (likely due to transient operating events) for the HDE bus type that increase the mean but have little impact when calculating the median emissions. The conventional diesel has a similar discrepancy between the mean and median but of lesser magnitude.

Due to the varying traffic conditions, operating conditions and geometric design of the sections of the test route, it was hypothesized that the two bus types would produce statistically different emissions based on the section of the route it was traveling. Mean particle number emissions rate by test section (Figure 8) compares CD (light-colored boxes) and HDE (darker boxes) bus types, with the error bars representing one standard deviation. Certain sections of the test routes have similar means however there are sections like the Avon West Up that have drastically different mean emissions based on engine type. One the majority of the routes it appears the HDE actually has a higher mean PN emissions rate than the CD. This could be attributed to transient spikes in emissions that inflate the mean. As mentioned before the HDE had peak PN emissions that were larger than the peak CD emission spikes.

Statistical analysis of PNER by route involved identifying which sections of the test routes produced PN emission rates that were statistically different from each other. Furthermore the data were analyzed by bus type to determine if the HDE and the CD buses performed significantly different along these sections. Results of the generalized linear model (GLM) analysis and the Waller-Duncan k-ratio T-test can be found in Table 2. (Note: results for the Waller and Duncan tests were identical therefore only the results from the Waller test are displayed here). The Route segment bus type combinations with the same letter grouping are **not** statistically different from each other. From this analysis (Table 2), the following observations about PNERs on each route can be made:

- **Enfield routes** (groups A and B): the HDE and CD bus emissions rates were not significantly different. However, for the CD bus type only, the Enfield South and Enfield North route emissions were statistically different.
- **Avon Uphill** (groups C, D and E). The PN emissions rates for the HDE buses were larger and statistically different than the CD bus type PNERs.
- **Avon Downhill** (groups F, G and H). The HDE and CD bus type PNERs were not different for the Avon West Down and for the Avon East Down sections of the driving route. However, the HDE bus type emissions on Avon West Down (group F) were statistically different from the Avon East Down emissions (groups G,H) for both bus types.
- **Avon West** (group I). The mean PN rates were not different based on bus type when the entire westbound Avon route was examined.
- **Farmington West** and **Avon East** routes (group K) were not different from each other based on vehicle type.
- The test route with the lowest mean PN emissions rate occurred on the **Farmington East** route with the **CD bus**. (Group M)

The analysis in this section determined that driving routes and vehicle type have a significant effect on the mean particle number emissions rate generated by the bus. This

indicates an interaction effect, where the vehicle type becomes significant based on the test route and vice versa. These results using particle **number** (and the same dataset) are different from Holmén, et al. (2005) results for particle **mass** emissions from the CD and HDE buses that were not statistically different from each other. Thus, particle **number** emissions rates and particle **mass** emissions rates must be modeled separately.

Study Summary and Recommendations

This research investigated differences in vehicle operation and particle **number** emissions rates from conventional diesel transit buses and hybrid electric diesel. The first objective of this research was to investigate the differences in vehicle operation between the hybrid and conventional buses. The results indicate the standard measure of **vehicle** operation (VSP) does not vary based on bus type. However, when the operation of the diesel engine of each bus type was analyzed there were obvious differences in **engine** operation. Operation of the hybrid bus was assisted by an electric motor which affected the way the on-board diesel engine operated. Figures 4, 5 and 6 indicate differences in RPM and load distributions on the diesel engines of both vehicles for each speed/acceleration combination. If the diesel engines of these two bus types are operating differently then one can expect there to be differences in exhaust emissions. Therefore, if VSP is to be used as a metric or predictor for heavy duty vehicle emissions new coefficients or methods must be developed for HDE buses. The increasing number of HDE buses and popularity of HDE buses indicate newly developed emissions models will be inaccurate unless this issue is addressed.

The second objective of this research was to investigate particle number emissions from the CD and HDE buses. The results presented in Table 2 indicate there are certain situations where bus type creates significant differences in particle emissions output. While both buses had similar emissions output on the interstate, steep grade sections proved to induce higher emissions rates from the HDE bus than the CD. Furthermore, CD on the Farmington Eastbound route produced the smallest PN mean emissions. The results of this analysis are contradictory to the common belief that a HDE will produce significantly lower emissions than a CD, at least with respect to PN emissions.

