PARTICULATE MATTER EMISSIONS FROM HYBRID DIESEL-ELECTRIC AND CONVENTIONAL DIESEL TRANSIT BUSES: FUEL AND AFTERTREATMENT EFFECTS

August 2005

JHR 05-304 Project 03-8

Final Report
to

Connecticut Transit (CTTRANSIT)
and
Joint Highway Research Advisory Council (JHRAC) of the
Connecticut Cooperative Highway Research Program

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16. Abstract

This study compares the particulate emissions from two hybrid diesel-electric (HDE) and two conventional diesel (CD) transit buses of similar performance characteristics measured under three different fuel and aftertreatment configurations over one-year of on-board emissions testing:

Phase 1. No. 1 diesel fuel + diesel oxidation catalyst (DOC) aftertreatment.
Phase 2. Ultralow sulfur diesel fuel (ULSD) + diesel oxidation catalyst (DOC).
Phase 3. ULSD + diesel particulate filter (DPF); where the ULSD used in this study had measured sulfur levels $\leq$ 50 ppm.

The Allison parallel hybrid buses, in their tested control configuration, did not have any significant particulate emission benefits over the conventional diesel buses, but may have other fuel economy and maintenance benefits that were not addressed by this study. CTTRANSIT should investigate whether a series hybrid design will offer more emissions benefits without sacrificing other advantages of the hybrid bus such as lower noise, smoother rides and performance characteristics comparable to conventional diesel transit buses on freeway commuter routes and routes with high grade (up to 9% in this study).

While operation on ULSD did not lower PM emissions relative to No.1 diesel for the buses tested, operation on ULSD does enable the use of diesel particulate filter aftertreatment, which reduced the particulate emissions by over 95%. The use of DPFs on older engine buses in the CTTRANSIT fleet should be a targeted goal for CTTRANSIT over the next 5-10 years to cover the gap as the current fleet is replaced by newer technologies.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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INTRODUCTION

Two GM Allison/New Flyer parallel drive hybrid diesel-electric (HDE) transit buses were purchased by Connecticut Transit, CTTRANSIT[1], and placed into revenue service in mid-June 2003. These buses were obtained as demonstration vehicles to be evaluated in terms of their fuel economy, maintenance costs and exhaust emissions prior to making purchasing decisions for the "next generation" future CTTRANSIT fleet. The University of Connecticut was contracted to measure the emissions from the two HDE buses in comparison to two virtually identical conventional diesel (CD) buses. This report summarizes the particulate matter exhaust emissions from the four study vehicles. The exhaust emissions were quantified using on-board tailpipe measurements during real-world driving of three different bus routes within the CTTRANSIT system. As discussed in detail below, both particulate matter (PM) <u>mass</u> and particle <u>number</u> emissions were quantified using a suite of laboratory instruments. These instruments were outfitted for on-board emissions testing (i.e., while vehicles were traveling down the road) after it was discovered that the heavy-duty vehicle laboratory chassis dynamometer at CTTRANSIT was not capable of replicating the coastdown characteristics of the hybrid vehicles that are critical to achieving fuel economy and emissions benefits with the hybrid design.

Background. CTTRANSIT serves over 27 million passengers per year in the Hartford (14 million), New Haven (9 million) and Stamford (3.3 million), Connecticut greater metropolitan areas (CTTRANSIT 2005). CTTRANSIT is a private company that is owned by the Connecticut Department of Transportation (ConnDOT) and currently operates 395 transit buses in various fuel and aftertreatment configurations (see Table 1).

Table 1. Current CTTRANSIT in-use transit bus fleet configurations (as of June 2005) [*]

Type (#)	Fuel	Aftertreatment	Fleet Location
Diesel (232)	#1 Diesel	CAT & DOC	Hartford
Diesel (108)	#1 Diesel	DOC	NewHaven
Diesel (21)	ULSD	DOC	Stamford
Diesel + DPF (32)	ULSD	Engelhard DPX™	Stamford
Hybrid diesel-electric + DPF (2)	ULSD	Johnson Matthey CRT™	Stamford

[*]ULSD = ultralow sulfur diesel (< 30ppm S); CAT= catalytic muffler; DOC = diesel oxidation catalyst; DPF = diesel particulate filter.

The majority of buses in the CTTRANSIT fleet (59% in Hartford and 27% in New Haven, see Figure 1) currently operate on #1 diesel fuel (250~350 ppm S). The entire Stamford fleet of 53 diesel buses operates on ultralow sulfur diesel (ULSD, sulfur < 30 ppm) fuel and 32 of these buses have diesel particulate filters (Englehard DPX™). The majority of CTTRANSIT's fleet will be replaced with lower emission vehicles in the next decade for three reasons: (1) to achieve mobile source emissions credits in Connecticut's State Implementation Plan and meet regulatory requirements of the Urban Bus Retrofit/Rebuild program; (2) in response to the new June 2006 diesel fuel sulfur requirements that will lower diesel fuel sulfur to below 15 ppm and enable

[1] Connecticut Transit (CTTRANSIT) is the Connecticut Department of Transportation-owned bus service, serving the greater Hartford, New Haven, Stamford, Waterbury, New Britain, Meriden, Bristol and Wallingford areas.

more widespread use of aftertreatment control technologies; and (3) due to new highway heavy-duty diesel emission standards for model year 2007 diesel engines (see Table 2).

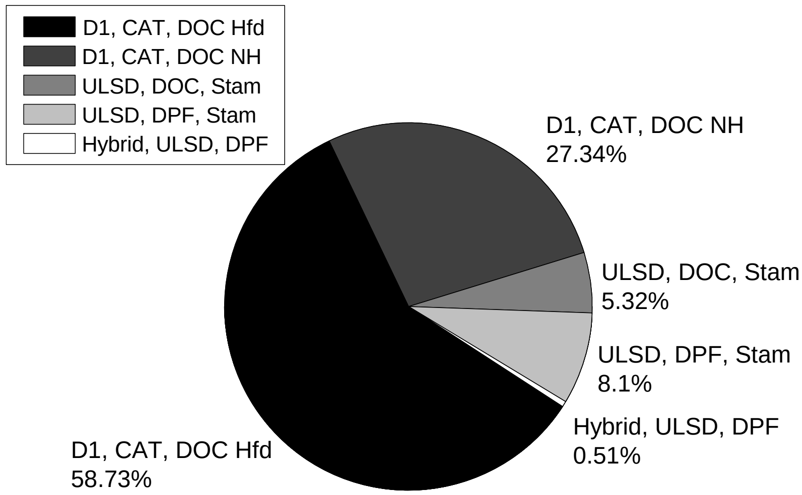

FIGURE 1. Percent of different types of transit buses operating in CTTRANSIT fleets in Hartford (Hfd), New Haven (NH) and Stamford (Stam), Connecticut. The two HDE buses represent 0.5% of the entire fleet.

Table 2. Urban Bus Engine Emission Standards (g/bhp-hr)

M.Y.	NOx	HC	CO	PM
1988*	10.7	1.3	15.5	0.6
1990	6	1.3	15.5	0.6
1991	5	1.3	15.5	0.25
1993**	5	1.3	15.5	0.1
1994	5	1.3	15.5	0.07
1996	5	1.3	15.5	0.05***
1998	4	1.3	15.5	0.05
2004	2.4 #	#	15.5	0.05
2007	0.2	0.14	15.5	0.01

*Prior to 1988, only smoke standards applied to heavy-duty diesel engines

**In 1993, urban buses assigned separate, more stringent emission standard.

***In 1996, PM certification level set at 0.05, but in-use level remained 0.07.

In 2004, options are NOx + NMHC = 2.4 **or** NMHC = 0.5 and NOx + NMHC = 2.5

Urban Bus Retrofit/Rebuild Program. Under the Clean Air Act Amendments of 1990, the Environmental Protection Agency (EPA) established a program in 1993 to reduce particulate matter emissions from buses in urban areas having 1980 populations of 750,000 or more. The program required affected transit agencies to choose between two options with regard to pre-1994 model year heavy-duty diesel engines. Option 1 required retrofitting pre-1994 engine buses such that they meet lower PM emissions certification levels (either 0.1 g PM/bhp-hr or a

25% reduction from that engine's certification PM level). Under Option 1, the older engines were required to meet more stringent emissions standards only when that engine was rebuilt or replaced after January 1, 1995. Option 2 was designed to meet the same overall PM emissions reductions as Option 1, but by using a fleet-averaging approach. In other words, the transit agency could opt to replace pre-1994 engines with significantly cleaner technologies under Option 2 to achieve fleet-average emissions reductions equivalent to those that would be achieved if every pre-1994 engine met the 1994 emissions standards. An important outcome of the Urban Bus Retrofit program was awareness by transit agencies of the technological options available to them to comply with the program and improve air quality. These options include adoption of alternatively-fueled vehicles, such as natural gas, as well as new vehicle and aftertreatment technologies, including the hybrid drivetrains and diesel particulate filters examined in this study. The Hartford-New Britain-Middletown CT areas were on the EPA list of affected counties under the Retrofit/Rebuild program (Schiavone 1994).

Data obtained in this research effort was intended to help CTTRANSIT managers answer the following general question: ***what is the most cost-effective long-term composition of the fleet that will have the combined benefits of improved air quality, lower capital and operating/maintenance costs as well as long-term effectiveness?*** Specifically, this report compares the particulate emissions of two transit bus designs – CD and HDE – as a function of fuel, route and aftertreatment alternatives.

Research Objectives. This study compares the particulate matter mass and ultrafine particle number emissions from two different transit bus configurations currently available to the CTTRANSIT fleet in order to determine the combination that will best meet current and future particulate matter emission standards. Specifically, particulate emissions from two hybrid diesel-electric (HDE) and two conventional diesel (CD) transit buses of similar performance characteristics were measured under three different fuel and aftertreatment configurations over the course of one-year of on-road testing:

Phase 1. No. 1 diesel fuel + diesel oxidation catalyst (DOC) aftertreatment.
Phase 2. Ultralow sulfur diesel fuel (ULSD) + diesel oxidation catalyst (DOC).
Phase 3. ULSD + diesel particulate filter (DPF).

where the ULSD used in this study had measured sulfur levels $\leq$ 50 ppm.

More specific research questions based on the Allison *parallel* hybrid design used in this study are:

1. Does the parallel hybrid design (without the smaller diesel engine typical of series hybrids) offer significant emissions benefits on stop-and-go, low-speed routes compared to conventional diesel buses?
2. How much does the switch to ULSD fuel reduce PM emissions from the conventional and the hybrid buses?
3. What PM emission reductions, both by number and mass, can be achieved on a single bus with diesel particulate aftertreatment?
4. Do the particulate mass and number emissions vary with driving route for a given bus type?

5. Do the particulate number *distributions* vary with bus type on a given driving route for a given fuel type?
6. Are mean emissions of the same bus type statistically equivalent when averaged over all routes for a single fuel type?
7. Under what specific transit bus route conditions will the Allison *parallel* design hybrid buses give the best improvement in particulate emissions?

After a brief review of the hybrid designs and previous work on emissions from HDE transit buses, this report summarizes the measurement techniques used to collect real-world exhaust emissions (Experimental Methods) and provides preliminary comparisons between emissions from the different bus types over the three phases of the field study on the basis of "route-average" emissions (Results and Discussion). Based on the results, the Recommendations section outlines the most cost-effective approach for reducing particulate emissions from the CTTRANSIT fleet buses.