Further research is warranted to account for these significant differences in PN emissions rates by bus type given the minimal difference in VSP distributions. This research is critical to developing accurate PN emissions models that are sensitive to increasing implementation of new engine and vehicle technology. In the case of the HDE and CD buses, *use of VSP and speed alone would not allow for a distinction between the two vehicle types even though there are significant differences in PN emissions output*. Furthermore, the observed high particle emissions on steep uphill grades for hybrids indicate route selection for hybrid buses should be investigated to optimize the environmental benefits of the hybrid vehicles.

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Table 1. Summary of Previous Research on Transit Bus Particle Number Emissions

Author (Year)	Bus Details (Engine/Model year/Age)	Aftertreatment	Fuel	Testing cycle, (measurement)	Particle number concentrations
Morawska et al. (1998) [12]	11 diesel buses with Volvo chassis (in fleet 2-13 yrs) 1 Caterpillar bus (new)	None	No information (assume 5000 ppm ^a sulfur content)	15 steady-state mode cycle	$0.7\text{--}3.9 \times 10^7$ (#/cm ³) ^b
Holmén and Ayala (2002) [2]	DDC series 50 engine: EC50 (1998)	1) Catalyst 2) DPF Johnson-Matthey CRT	ULSD (11 ppm)	Idle & steady-state 55 mph cruise	1) $0.8\text{--}3 \times 10^6$ (#/cm ³) 2) $0.5\text{--}9 \times 10^4$ (#/cm ³)
Lanni (2003) [3]	1999 DDC series 50 engine, Orion V chassis	1) Catalyst 2) DPF Johnson-Matthey CRT	#1 Diesel (247 ppm) and ULSD (27 ppm)	CBD Cycle	1) $10^9 \sim 10^{10}$ (#/cm ³) ^c 2) $10^7 \sim 10^8$ (#/cm ³)
Holmén and Qu (2004) [4]	DDC series 50 engine (late model year from 2001 in-service fleet)	1) Catalyst 2) DPF Johnson-Matthey CRT	ULSD (11 ppm)	Idle, steady-state cruise (55mph), CBD, NYB, UDDS cycle ^d	1) $.2\text{--}4 \times 10^6$ (#/cm ³) 2) $.01\text{--}2 \times 10^4$ (#/cm ³)
Jamriska et al. (2004) [6]	300 diesel buses from Brisbane bus fleet (ave. in-fleet 10 years)	None specified	No information (Assume 500 ppm) ^a	Buses tested in 500-meter long tunnel. Speed limit 60 km/h	$.5\text{--}8 \times 10^4$ (#/cm ³) ^e $3 (\pm 2.4) \times 10^{15}$ (#/km) ^f
Nylund et al. (2004) [5]	European origin (make not specified) 2003 MY	1) No catalyst 2) Catalyst 3) DPF, CRT	ULSD (23 ppm)	Braunschweig and Orange County Cycle	1)-2) $10^{14} \sim 10^{15}$ (#/km) $10^{11} \sim 10^{13}$ (#/sec) 3) $10^{12} \sim 10^{13}$ (#/km), $10^9 \sim 10^{10}$ (#/sec)
Ristovski et al. (2006) [20]	12 Diesels with Volvo chassis. Entry date to service: 1982 (2), 1998 (1), 1993 (3), 1995 (3), 2000 (3)	None	LSD (500 ppm) and ULSD (50 ppm)	4 steady state cruise-tests 1) idle 2) 25% power 3) 50% power 4) 100% power	(idle mode) $10^{10} \sim 10^{12}$ (#/sec) (non-idle modes) ^g $10^{12} \sim 10^{14}$ (#/sec)
^a . Australian regulations until 2002 when 500 ppm became standard. [20]. ^b . On average particle concentrations were 15 times higher in higher power mode compared to idling. ^c . ULSD reduced particle mass by 29% from #1 Diesel, but no significant difference in particle number. ^d . Central business district (CBD), New York bus (NYB), urban dynamometer driving schedule (UDDS). ^e . Ambient concentration at tunnel exit during bus traffic. ^f . Estimated particle number emission rate per bus (plus or minus standard deviation). ^g . Emission rates for the ULSD were from 30 to 60% lower than LSD.					

Table 2. Hybrid and Conventional Diesel Waller Grouping**Means with the same letter are not significantly different.**

Waller Grouping			Mean	N	Route XY	Bus Type
	A		3.46E+12	10046	Enfield North	CD
B	A		3.42E+12	14106	Enfield South	HDE
B	A		3.40E+12	13082	Enfield North	HDE
B			3.36E+12	11893	Enfield South	CD
	C		2.62E+12	2334	Avon West Up	HDE
	C		2.53E+12	2100	Avon East Up	HDE
	D		2.04E+12	1896	Avon East Up	CD
	E		1.74E+12	2178	Avon West Up	CD
	F		7.53E+11	1938	Avon West Down	HDE
G	F		7.07E+11	1754	Avon West Down	CD
G	H		6.54E+11	2061	Avon East Down	CD
G	H		6.42E+11	2416	Avon East Down	HDE
I	H		6.14E+11	7665	Avon West	HDE
I	J		5.37E+11	6556	Avon West	CD
K	J		5.19E+11	17747	Farmington West	HDE
K	J	L	5.09E+11	5564	Avon East	HDE
K	J	L	5.00E+11	5362	Avon East	CD
K		L	4.31E+11	15276	Farmington West	CD
		L	4.30E+11	18840	Farmington East	HDE
	M		3.35E+11	17193	Farmington East	CD

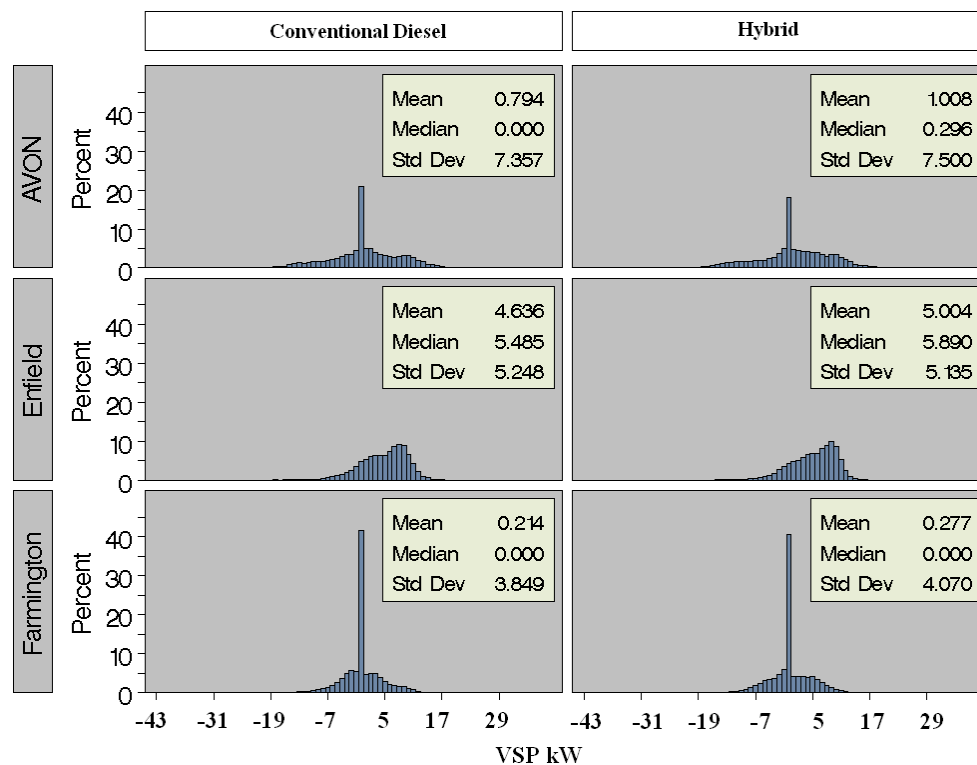


Figure 1. VSP Histograms by Bus Type and Route: 16 bins at 1kW intervals (i.e. bin 7= 6.5 kW to 7.5kW)