Parallel Hybrid Design Benefits. Hybrid vehicles consist of two power sources, an internal combustion engine (ICE) and an electric motor/energy storage system (ESS, typically a battery pack), that can be arranged in either a parallel or a series design, to drive the wheels of the vehicle. In the series design, only the electric motor/generator is able to provide mechanical power to the wheels while the ICE, operating as a generator for the electric motor, is operated only over a limited range of speed and torque settings to give the best efficiency and highest fuel economy. Series hybrid transit buses are in-use in New York City and Orange County, California and have shown significant fuel economy benefits in laboratory tests compared to conventional diesel buses (see Table 3 below). Reduced fuel consumption and lower emissions from hybrid vehicles are made possible through the use of regenerative braking and power management system algorithms that allow the diesel engine to operate more often at its most efficient speed and torque ranges (McKain et al. 2000; Wayne et al. 2004).

In 2002, Allison Transmission, a division of General Motors, began supplying the Allison E^{p} 40 parallel hybrid transmission for transit buses under its "Preview Program". The parallel hybrid design offers higher overall efficiency compared to the series design and can use a smaller battery pack (German 2001). In the parallel-drive hybrid configuration (Figure 2), the engine and the electric motor are both coupled directly to the drivetrain. Thus, the engine and the electric motor can drive the wheels simultaneously. A few laboratory studies have also demonstrated the lower emissions and higher fuel economy benefits of the parallel hybrid design (Meyer and Rideout 2002) compared to CD buses as outlined in Table 3 below.

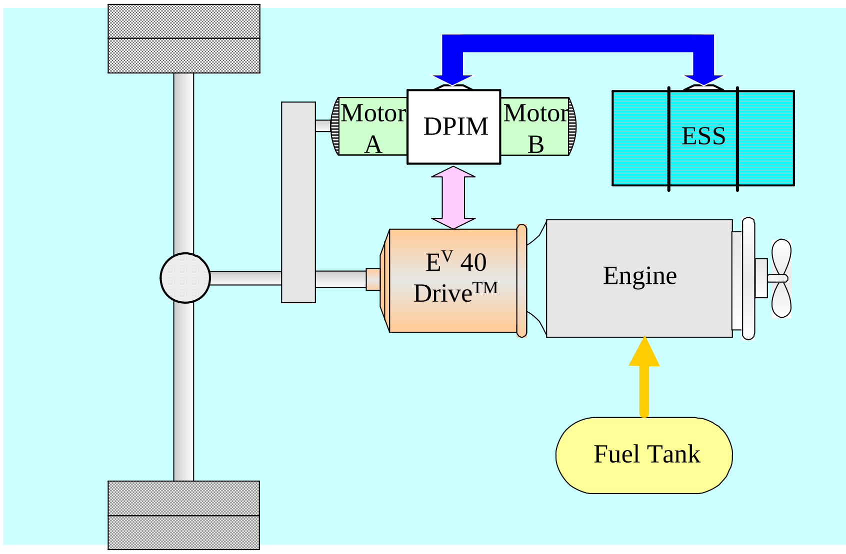

FIGURE 2. The Allison Transmission E^P-40 parallel hybrid configuration allows both mechanical (from internal combustion engine) and electrical (from electric motor) power to the wheels. *Modified from(Allison Transmission 2002). ESS = Energy Storage System; DPIM = Dual Power Inverter Module.*

By use of a simplified energy balance, Bass and Alfermann (2003) outlined the factors affecting the degree to which hybrid drive technology offers fuel economy benefits. These factors are average speed, percent idle time, accessory load, vehicle weight and extreme terrain. Factors that result in a higher proportion of the driving time with output energy coming from the battery, instead of the internal combustion engine, lead to improved fuel economy (Bass and Alfermann 2003). So, driving cycles with higher frequencies of stopping will result in the greatest hybrid benefits, chiefly because the fraction of overall energy coming from the battery is high. In contrast, cycles with higher average cruise speeds will rely more on the energy from the ICE, not the battery, therefore one expects lower benefits to accrue for hybrids on freeway routes compared to stop-and-go driving (typically lower average speeds). Furthermore, Bass and Alfermann (2003) identified "parasitic" energy losses from the internal combustion engine and the hybrid drive unit, for example high percentages of idle time and high accessory loads, as additional limits to the benefits of hybrids. Driving conditions with high deceleration rates also increase the use of the friction brakes (relative to acquiring the benefits of regenerative braking) and will limit opportunities for fuel economy and associated emissions benefits (McKain et al. 2000).

Hybrid –Electric Diesel Transit Bus PM Emissions

Hybrid–electric diesel buses are promoted as having better fuel efficiency, lower tailpipe emissions and lower maintenance costs than conventional diesel buses (Allison Transmission 2001). These advantages accrue because (i) the buses gain a power advantage by use of regenerative braking, and (2) engine load is not directly tied to vehicle speed, therefore transient operations associated with elevated tailpipe emissions are reduced (Ciccarelli and Toossi 2002).

It is important to point out that previous laboratory emissions studies on hybrid transit buses (Table 3) have typically employed diesel particulate filter (DPF) aftertreatment in order to achieve significant (over 90%) particulate matter mass emissions reductions relative to conventional diesel vehicles (without DPFs). Furthermore, previous studies on hybrid transit bus emissions have only quantified particulate emissions on the basis of total PM gravimetric mass, not particle number emissions. In this study, both gravimetric mass and particle number measurements were made simultaneously. The temporal resolution of the two types of PM measurements was different, however: gravimetric mass measurements were integrated over the entire driving route, but particle number concentrations were measured on a second-by-second basis and were averaged over the route for comparison purposes.

Table 3 summarizes PM mass emission rates (g/mi) for hybrid and conventional diesel transit buses from recent literature. No studies to date have reported the particle size distributions and number concentrations of particles in hybrid transit bus exhaust. The few studies that have measured the emissions from hybrid–electric diesel transit buses have focused on regulated emissions of hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM, by gravimetric mass). A study by the Northeast Advanced Vehicle Consortium (NAVC) reported emission results for series design hybrid–electric diesel buses manufactured by Orion and Nova-Allison and outfitted with diesel particulate filters. Six different driving cycles were tested with average speeds ranging from 3 to 17 mph and 4 to 18 stops per mile (NAVC 2000). The emissions measurements included NO_x, CO, CO_2, HC and PM. The baseline bus for comparison was a diesel bus outfitted with an oxidation catalyst and both #1 diesel and ULSD fuels were tested for different vehicle configurations. PM g/mi emissions reductions for hybrid diesel-electric buses (with NETT Technologies DPF) compared to conventional diesel bus (with catalytic converter) emissions varied with driving cycle and ranged from 50% on the CBD cycle to 99% on the Manhattan cycle (Chandler et al. 2002) when operating on New York City Transit (NYCT) fuel with sulfur < 30 ppm.

Vehicle Descriptions. Four in-service transit buses from the CTTRANSIT fleet with identical 40-foot low-floor New Flyer chassis were studied. Two of the buses (fleet numbers 201 and 202) were conventional diesel buses equipped with model year 2002 Detroit Diesel Corporation Series 40 engines and two were hybrid diesel-electrics (fleet numbers H301 and H302) equipped with model year 2003 Cummins ISL 280 engines and the Allison E^p 40 electric drive parallel hybrid transmission (Table 4). During all emissions sampling, the bus air conditioning was off and all instrumentation was powered from an external generator so there was no additional load on the vehicles.

Table 3. Literature Particulate Matter Mass Emissions Results for Transit Buses*

Vehicle Type/Fuel /Aftertreatment	Engine Manufacturer/ Model Year	Fuel Economy* (mpg)	Total PM (g/mi)	Ref.
CONVENTIONAL DIESEL BUS RESULTS				
Boulder, CO Small conventional diesel transit bus	Cummins ISB 5.9L/ 1997		0.7 (2 - 12 aggressive)	Clark et al., SAE 1999-01-1469
NYC, NovaBUS Transit bus, Conventional Diesel/ No. 1 diesel/DOC	DDC Series 50/ 1998	2.25 MAN, 3.46 CBD, 1.36 NYB	0.48 MAN, 0.24 CBD, 0.71 NYB	Clark et al., SAE 2000-01-2955
EC Diesel MTA 3007/ 11 ppm S/ Nelson Exhaust System catalyzed muffler	DDC Series 50/ 1998	4.33 CBD, 5.9 UDDS	0.10 - 0.11	CARB Report 01-01; Ayala et al. SAE 2002-01-1722
Conventional Diesel and Emission Control Diesel (various studies)			0.17-0.51 CD; 0.01-0.09 ECD	Cohen et al. 2003 ES&T 37
Transit bus, conventional diesel/ Nelson oxidation catalyst	DDC Series 50/ 1997	3.93 MAN, 7.98 UDDS, 5.90 OCTA	0.78 MAN, 0.28 UDDS, 0.45 OCTA	Wayne et al. 2004 Energy & Fuels 18
HYBRID BUS RESULTS				
New York City Transit, OrionVI - LMCS Transit bus, Series Hybrid/ No. 1 diesel/integrated DOC+NETT DPF	DDC Series 30/ 1998	4.11 CBD	0.12 CBD (SOC-corrected)	Clark et al., SAE 2000-01-2955
OCTA 1999 New Flyer Hybrid Electric bus/ <15ppm S/ Englehard DPF	Cummins ISB 5.9L/ 1997	4.9 CBD, 7.3 UDDS	0.02 - 0.03	CARB report 01-01
BAE SYSTEMS/ Orion VII Hybrid, 40-ft (31350 lb) transit bus; lead-acid batteries/ NEX 0311-5 DPF	Cummins ISB 270	5.3 CBD	0.013 CBD (SOC corrected)	Envt Canada ERMD 01-12
Gillig 40-ft transit bus, Allison E^p hybrid/13 ppmS / Englehard DPX	Cummins ISL/ 2002	4.08 MAN, 5.5 CBD, 7.52 UDDS	0.02 - 0.03	Envt Canada ERMD 02-25-1
Transit bus, Allison Series hybrid/Englehard DPX catalyzed DPF	Cummins ISB275 5.9L/ 1998	4.4 MAN, 5.12 CBD, 7.88 UDDS, 5.15 OCTA	0.004 MAN, 0.023 CBD, 0.015 UDDS, 0.034 OCTA	Wayne et al. 2004 Energy & Fuels 18

*MAN = Manhattan cycle, CBD = Central Business District cycle, UDDS = Urban Dynamometer Driving Schedule, NYB = New York Bus; OCTA = Orange County Transit Authority cycle. (Clark et al. 1999; Clark et al. 2000; Osborn and Gutierrez 2001; Rosenblatt 2001; Ayala et al. 2002; Meyer and Rideout 2002; Cohen et al. 2003; Wayne et al. 2004)