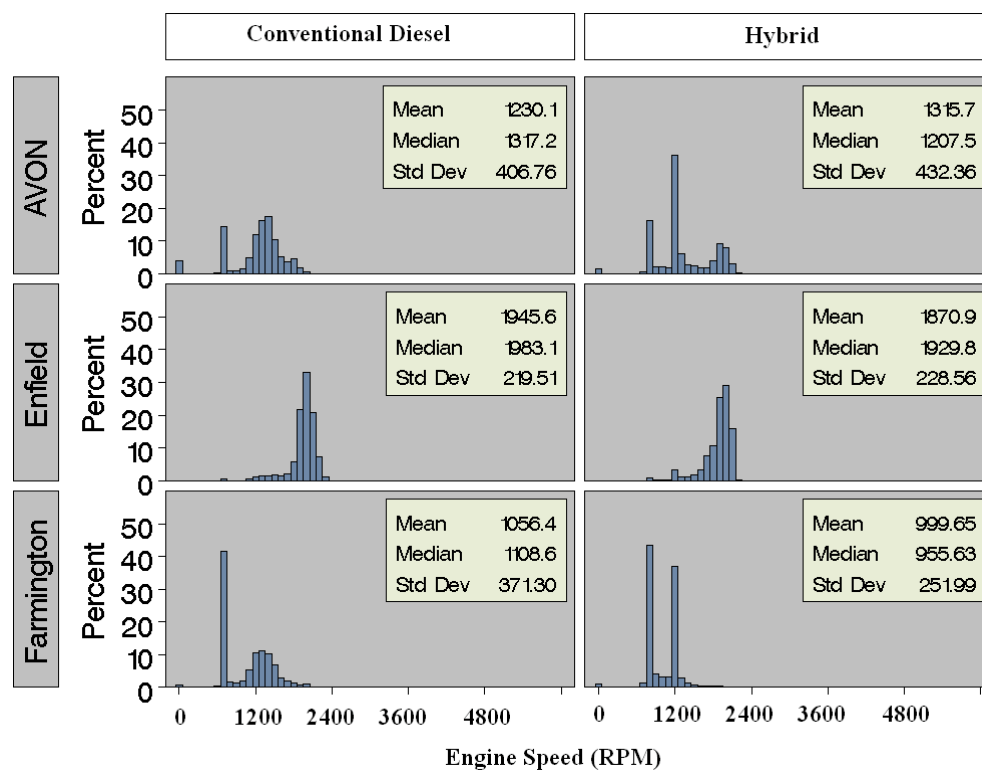


Figure 2. Engine Speed (RPM) Histograms for CD and HDE Bus Types by Route

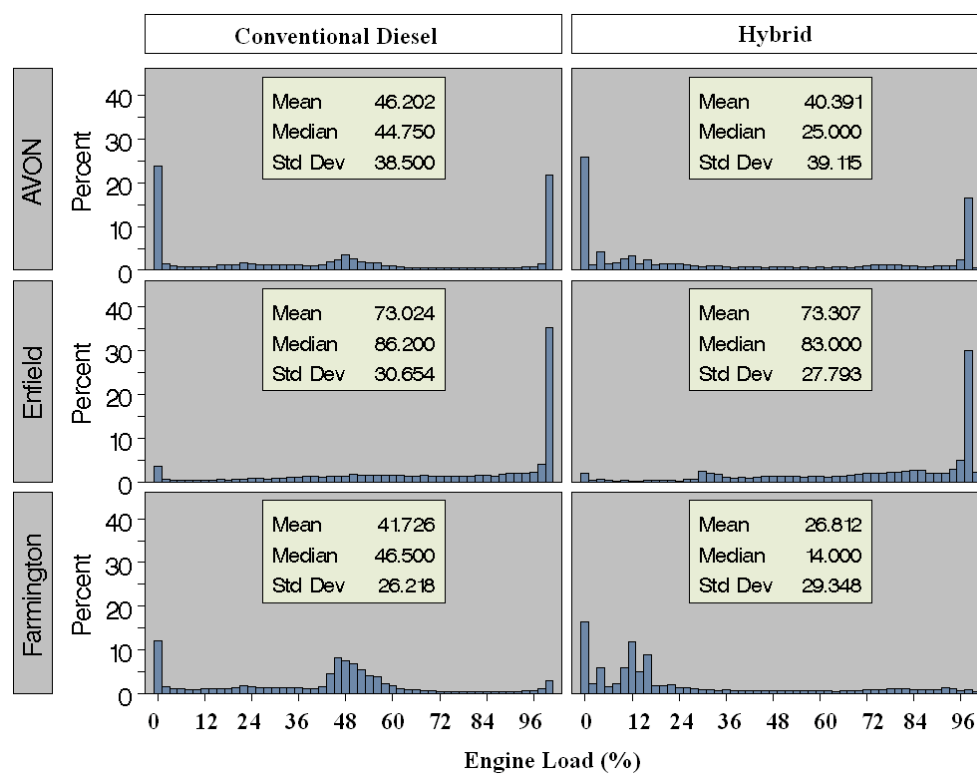