Table 4. Specifications of the Vehicles Tested*

Specification	Hybrid Diesel-Electric (HDE)	Conventional Diesel (CD)
Engine	Cummins ISL	Detroit Diesel Series 40E
Transmission	Allison E^P 40	Allison B400R Automatic
Rated Power @ 2000 RPM, bhp (kW)	289 (205)	280 (205)
Peak Torque, lb-ft (N-m)	900 (1220)	900 (1166)
Combustion/Fuel System	Electronic Timing Control	Direct Injection
# cylinders, displacement (L)	6 cyl., 8.9 L	6 cyl., 8.7 L
Compression Ratio	16.6:1	17.2:1
Aspiration	Turbocharged, Charge Air Cooled	Turbocharged Air-to-Air Cooled
Emissions Certification	2001 EPA/ CARB	Certified through Dec. 31, 2003
EGR System	None	None
Blowby	Yes	Yes
Exhaust Aftertreatment	dual-brick DOC; Johnson-Matthey CRT DPF	single-brick DOC; Engelhard DPX
Weight, kg	13318 (empty) 13816 (w/driver) 15005 (+ trailer+equip)	13,086
Size (L x H x W), m	12.19 x 3.32 x 2.59	12.19 x 2.82 x 2.59
Seats	38	38
Electric motors	Two Concentric AC Induction Motors	N/A
Battery	Sealed Nickel-Metal Hydride	N/A
Bus mileage prior to testing, mi	29,600 (H301); 28,800 (H302)	78,400 (201); 67,000 (202)
Bus mileage after testing, mi	56,300 (H301); 49,500 (H302)	111,500 (201); 102,700 (202)

* Information obtained from Detroit Diesel Series 40 specifications for urban bus, Cummins ISL data sheet and CTTRANSIT comparison chart. During emissions testing, bus weight was modified by equipment, driver, trailer and 6-7 researchers. (For example, H301 weights were: *Bus/Driver/Trailer/All Equipment = 33080 lbs and Bus/Driver/ Stripped (no trailer) = 30460 lbs.)*

Throughout the study period, these four buses were operated on equivalent bus routes each day they were in service. The maintenance history and performance data for each bus (mileage, brake wear, oil, coolant and fuel consumption, etc.) were collected by CTTRANSIT using their in-house computerized data logging system.

The Allison E^P System™ has three major components, in addition to a conventional diesel engine, to provide various combinations of electrical and mechanical power that lead to improved fuel economy and lower exhaust emissions: (1) a two-mode, compound split transmission, the Allison E^v Drive™; (2) a smart technology nickel-metal hydride (NiMH) battery energy storage system (ESS); and (3) a dual power inverter module (DPIM) that converts alternating current of the motor/generators to direct current for battery storage (Allison Transmission 2002) . The transmission allows constantly variable output using two induction motors, three planetary gear sets and two clutches. The DPIM creates variable frequency three-phase power to produce motor torque. The E^P System's diesel engine decoupling feature allows operation at a number of torque-speed points at any power level such that engine speed does not directly relate to throttle position (Allison Transmission 2002). The hybrid bus recaptures its stopping energy by converting the momentum of the bus into electric current, which is stored by the batteries during regenerative braking events. An exhaust brake provides a third braking system (in addition to the friction brakes and regenerative braking) and helps maintain the ESS state-of-charge at an appropriate level. Specifications for the Allison E^P 40 parallel design components for the buses used in this study are given in Table 5.

Table 5. Allison E^P 40 Hybrid Bus Specifications*

A. MOTOR GENERATOR:	
1). Type -- Three-Phase AC Induction Motor	
2). Power	75 kW
3). Max Torque	983 N.m @ stall
4). Weight	77 kg
B. INVERTER:	
1). Capacity:	75 kW per side, continuous
2). Nominal Voltage	600 V
3). Mass	75 kg
C. BATTERY PACK:	
1). Type -- Ni-MH	
2). Nominal Voltage	600 V
3). Capacity [Ah]	Proprietary
4). Max Power [kW]	Proprietary
5). Mass	437 kg

* Data provided by Allison Transmission.

Note that none of the data reported here were corrected for the state of charge (SOC) of the hybrid bus battery.

Fuel and Afterteatment Options. The buses were run on two different diesel fuel compositions to study the effect of fuel sulfur level on PM emissions. A relatively high sulfur fuel, No. 1 diesel (S = 230 to 320 ppm_w) was used for the tests conducted from January through June 2, 2004 (Phase 1). Ultralow sulfur diesel fuel, ULSD (S measured 8 to 51 ppm_w, see Figure 3), was used from June 29 to November 17 (Phases 2 and 3). Over the last two months of testing on ULSD, namely October 12 to November 17 (Phase 3), the buses were also outfitted with diesel particulate filters (DPFs) in addition to the diesel oxidation catalysts (DOCs) that were present on the buses for the entire study. Thus, the HDE and CD bus emissions were measured under three different fuel/aftertreatment configurations as summarized in the testing schedule (Table 6, see Appendix C, Tables C-1 to C-3 for details).

Table 6. Testing Dates by Bus ID and Fuel/Aftertreatment Configuration*

Configuration	201	202	H301	H302
No. 1 Diesel / DOC	*(Phase 1)*			
	23-Jan-04	11-Feb-04	6-Jan-04	27-Feb-04
	30-Jan-04	13-Feb-04	21-Jan-04	30-Apr-04
	23-Apr-04	18-Feb-04	16-Apr-04	
		28-Apr-04	21-Apr-04	
		26-May-04	28-May-04	
		27-May-04	2-Jun-04	
ULSD / DOC	*(Phase 2)*			
	6-Aug-04	29-Jun-04	29-Jul-04	25-Aug-04
	10-Aug-04	20-Sep-04	3-Aug-04	26-Aug-04
		21-Sep-04	4-Aug-04	
ULSD / DOC+DPF	*(Phase 3)*			
	20-Oct-04	9-Nov-04	12-Oct-04	2-Nov-04
	25-Oct-04	10-Nov-04	13-Oct-04	3-Nov-04
			15-Oct-04	
			16-Nov-04	
			17-Nov-04	

* Testing dates highlighted in green indicate different driver for January and February tests. The NOx and pitot tube data for total exhaust flow rate are also less certain for these early testing dates due to Horiba OBS-1000 calibration issues.

The fuel composition variation over the study (Figure 3) is based on samples collected at the end of some of the sampling days. While ultralow sulfur diesel fuel regulations that will go into effect in June 2006 require sulfur concentrations less than or equal to 15 ppm by weight, the ULSD used in this study had measured sulfur concentrations as low as 8 ppm and as high as 51ppm.

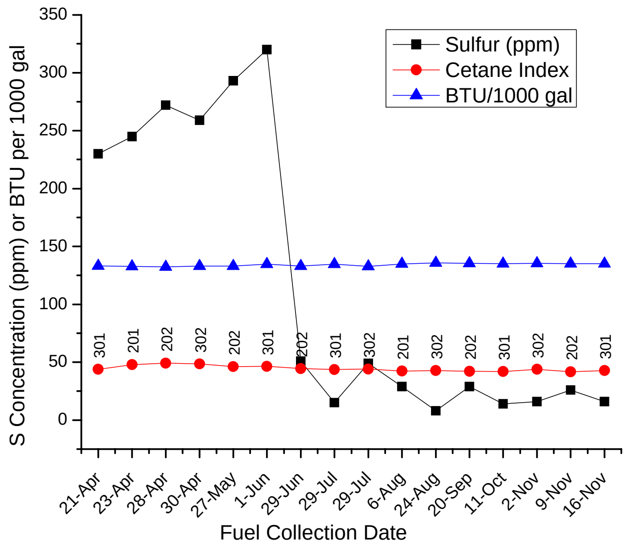

FIGURE 3. Sulfur content (parts per million), cetane index and energy content of fuel (BTU per 1000 gal) used during emissions testing. Fuel analyses were conducted by an independent laboratory (ANA Laboratories, Inc. Bellmawr, NJ). Labels adjacent to cetane points are bus from which fuel was sampled.

Environmental Conditions. Ambient temperature and relative humidity varied over the study period as shown in Figure 4 where the dry bulb temperature (^oC) and relative humidity (%) recorded at Bradley Airport are plotted for the time corresponding to the beginning of the Avon Inbound route for each sampling date. There were no meteorological data available for February 13, 2004.

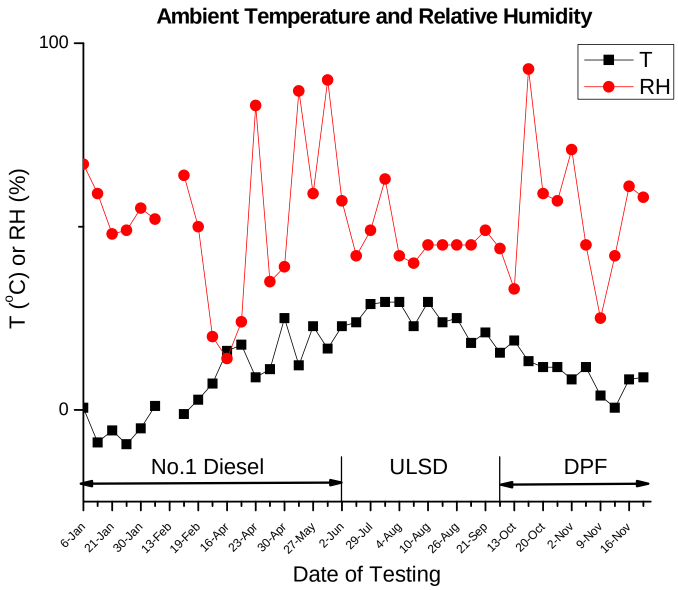

FIGURE 4. Bradley Airport ambient dry bulb temperature and relative humidity over study testing period.

Driving Routes. Three CTTRANSIT bus routes were selected, representing high-speed steady-state freeway cruise (65 mph) on a commuter route (ENFIELD, Figure 5), start-stop activity on a local city street with frequent bus stops (FARMINGTON, Figure 6) and a combination of steady-state arterial travel with a high grade section (AVON, Figure 7). Table 7 provides details of the test routes based on scan tool data. The Connecticut Department of Transportation automatic road analyzer (ARAN) videolog vehicle was used to obtain data on road grade every 0.01 miles along each driving route as part of a separate project. These data are plotted in Figure 8.

Table 7. Test Driving Routes*

	Enfield		**Farmington**		**Avon**	
	Freeway		**Local stop-start**		**Arterial w/grade**	
	IN	OUT	IN	OUT	IN	OUT
Distance (mi)	16.4	16.4	5.2	5.2	8.2	8.2
Average Speed (mi/hr)	59.3	58.4	9.8	10.3	35.4	35.7
Number of Stops	1	1	23	21	1	1
Average Percent Load	72	78	41	42	48	55
Max/Min Acceleration Rate (mph/s)	2.3/-4.0	2.8/-3.6	5.5/-4.3	5.5/-4.2	10.5/-16.1	8.3/-12.5
Max/Min Grade (%)	3.1/-5.6	4.1/-3.3	5.6/-6.7	6.9/-5.3	8.99/-8.66	8.41/-9.15
Average % Idle Time	0.5	1.0	34.3	33.4	6.6	5.8
Map	**Figure 5**		**Figure 6**		**Figure 7**	

* Route parameters data are averages of diesel vehicle VANSCO scantool data.

FIGURE 5. Enfield Route on interstate 91 north of Hartford, CT. This is the freeway commuter route.

FIGURE 6. Farmington Avenue Route. This route included simulated bus stops at every third bus stop along the avenue.

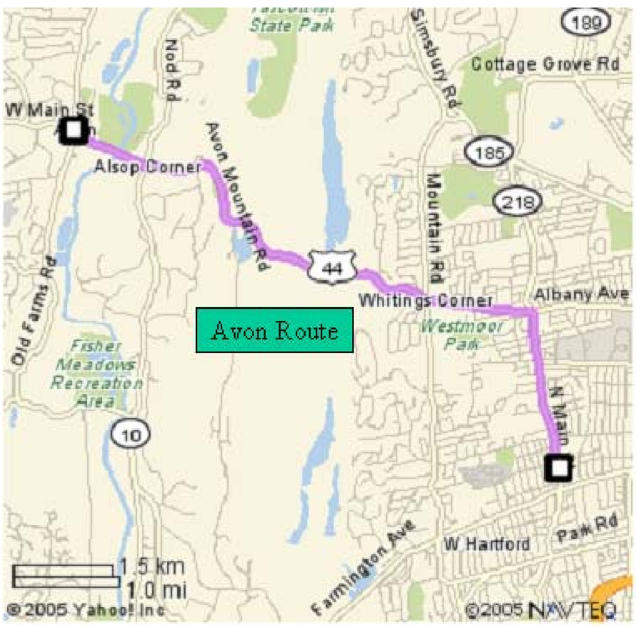

FIGURE 7. Avon Route. The steep grade over Talcott Mountain in Avon is in the middle of the route.

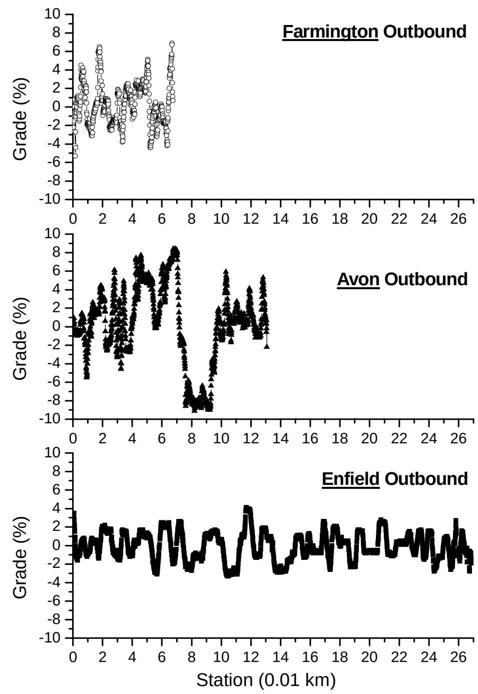

FIGURE 8. Percent grade as measured every 0.01 km by the Connecticut Department of Transportation ARAN van. Data shown is for the outbound routes only.

EXPERIMENTAL METHODS

On-Board Sampling Setup. The on-board sampling setup is outlined in Figure 9. The particle instrumentation was installed on the bus into special plywood modules that replaced or were specially fit to seats in the bus and provided vibration isolation for the particle number instruments (ELPI and SMPS, described below). The Horiba gas sampling instrument was located in the rear seats and operated off its battery supply. The other instruments and all laptop computers were powered from a generator (15 kW, Generac Power Systems, Inc.) carried on a trailer behind the bus. A large cable ran from the generator, through the rear hatch in the roof of the bus to an electrical panel located inside the bus. Similarly, the compressed air hose connected the air compressor (Sears 5.5 hp, oil-free), located on the trailer, to the inlet of the series of three condensate traps (“De-aquavator”, Figure 9a) at the inlet of the dilution system’s silica gel dryer tube.

A six-inch diameter exhaust pipe extension fitted to the exhaust pipe of the buses had a 90-degree elbow and then ran horizontally along the rear end of the bus (Figure 9b; Photographs in Appendix D). Near the 90-degree elbow, a stainless steel perforated probe was installed across the full diameter of the exhaust pipe to collect samples for all particulate measurements. A five-foot long 5/8-inch diameter stainless steel heated (over 100^{o}C) transfer line entered the bus via the rear roof hatch and connected the perforated probe to a “tee” that brought exhaust samples into the inlets of both mini-diluters (see below) which were strapped to the overhead handrails on either side of the bus (see Photographs in Appendix D).

The Horiba OBS-1000 recorded total exhaust flowrate using a pitot tube mounted near the end of the exhaust pipe extension (Figure 9b, Appendix D photographs). At the beginning of the study, Horiba calibrated the pitot tube for use in this study and the pitot tube pressure transducer was recalibrated in April 2004 after it was noted that many of the exhaust flowrate measurements were negative when the bus was running. Furthermore, to help reduce the possibility of backflow due to wind during idle conditions, an additional exhaust pipe extension was added on April 16, 2004 and new procedures were implemented to re-zero the pitot tube calibration setting during engine off periods between each driving subroute.

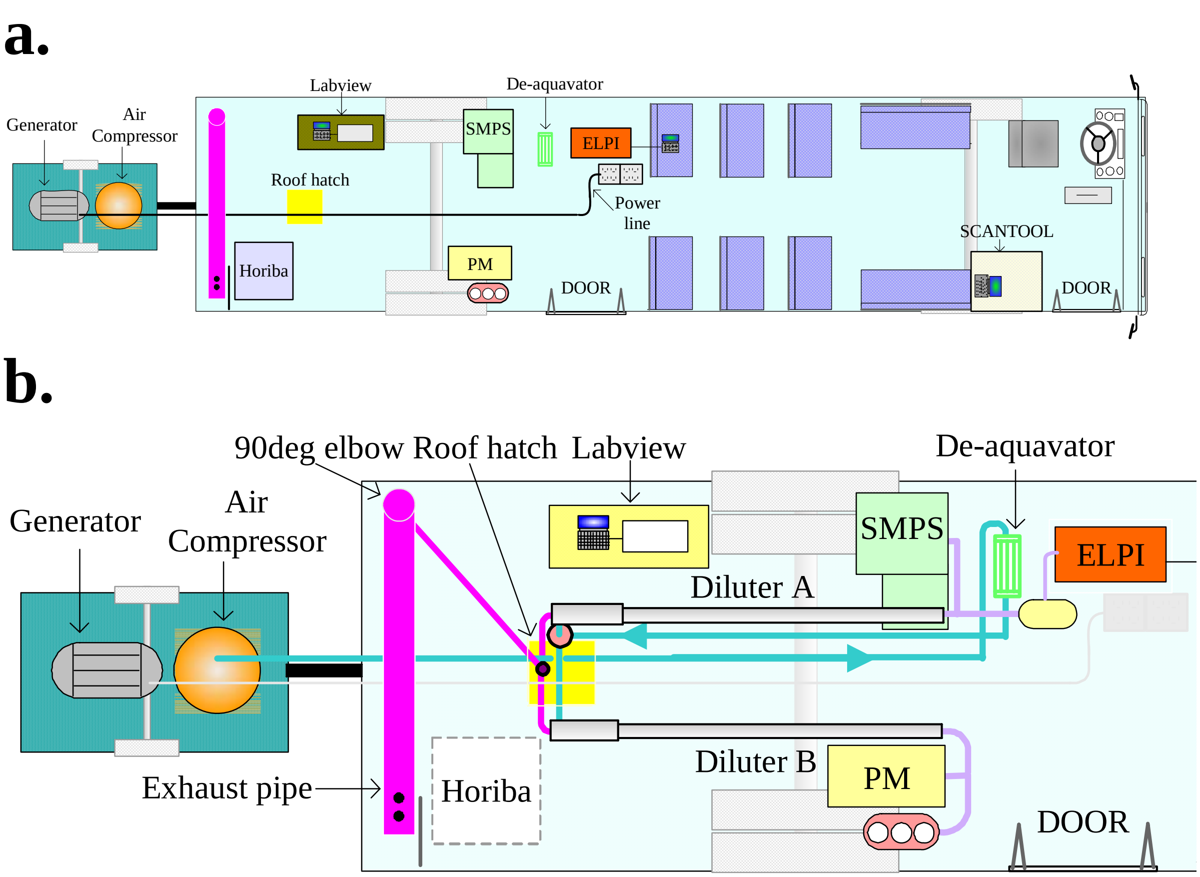

FIGURE 9. Schematics of instrument layout during on-board emissions sampling. (a) Bus and trailer and (b) closeup of equipment and transfer/dilution lines for particulate matter sampling. Photographs of the equipment can be found in Appendix D.

Mini-Dilution System. The mini-dilution system (see Figure 10 for details) was modified from that used in a previous laboratory study (Holmén and Ayala, 2002). Modifications were made to enable simultaneous measurement from four instruments at a total flow of approximately 72 L/min within the space confines of the rear of a 40-foot low-floor bus. The addition of a stainless steel "tee" at the end of the exhaust probe allowed setup of two parallel mini-dilution tunnels (denoted diluters A and B in Figure 9, each with its own ejector-diluter).

The dilution air entering the side-arms of both ejector diluters was ambient air that was pre-conditioned to remove water (condensate traps and silica gel), hydrocarbons (activated carbon) and particles (HEPA filter).

Flow rates for the full mini-dilution system were regularly calibrated in the laboratory throughout the study period using a BIOS DC-2 flow meter to measure sample flow rate and a dry gas meter (DTM-200A American Test Meter) for total flow rate. The dilution ratio (DR) is defined as the ratio of the total flow (exhaust sample plus dilution air, Q_{tot}) to the exhaust sample flow rate (Q_s):

$$DR = Q_{tot} / Q_s \qquad (1)$$

Under field sampling conditions, the flow rates of sample exhaust were monitored continuously using an orifice meter and transmitting magnehelics and dilution air flow rates were recorded using mass flow meters. Labview 6 was used to record 1-second voltages from the magnehelics and flow meters as well as temperatures from Type-K thermocouples that measured temperature at the exhaust "tee", after the dilution of sample exhaust with dilution air and the skin temperature at the end of the six-foot long residence tube just prior to entering the particle instrumentation. Individual flows varied between sampling days due to changes in mini-diluter hardware over the course of the study (changes in fittings, etc.). Dilution ratios, averaged over the time period encompassing an individual (one-way) driving *subroute* (i.e., Enfield Inbound), were calculated based on the recorded Labview voltages and the calibration relationships between flow rate and voltage. Because there was no significant difference in dilution ratio between subroutes for a given sampling day, a daily dilution ratio value was applied to all the emissions data. Dilution ratios (see Appendix C, Table C-4) varied between diluter A (SMPS and ELPI instruments) and diluter B (PM mass filter), with dilution ratios for diluter A (22 to 35, mean = 27) slightly higher than diluter B (20 to 31, mean = 22), due to differences in applied pressure to each of the ejector-diluters. Diluter A used the Dekati diluter and diluter B used a stainless steel Air-Vac Engineering (Seymour, CT) TD 110H vacuum pump as the ejector-diluter.