Figure 3. Engine Load Histograms for CD and HDE Bus Types by Route

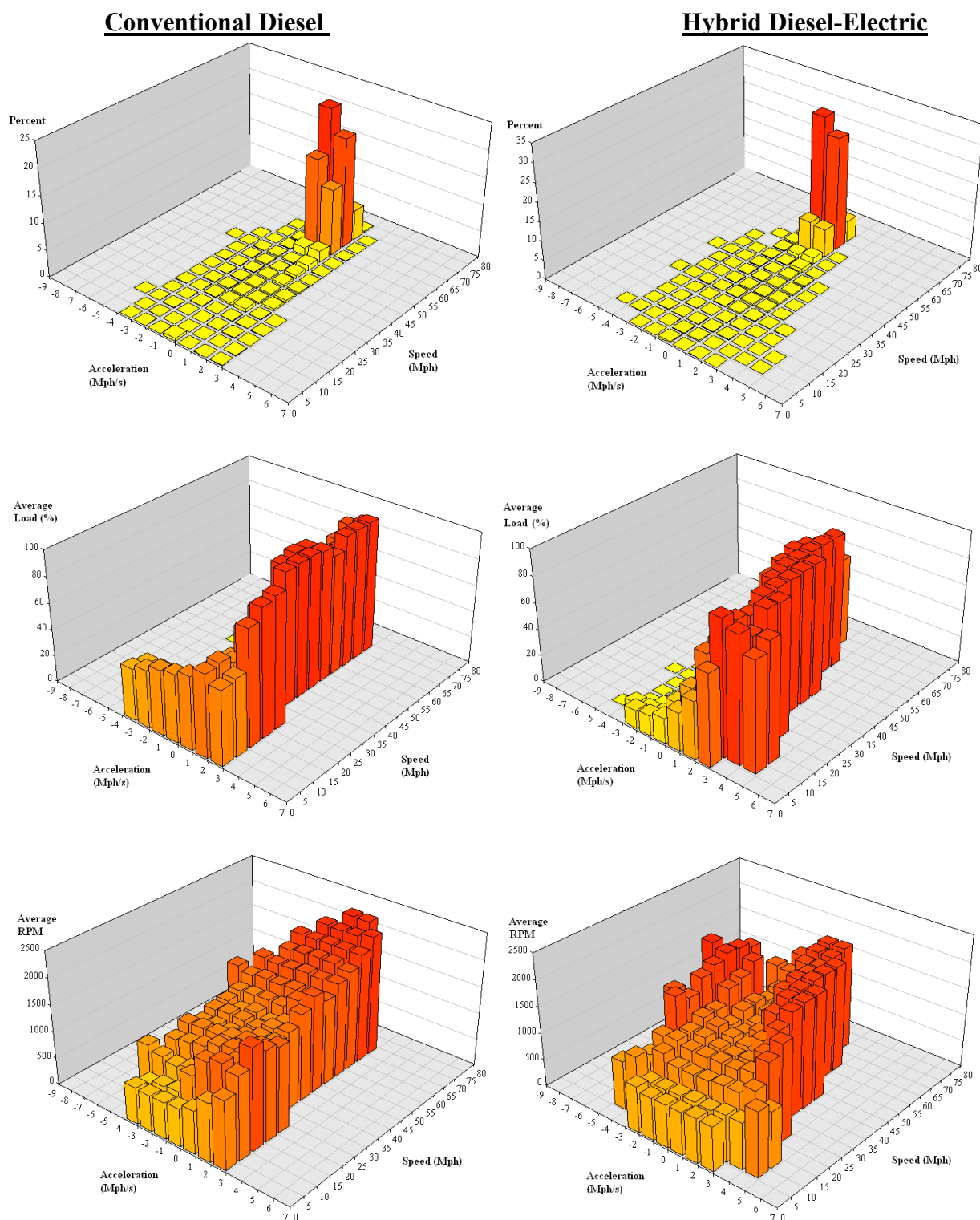


Figure 4. Enfield Route Speed, Acceleration Profile (Top), Engine Load (Middle) and Engine RPM (Bottom)