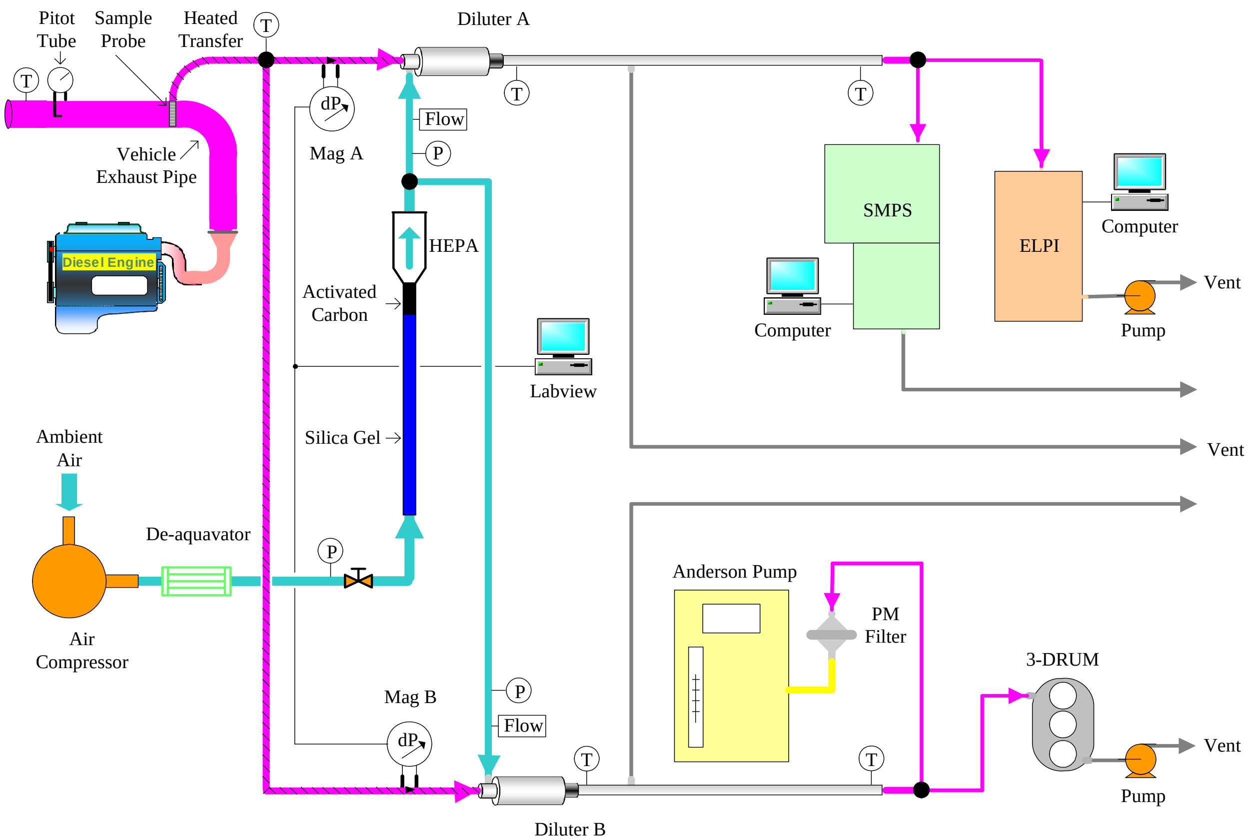

FIGURE 10. Mini-dilution system schematic. Two parallel ejector-diluter systems were used to provide diluted vehicle exhaust to four particle measuring instruments. Diluter A was used with the SMPS and ELPI particle number instruments and diluter B was used for the PM gravimetric mass measurement. The 3-DRUM cascade impactor collected PM for future chemical analysis.

Table 8. Dilution ratios by day and diluter

Date	Average		Standard Deviation	
	Diluter A	Diluter B	Diluter A	Diluter B
1/21/2004	28	23	N/A	N/A
1/23/2004	27	23	N/A	N/A
1/30/2004	31	22	N/A	N/A
2/11/2004	31	31	N/A	N/A
2/13/2004	30	23	N/A	N/A
2/18/2004	27	25	1	1
2/18/2004	26	25	1	0
2/27/2004	27	23	1	0
4/16/2004	27	20	6	5
4/21/2004	27	21	6	1
4/23/2004	23	22	6	1
4/28/2004	23	21	5	1
4/30/2004	25	21	6	1
5/26/2004	23	21	5	1
5/27/2004	23	21	5	1
5/28/2004	30	21	7	1
6/2/2004	35	22	9	1
6/29/2004	27	22	7	1
7/29/2004	27	21	8	4
8/3/2004	26	21	9	2
8/4/2004	25	28	8	3
8/6/2004	28	23	11	2
8/10/2004	28	23	7	1
8/25/2004	30	23	7	1
8/26/2004	28	23	7	1
9/20/2004	31	23	7	2
9/21/2004	29	22	6	1
10/13/2004	27	23	6	1
10/15/2004	28	23	7	2
10/20/2004	26	23	7	2
10/25/2004	32	23	9	2
11/2/2004	22	23	6	2
11/3/2004	22	23	6	2
11/9/2004	26	21	2	2
11/10/2004	26	21	2	2
11/16/2004	29	21	2	1
11/17/2004	28	21	3	2
All Dates	27	22	7	2

PM Gravimetric Mass Measurement. Total particulate mass measurements were carried out by diluting raw exhaust with the single-stage mini-diluter B and collecting particles on Teflon-coated glass fiber filters (Pallflex T60A20) in a 47mm stainless steel filter holder located upstream of an Andersen pump (Sierra Instruments Series 110 Constant Flow Air Sampler) operating at 18.5 – 24 L/min. The temperature of the diluted exhaust sample was maintained below 52^{o}C prior to collection of total PM mass as outlined by EPA methods for laboratory certified measurement (CFR). Prior to use, all filters were conditioned at 39±10% relative humidity and 26±1^{o}C for 12 – 24 hours in a laboratory weighing chamber at the University of Connecticut. Blank, reference and sample filters were pre-weighed on a microbalance (Cahn Model C-33) with 1 microgram sensitivity prior to sampling. The pre-weighed filters were stored in covered Petri dishes in the weighing chamber. The filters were removed from the chamber on the morning of sampling, transported to the bus in a cooler and placed in the stainless steel filter holder at the inlet of the Andersen pump prior to each test period. After sample collection, the filters were immediately removed from the filter holder using forceps and stored in their Petri dish until transfer to the weighing chamber for post-sampling reconditioning. After 12 –24 hours at chamber conditions, the filters were post-weighed to determine the net mass of diesel particulate collected over each driving subroute. The total volume of air sampled was calculated from the recorded sampling times and Andersen pump flow rate (calibrated daily). To compute total exhaust g/mi PM mass emissions by subroute, the PM mass on each filter (M_{PM}) was corrected for the miles traveled on each subroute (see Table 7), X_{route}, the daily dilution ratio (DR, from Table 8) and the average fraction of total exhaust sampled by mini-diluter B, F_B, over the driving subroute. F_B was computed as the ratio of raw exhaust sample entering diluter B (Qs for diluter B) and the total exhaust flow rate measured by the pitot tube, Q_{pitot}:

$$PM\left(\tfrac{g}{mi}\right) = \frac{M_{PM}}{X_{route}} * DR * F_B^{-1} = \frac{M_{PM}}{X_{route}} * DR * \left(\frac{Q_{s,B}}{Q_{pitot}}\right)^{-1} \qquad (2)$$

The volume fraction of exhaust sampled by the mini-diluters varied greatly with driving subroute, as one expects due to variation in total exhaust flowrate with engine operating conditions. The average and standard deviations of the second-by-second F_B data for each sampling date are summarized in Table C-5 (Appendix C).

Scanning Mobility Particle Sizer (SMPS). Route-average aerosol size distributions in the submicron range were quantified using a scanning mobility particle sizer (SMPS, Model 3936, TSI Inc., St. Paul, MN, Figure 11), outfitted with the long differential mobility analyzer (DMA) and a Model 3025A ultrafine condensation particle counter (CPC). In this study, the DMA was set to separate particles at 10, 20, 40, 80, 100 and 130 nm mobility diameters in order to determine the ultrafine particle size distributions in vehicle exhaust. Table 9 summarizes the DMA voltage settings, corresponding particle diameter ranges and correction factors used to convert the raw CPC count data to one-second particle concentrations (dN/dlogDp). Appendix C Table C-6 outlines the steps taken to convert the raw SMPS data to number concentrations.

Table 9. SMPS Particle Diameters for each DMA Voltage Setting Selected

Nominal Mobility Diameter, Dp	Diameter Range (nm)	DMA Nominal Setting Volts	Correction Factor Counts → dN/dlogDp
10nm:	9.743 - 10.25	-30	1133
20 nm:	19.48 - 20.508	-118	543
40 nm:	38.93 - 41.05	-453	300.15
80 nm:	77.73 - 82.24	-1650	205.1
100 nm:	97.1 - 102.9	-2450	190.5
130 nm:	126.03 - 133.9	-3862	180.3

The SMPS instrument's electrostatic classifier (EC) separates charged particles by electrical mobility and the condensation particle counter (CPC) detects and counts the separated particles. Although the SMPS is capable of measuring particle number *distributions* with high size resolution under steady-state source sampling conditions, for applications where the particle size distribution changes on short timescales (i.e., real-world, on-road driving), the SMPS instrument's slow scanning rate does not allow collection of realistic particle size distributions (Fierz et al. 2002). Thus, the SMPS was employed in this study to count particles with very high temporal resolution (0.1 sec raw data intervals) only over the very narrow ranges of particle electrical mobility diameter (Table 9) during on-road data collection. This mode of using the SMPS is termed "panel mode" or "single-diameter" mode and the diameters being counted by the CPC are determined by the selected aerosol flow rate (1.5 L/min), classifier sheath flow rate (15 L/min), the DMA geometry (long DMA, TSI model 3081) and the voltage setting on the DMA rod as set on the electrostatic classifier panel. The single-diameter SMPS data from individual particle mobility diameters collected over multiple sampling days on a single bus route was aggregated to generate "route average" SMPS particle number distributions for each bus type (HDE or CD).

The CPC raw count data were logged at 0.1 second intervals by the Aerosol Instrument Manager (AIM) software, version 5.2.0 from TSI, Inc. Due to the sensitivity of the CPC's optics to internal liquid butanol contamination from excessive vibration while traveling down the road, the external butanol reservoir was connected to the CPC at the beginning of each sampling day only until the CPC indicators confirmed the butanol wick was saturated. The butanol reservoir was disconnected from the CPC during on-road travel. Laboratory tests confirmed that disconnecting the butanol external reservoir had no effect on measured particle size distributions. The SMPS data for each driving route was saved to a specific file for each driving route (see Appendix Table C-7) and the raw count data were converted to particle concentrations in units dN/dlogDp in order to normalize for the differences in the diameter range selected for each nominal diameter setting (Table 9). Details of the conversion calculation are found in Appendix C, Table C-6.

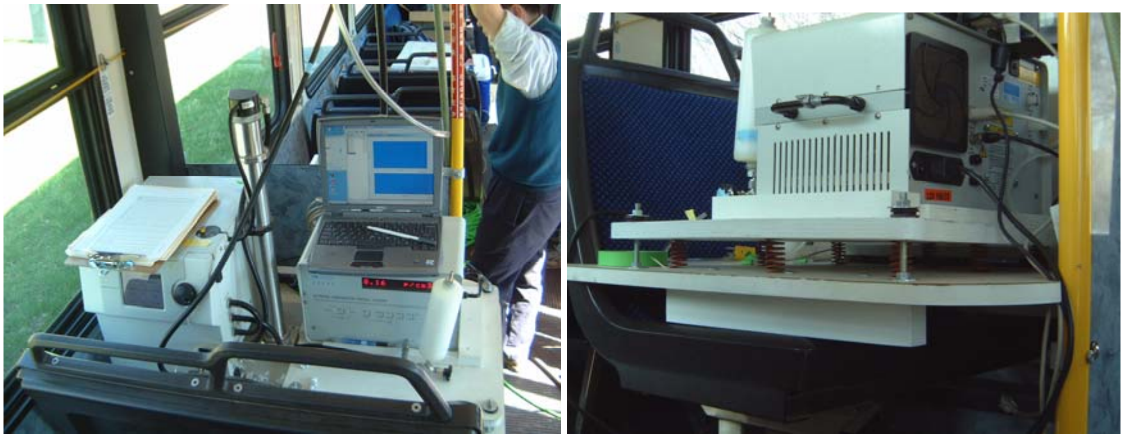

FIGURE 11. Scanning Mobility Particle Sizer (SMPS) showing the classifier, long DMA and ultrafine CPC in its operating position on the bus (left) and vibration mount for CPC (right). The laptop computer used to log SMPS and Garmin GPS data for synchronizing all instrument times is located on top of the CPC in the left image.