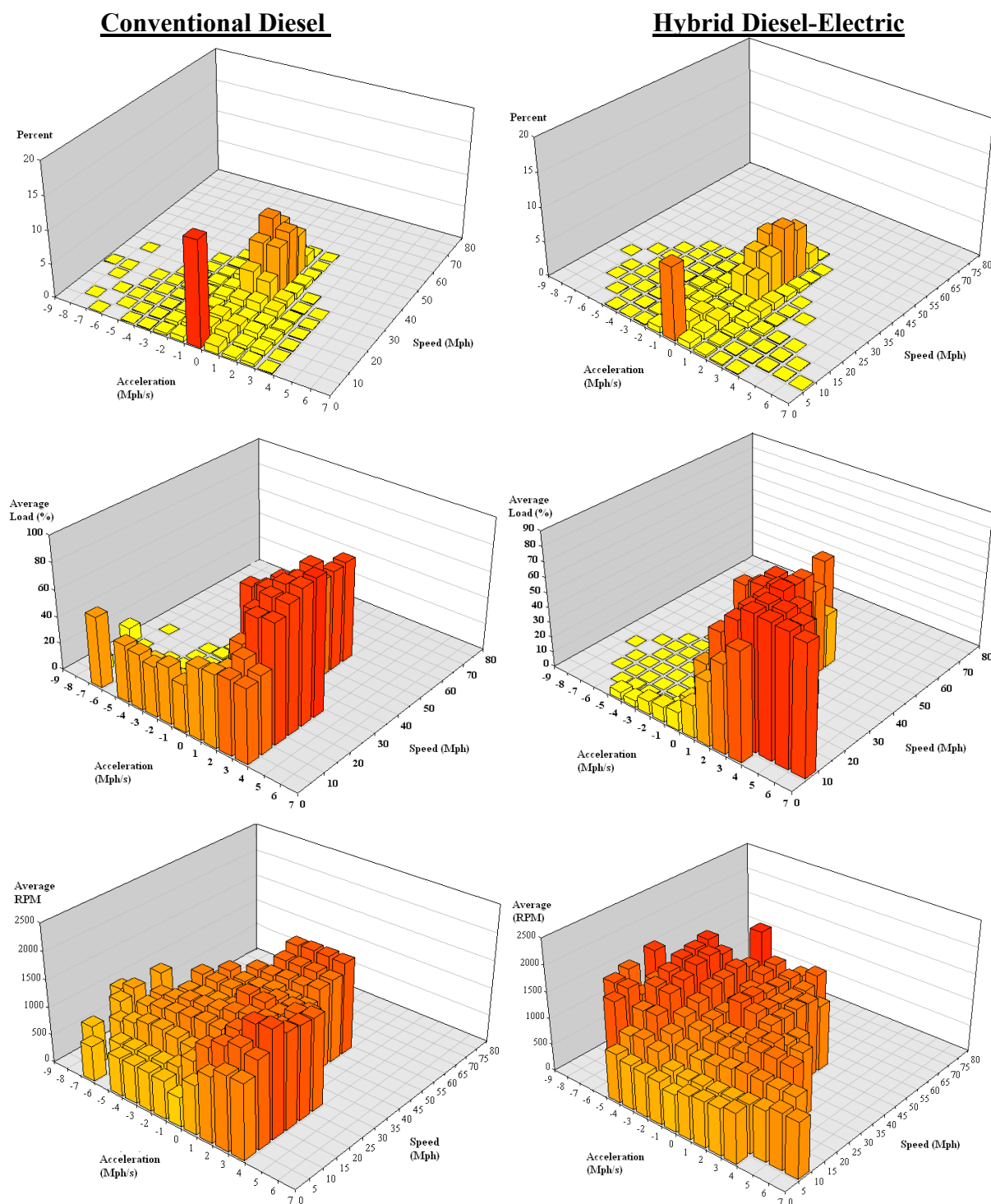


Figure 5. Avon Route Speed, Acceleration Profile (Top), Engine Load (Middle) and Engine RPM (Bottom)

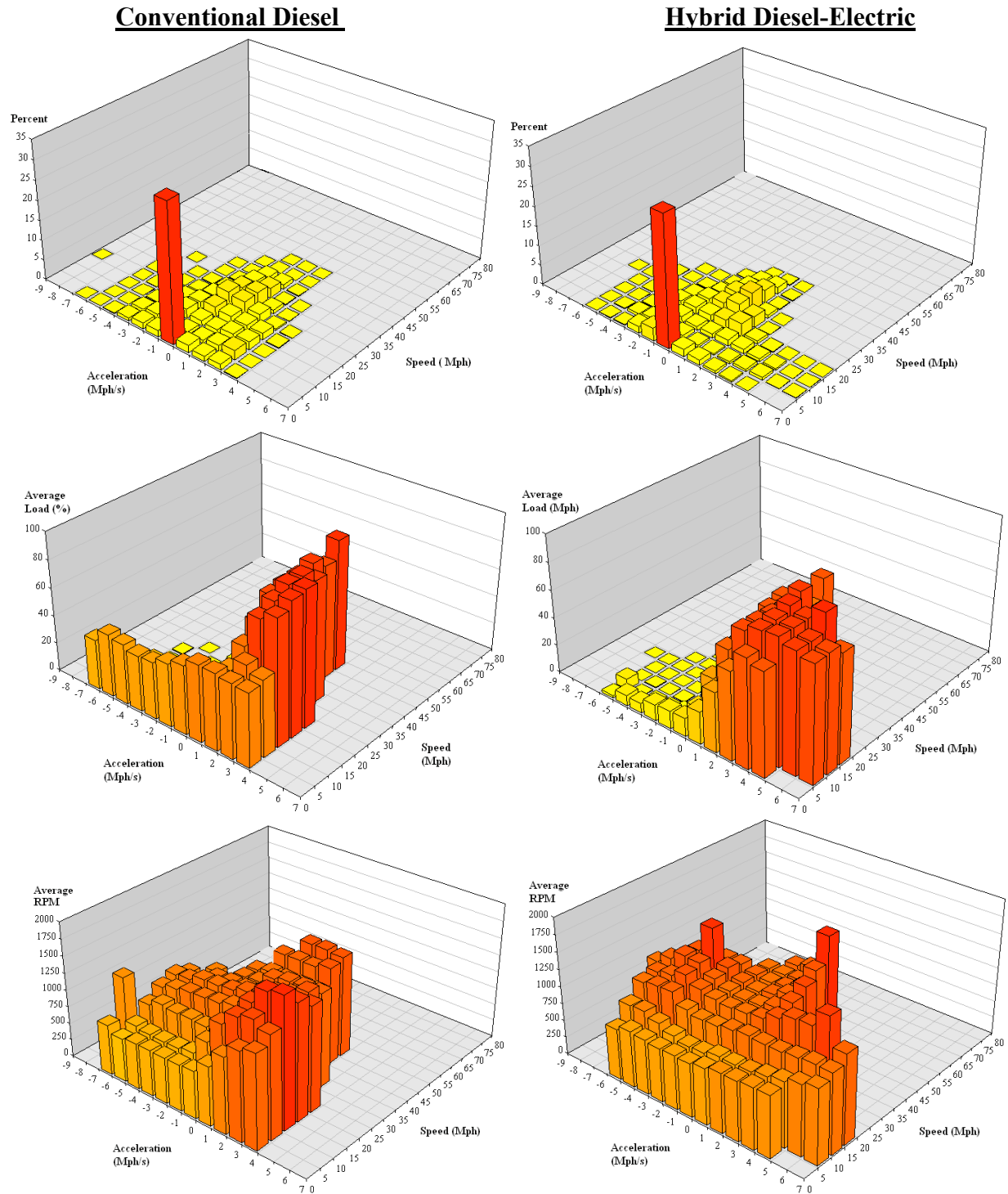


Figure 6. Farmington Route Speed, Acceleration Profile (Top), Engine Load (Middle) and Engine RPM (Bottom)