SMPS Lag Time Estimation. Because sample flows must past through the dilution system before entering the particle sampling equipment, a time lag occurs between an event in the engine and the associated PM emissions measurement. Lag time estimates between engine event and emissions data were calculated so that engine parameter data could be properly associated with the corresponding emissions and to ensure proper data analysis. These lag times were calculated by the difference from the engine start time and the first noted PM count time for the SMPS. Thirty-three randomly selected engine start times were selected to calculate the lag time between engine start and the first particle count time. The engine start times came from all subroutes, not just the first time the engine was started at the beginning of a sampling day. Results indicate that the average SMPS lag time from engine start to the first identified PM count was 11.6 seconds with a standard deviation of 2.05 seconds. Therefore, a lag of 12 seconds was applied to all SMPS data.

Electrical Low Pressure Impactor (ELPI). The Electrical Low Pressure Impactor (ELPI, Figure 12) combines the PM collection technique of a cascade impactor with electrical detection of charged particles. The ELPI collected the full particle size distribution (over twelve size cuts, 7 to 10,000 nm) with ~ 1-2 sec temporal resolution along all driving routes every sampling day.

ELPI Operating Principle. Air is drawn into the ELPI by a vacuum pump operating at a flow rate of 30L/min. A corona needle at 5 kV positively charges the sampled air particles before the particles enter a cascade impactor with the cut diameters for each impactor stage defined by the aerodynamic diameter of particles per the manufacturer’s calibration (Table 10). The typical ELPI measures airborne particle size distributions in the size range of 30 – 10,000 nm with 12 different channels. When outfitted with the ELPI electrical filter stage accessory, as in this study, the ELPI lower size cut is extended down to 7 nm. Particles striking the electrically insulated impactor stages induce a current that is read by a multi-channel electrometer at 1-2 second time resolution. The filter stage (Stage #1) was outfitted with the Dekati low pressure drop filter (Dekati model ELA-652). These current readings are converted to particle concentration measurements in the units of number of particles per cubic centimeter of air sampled after correction for charger efficiency and small particle losses (Dekati 2000; Marjamaki 2000).

Previous studies have compared ELPI measurements to those of other instruments to show that the ELPI accurately measures particle concentrations at a real-time frequency (Marjamaki 2000). Additionally, the ELPI's 1-2 second time resolution is essential to mapping the emission concentrations as a function of instantaneous changes in driving mode. The high sampling rate improves the ability to align emission measurements to changes in vehicle operation or driving mode. The high sampling rate also improves the ability to correct for the exhaust travel time in sampling lines between the diesel engine and the ELPI (Holmén and Qu 2004). In this study, the ELPI emissions measurement lag time was determined to be 10 seconds.

ELPI Lag Time Estimation. Lag time estimates between engine event and detection of the emissions event by the ELPI were based on 48 engine start cases (8 days of data over 6 routes). Results indicate that the average ELPI lag time from engine start to the first identified PM count was 10.04 seconds with a standard deviation of 2.01 seconds. All ELPI data presented are corrected for a 10-sec ELPI delay relative to the GPS clock.

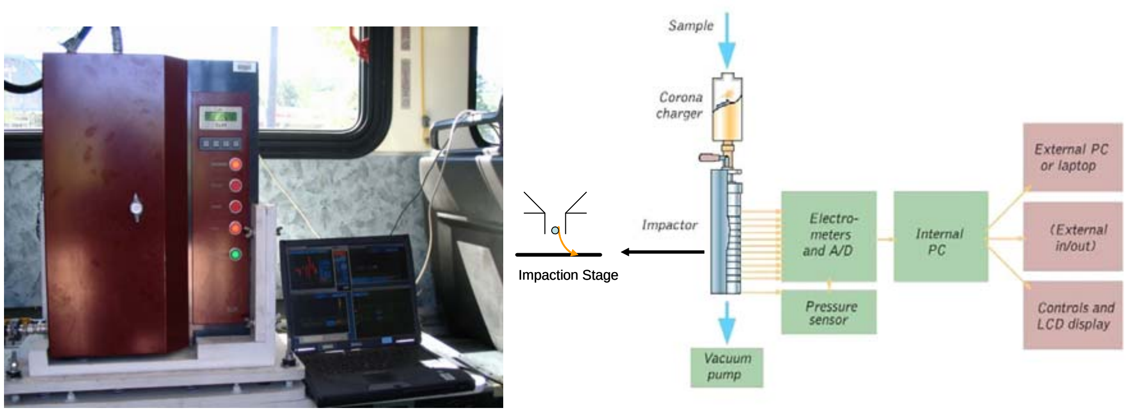

FIGURE 12. ELPI setup in transit bus for particle number distributions (left) and Dekati, LTD schematic of ELPI operation (right, from *http://www.dekati.com/brochures/ELPI_esite_engl_pictorion.pdf*)

Table 10. ELPI lower aerodynamic diameter cuts (D_p) and geometric mean diameters (D_i) for 30 L/min sample flow rate when operating with Filter Stage

Stage ID	Substrate/ Stage Type	Lower Bound D_p (nm)	Geometric Mean Diameter D_i (nm)	Stage Width (nm)
1	Electrical Filter Stage	7	14.2	21.8
2	Al-foil	28.8	40.3	27.6
3	Al-foil	56.4	73.2	38.7
4	Al-foil	95.1	123	63.9
5	Al-foil	159	205.7	107
6	Al-foil	266	320.8	121
7	Al-foil	387	490.2	234
8	Al-foil	621	772.1	339
9	Al-foil	960	1247.1	660
10	Al-foil	1620	1980.0	800
11	Al-foil	2420	4014.6	4240
12	Al-foil	6660	8185.3	3400
Inlet	None	10060	1414.1	NA

Horiba Exhaust Emissions System. A Horiba OBS-1000 gas emission analyzer unit was employed to measure the second-by-second gaseous exhaust emissions (CO, CO_2, NOx, unburnt hydrocarbons) as well as to record exhaust temperature, exhaust flow rate (using a calibrated pitot tube), ambient temperature and relative humidity, bus location with a GPS antenna and, for the hybrid bus runs battery current and voltage (in November 2004 only). The gas exhaust emissions are summarized in a separate report (Cetegen and Chaparro 2005). The Horiba system's pitot tube measurements of total exhaust flow rate were used to compute the fraction of total exhaust sampled by the mini-dilution system for particle exhaust emissions, as shown in Equation (2) above.

Global Positioning System (GPS) and Time Synchronization. Two separate GPS receivers were also logging bus location every second. A Garmin receiver running Fugawi software was used to synchronize time among all instrument laptops. Readings of each laptop's clock time were made at the beginning of each subroute run and the offsets relative to the Garmin receiver GPS time were noted. A Geologger portable GPS receiver with its own memory card served as a backup GPS receiver.

Engine Diagnostic Scan Tool. All vehicle diagnostic data for the study was collected using three separate types of scan tools (Table 11). For the hybrid diesel-electric 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 from April to November 2004. However, the Vansco DLA used different software and communication protocols for each bus type due to differences between the vehicles and engines. The diesel buses were communicating using the Society of Automotive Engineers (SAE) J1587/J1708 protocols, and the hybrid buses used the SAE J1939 protocol. For the conventional diesel bus communications network, the CANsniff software provided by Vansco was used to log all network traffic and the hybrid bus data was recorded with the Vansco SIMGAUGES software (Vansco 2004). 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.

Prior to acquisition of the Vansco DLA scan tool in April 2004, all engine data was collected for the conventional diesel buses using Pro-Link 9000 software and a MPSI Prolink/MPC can tool. This scantool was capable of recording only three vehicle parameters in addition to engine time. These parameters were engine speed (RPM), engine load (%), and vehicle speed (MPH). Engine time was converted to actual time based on recordings of synchronization times between the laptop's computer and the Prolink engine time. Alignment of data was also possible using the recorded engine ON and engine OFF times at the beginning of each driving subroute.

Table 11. Vehicle Scan Tool Hardware and Software

	Conventional Diesel		**Hybrid-Electric Diesel**	
Communication Protocols:	**SAE J1708/J1587**		**J1939/CAN**	
	Hardware	**Software**	**Hardware**	**Software**
Prior to April 16:	**ProLink/MPC**	**Pro-Link 9000**	**Inline 1 Data Link Adapter**	**INSITE**
manufacturer	Micro Processor Systems, Inc. (MPSI)	MPSI	Cummins, Inc.	Cummins, Inc.
model	complies with J1708/J1939	Virtual Terminal Applic.	supports SAE J1708/J1587 data link	Lite
version #	http://www.mpsilink.com	1.01	http://inline.cummins.com/products/inline1.html	6.2.224.0
Apr 16 to Nov 17:				
manufacturer	**Same as above, plus:**		**Same as above, plus:**	
model				
version #				
	VANSCO Data Link Adapter		**VANSCO Data Link Adapter**	
manufacturer	Vansco, Inc., Winnipeg, Manitoba	**CANsniff**	Vansco, Inc., Winnipeg, Manitoba	**SIMGAUGES**
model	USB; CAN 2.0B, J1939, J1708/1587		USB; CAN 2.0B, J1939, J1708/1587	
version #	beta		beta	
URL	http://www.vansco.ca/pdf/DLA_brochure.pdf		http://www.vansco.ca/pdf/DLA_brochure.pdf	

All scantool data was aggregated to one-second temporal resolution by averaging data collected in individual one-sec timestamps. The one-second data were used to calculate route-average descriptors such as average (and standard deviation, minimum, maximum) vehicle speed, engine load, acceleration rate, deceleration rate, number of stops, etc.

Quality Assurance/ Quality Control Data. The daily data collection procedures included collection of samples intended to assure accurate operation of the SMPS and ELPI instruments as well as quantification of the particulate matter concentration in background ambient air that contributed to the measured exhaust concentrations. Valid operation of the SMPS and ELPI instruments was checked by placing HEPA filters on the instruments' inlets and collecting data at all particle diameters (SMPS) and all four instrument ranges (for ELPI) prior to connecting the instruments to the minidiluters. The HEPA measurements indicate "zero" response either in terms of raw counts for the SMPS or measured current for the ELPI. Furthermore, all emissions equipment (PM Filter, Horiba exhaust gases, SMPS and ELPI) measured a 20 minute Tunnel Blank (TB) from the tailpipe prior to starting the vehicle's engine. The TB samples document daily background concentrations of the pollutants of interest. High tunnel blank data may suggest that there is a leak in the sampling equipment or dilution system or that the HEPA filter and activated charcoal within the dilution system have failed. At the end of the sampling day, a second TB sample was collected for 15-20 minutes starting approximately 10 minutes after the bus engine was stopped, followed by 15 minutes of HEPA data collection to quantify any instrument drift over the sampling period. *Note that the data reported here do not have the corresponding tunnel blank data subtracted because of the difficulty of accurately comparing particle data collected at different temperatures (ambient temperature vs. exhaust temperature).* Nevertheless, the TB data are useful for comparing relative background levels between sampling days (i.e., effect of humidity on particle concentrations).

Data Analysis. Data collected during on-road driving of the experimental routes was compared to that collected for the HEPA and Tunnel Blank samples to determine whether the data were significantly above the instrument detection limit and background atmosphere levels. A criterion of three times above the blank levels was used to evaluate detectable particle concentrations. All analysis of variance (ANOVA) statistical tests were performed with Minitab software (version 14). Details of the specific statistical procedures are found in the relevant results section.

RESULTS & DISCUSSION

Table 12 summarizes the number of days with field testing SMPS, ELPI and PM filter mass data that were used for comparison of the HDE and CD exhaust emissions under different fuel and aftertreatment configurations. It should be noted that, due to instrument malfunctions on some sampling days, or portions of some days, the full driving route emissions data was not collected for every sampling date by every instrument. However, the data in Table 12 indicate that at least two days of testing were completed for each of the four buses under each of the three fuel-aftertreatment configurations.

Table 12. Number of On-Board Tesing Days for Each Transit Bus

Configuration	201	202	H301	H302
No. 1 Diesel / DOC	3	6	6	2
ULSD / DOC	2	3	3	2
ULSD / DOC+DPF	2	2	5	2

Raw Particle Number Data. The raw data for the SMPS and ELPI instruments on each driving *subroute* (one-way portions of Enfield, Avon or Farmington routes) are plotted as a function of time in the route in Appendices A (SMPS) and B (ELPI). The raw data is not corrected for dilution ratio or fraction of exhaust sampled by the dilution system. Appendices A and B also contain the mean particle counts or concentrations for the HEPA and TB samples collected daily that can be directly compared to the raw data. The SMPS and ELPI data compiled in this section of the report are aggregated over the different driving routes and have been corrected for dilution ratio. These aggregated data are used to evaluate the similarities and differences between the HDE and CD buses when operating on different fuels and with and without diesel particulate filters.

Total Particulate Mass Results. As indicated by the differences in mass on the filters between the tunnel blanks and the on-road route data, the route emissions of PM mass were all greater than three times the tunnel blanks for all dates of sampling with No. 1 diesel and ULSD (without the DPF) (Figure 13). With DPF aftertreatment, however, the PM mass collected on the filters during on-road sampling was at levels that were not very different from the tunnel blank samples (Figure 13b). The subroute raw filter mass data are tabulated in Appendix C, Table C-8.

The total mass of PM collected on each subroute filter, from engine ON to engine OFF (Figure 13) shows that there was generally no significant difference in PM mass emitted between sampling days when the buses operated on No. 1 diesel fuel compared to operation on ULSD. In other words, for these late-model year engine transit buses, all outfitted with diesel oxidation catalysts, reduction in the fuel sulfur content did not lead to a large observable reduction in PM mass emissions on any of the three real-world driving routes.

The data in Figure 13 also indicate a general trend in total PM mass collected by driving route. The Enfield route mass values were typically highest on all days and the Avon route values were typically lowest. The Farmington route PM mass emissions were generally in between these two routes, with the exception of one sampling day, August 3 (H301) where the Farmington route mass values were higher than those for Enfield. The data in Figure 13 also show that addition of DPF aftertreatment to the buses reduced the mass of PM by approximately an order of magnitude such that the sample filter masses were not always greater than three times the tunnel blanks (see Figure 13b, log-scale). These observations based on total mass collected (Figure 13) reflect differences in both vehicle operating and PM emission behavior as well as total operating time among the three routes. Thus, Figure 13 confirms that the Enfield route was of the longest duration and the DPFs were very effective in reducing PM mass emissions to near blank levels.

The emissions relationships between routes are more obscure when the PM mass data are normalized by travel distance, corrected for both dilution ratio and fraction of total exhaust sampled and plotted as g/mi emission rates (Figure 14). Note that for this analysis, the nominal route distances were used for both directions of each route (16.4 mi for Enfield each way; 5.2 mi for Farmington and 8.2 mi for Avon routes). Thus, switching to ULSD resulted in observably higher variability in PM mass emissions on a particulate mass emission per mile basis (Figures 14 and 15). The increased variability may have been due to variations in the sulfur content of the fuel (see Figure 3), but not enough fuel composition data were collected to evaluate this possibility quantitatively.

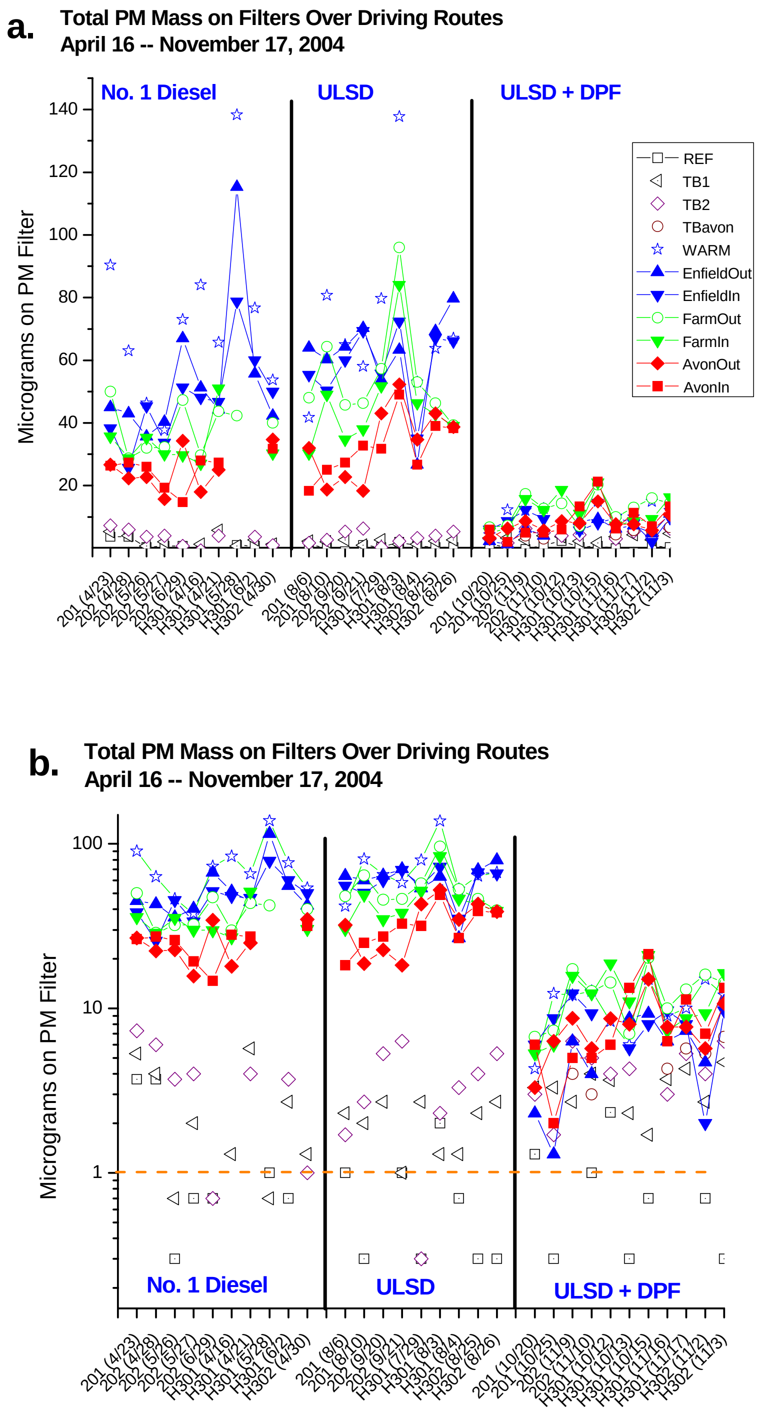

FIGURE 13. Raw total PM mass (micrograms) collected on individual subroute filters for each sampling day. The x-axis denoted BusID and date of sampling. (a) shows the data with linear y-axis scale and (b) shows the data with the y-axis plotted on a log scale to more clearly show the relationships between tunnel blank (TB) and route data for ULSD+DPF configuration data. The same legend applies for (a) and (b).

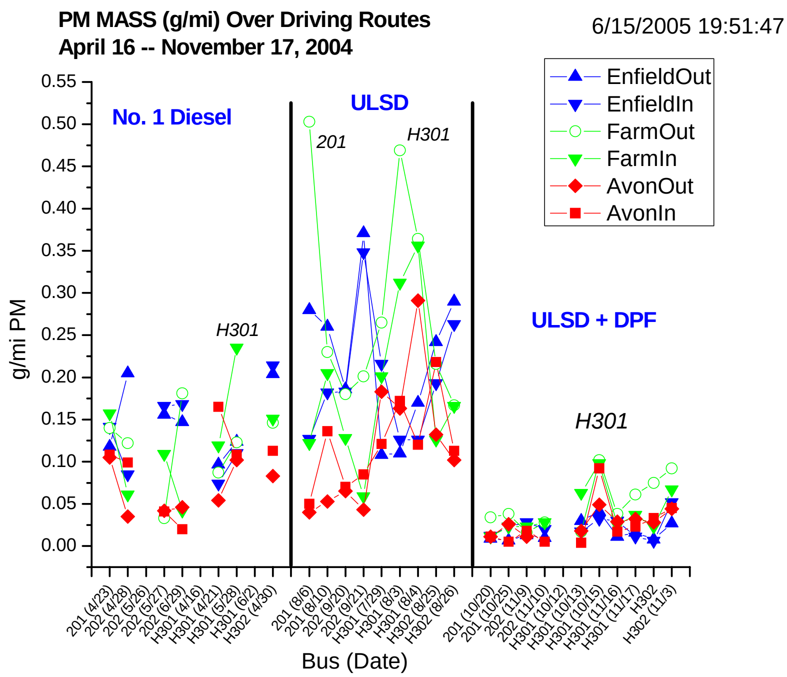

FIGURE 14. Total PM emissions rate (g/mi) for each subroute, ordered by BusID and date of sampling.

When aggregating the individual buses by vehicle type (hybrid or conventional), the data show no significant differences between PM mass emissions for the conventional diesel (CD) and the hybrid diesel-electric (HDE) on a given subroute (Figure 15). It is also interesting to note the seemingly higher <u>variability</u> in g/mi PM emissions when operating on ULSD and apparently higher variability on Farmington subroutes. The scatter in the data may also be related to the variability in the ambient environmental conditions between seasons (temperature and RH), but cannot be confirmed with the data available. Figure 15 also demonstrates that the PM emissions from CD and HDE buses were not significantly different for each fuel-aftertreatment configuration on each driving route.