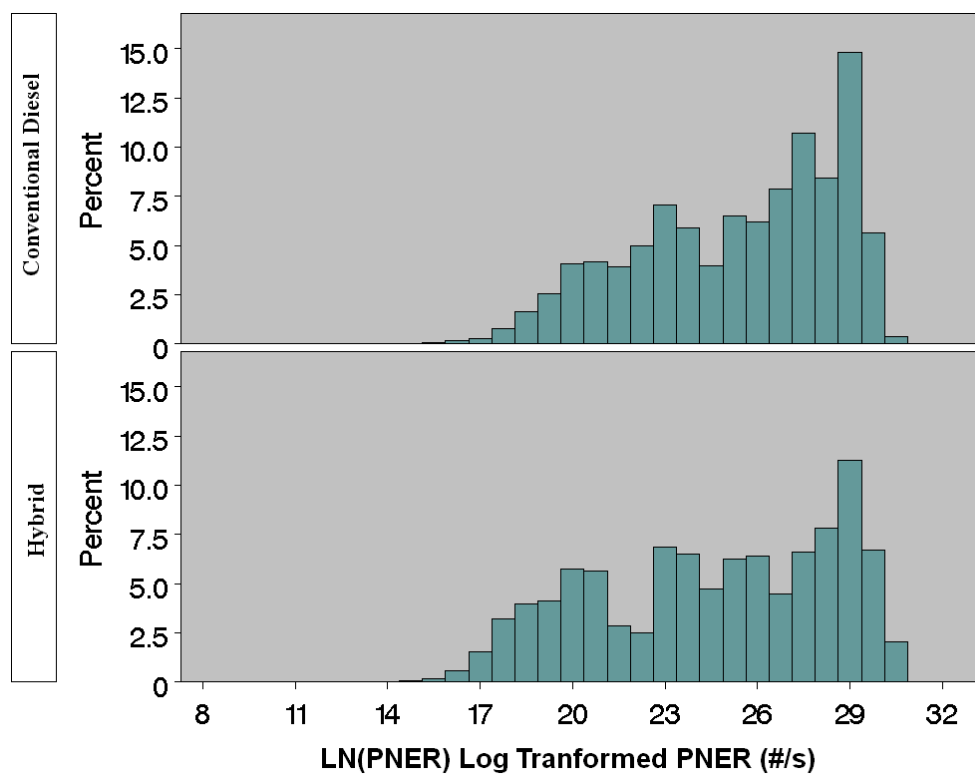


Figure 7. Log Transform PNER Histograms for CD (top) and HDE (bottom) Bus Types: All Routes, All Dates

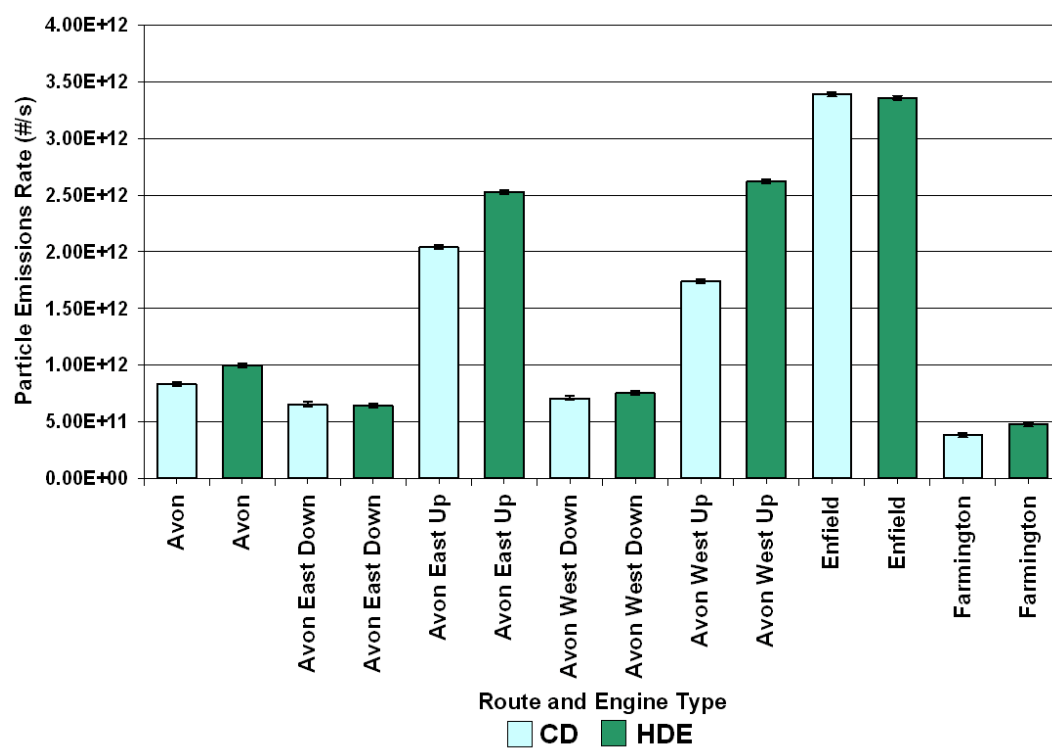


Figure 8. Mean Particle Number Emissions Rate (PNER) by Route and Bus Type.