A two sample t-test was performed to test whether there were significant differences in the PM mass emission factors (g/mi) between the conventional and hybrid buses over all subroutes and all testing days. The p-value of the t-test ($p = 0.261$) indicates that the null hypothesis cannot be rejected. In other words, the *mean PM mass emissions for the CD and HDE bus types were not significantly different at the 95% confidence level.*

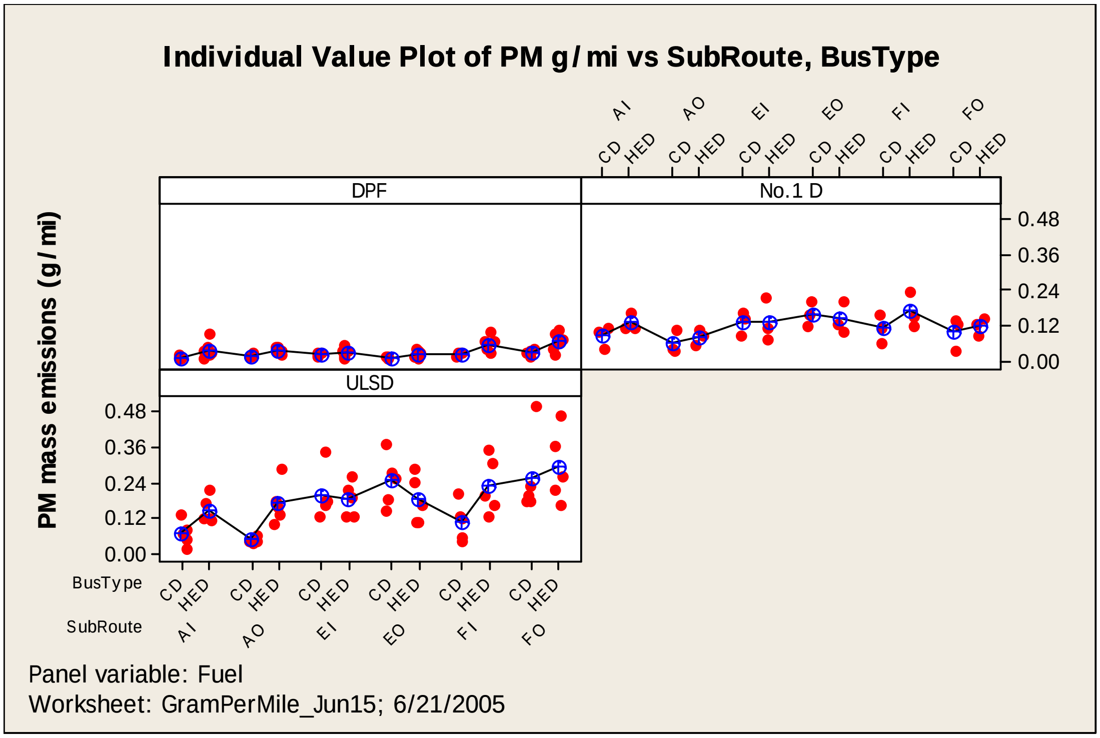

FIGURE 15. Grouped PM mass emissions rate data (g/mi) showing individual data (red points) and means (blue, connected with line) for each bus/ subroute combination. The y-axis scales are identical in each subpanel; note the higher variability for operation on ULSD fuel.

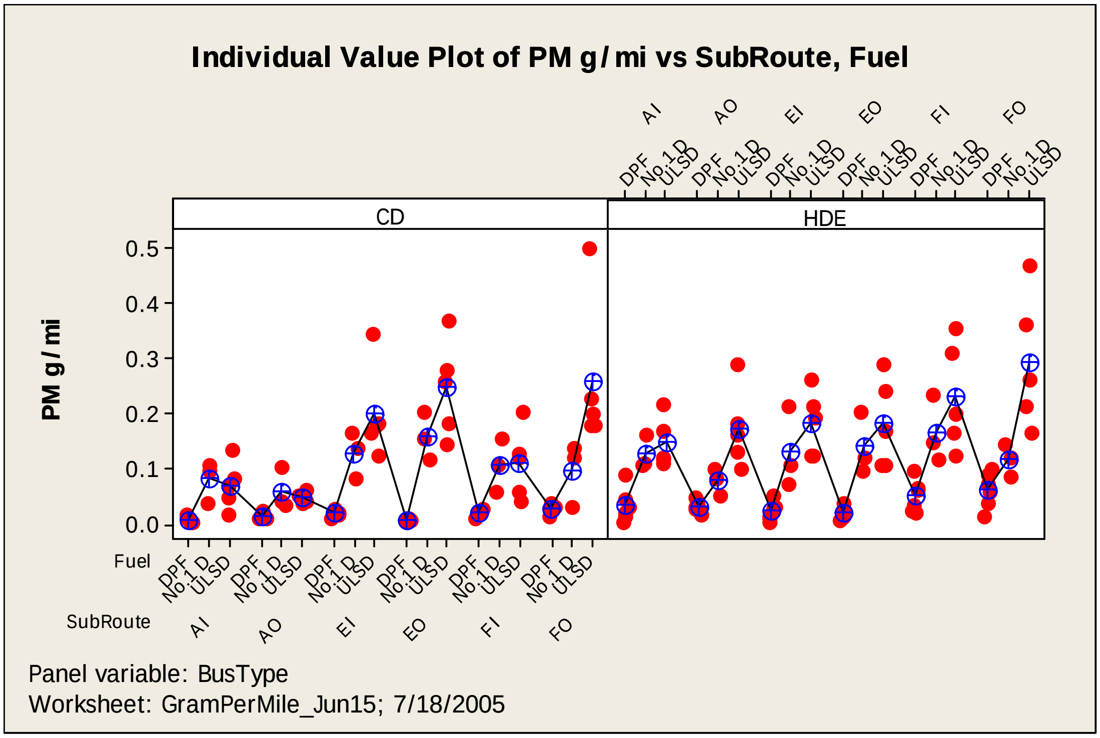

FIGURE 16. PM mass emissions rate data (g/mi) grouped by vehicle type (CD = conventional diesel, HDE = hybrid diesel-electric) for each subroute and fuel/aftertreatment configuration.

Particle Number Concentration by Diameter (SMPS). A substantial amount of single-diameter SMPS data was collected for each diameter on each route and for each bus with the exception of the 10 nm and 100 nm data for hybrid buses on the steep down-grade portion of Avon Mt. and for the 40 nm and 100 nm data on the uphill portion of Avon Mt (both using No. 1 diesel fuel). Because the uphill and down-grade portions of the Avon route were so short (approximately three minutes each) compared to other routes in the study (each about 30 minutes), and the arbitrary nature of changing the voltage settings on the classifier, no data happened to be collected for these diameters on these uphill/downhill routes. All SMPS raw count data, uncorrected for dilution, is plotted in Appendix A for all sampling days, particle diameters, bus types and fuels.

Recall that the data in Figures 17 to 22, representing the average and standard deviations of SMPS particle concentrations by diameter, were not collected from every sampling date. Because the SMPS could not measure the concentration of multiple particle diameters simultaneously, SMPS data from every diameter were not collected on every subroute each sampling day.

QA/QC Data. The SMPS raw count data collected during operation with the HEPA on the SMPS inlet typically had counts close to zero for all diameters with little variation between days (Table 13, mean plots in Appendix A). The TB tests typically resulted in counts slightly greater than HEPA data but never greater than one count on average for each reading at 0.1 second resolution. Tunnel blank test data also showed more variation than the HEPA tests (Table 13, see Appendix A plots). For May 26th and 27th, the HEPA and tunnel blank data were much higher than for other days due to a butanol spill inside the CPC the day prior to testing (May 25th). The butanol spill inside the CPC leads to contaminated optics and erroneously high particle counts even for HEPA measurement.

HEPA data for all diameters were never higher than 0.096 raw counts and never higher than 0.42 particles in the tunnel blank tests. Sample raw data from all of the routes was much higher than both the HEPA and tunnel blank averages (on-route counts exceeded three times the HEPA and TB counts) <u>except</u> for days sampled using the DPF aftertreatment device, where counts were less than 3 times the raw counts of the tunnel blanks.

Enfield Route. Number distributions for the Enfield route for different fuel types (No.1 Diesel and ULSD) and bus types (HDE and CD) (Figure 17) show that the freeway route particle number distributions peaked at 40 nm diameter and the number distributions were similar between the HDE and the CD bus types. Furthermore, the particle concentrations on the Enfield route were higher when operating on ULSD for both bus types and all particle diameters except for 10 and 20 nm, compared to operation on No. 1 diesel fuel. The Enfield route distributions (Figure 17) are similar to the number distributions seen for typical diesel engine exhaust under steady-state operating conditions (Kittleson 1998).

Table 13. Average and standard-deviation of HEPA and tunnel blank (TB) raw count data measured by the SMPS over all sampling dates.

		No. 1		ULSD		DPF	
	Dp	Ave.	Std.	Ave.	Std.	Ave.	Std.
HEPA	10	0.10	0.44	0.00	0.05	0.00	0.03
	20	0.01	0.36	0.01	0.10	0.00	0.04
	40	0.09	0.41	0.04	0.22	0.01	0.08
	80	0.09	0.40	0.04	0.22	0.01	0.09
	100	0.06	0.32	0.04	0.21	0.01	0.09
	130	0.08	0.38	0.04	0.20	0.01	0.08
TUNNEL	10	0.09	0.41	0.02	0.14	0.02	0.13
	20	0.09	0.42	0.04	0.21	0.04	0.20
	40	0.11	0.44	0.07	0.27	0.05	0.23
	80	0.08	0.41	0.08	0.28	0.05	0.22
	100	0.15	0.52	0.08	0.29	0.04	0.21
	130	0.18	0.48	0.07	0.28	0.03	0.18

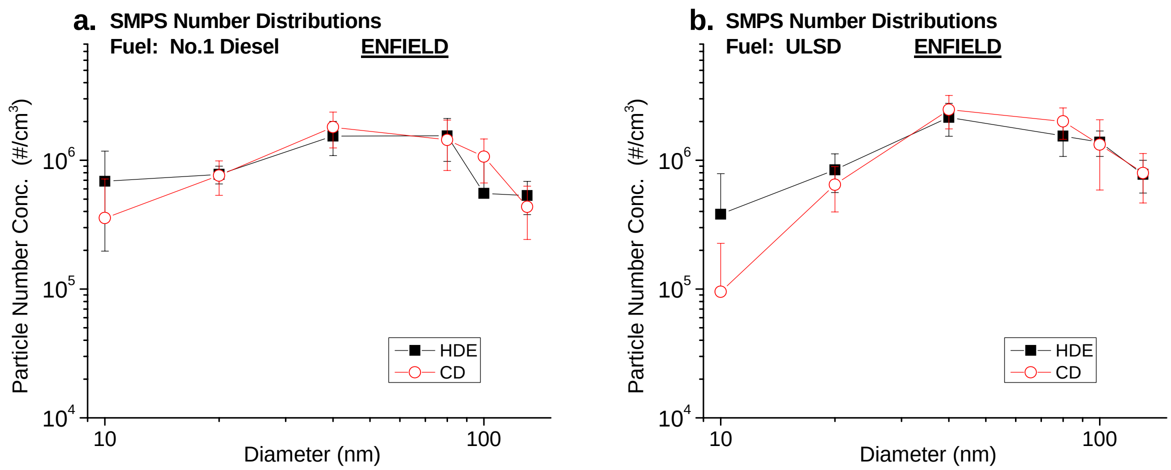

FIGURE 17. Particle number distribution for the Enfield route when operating buses on (a) No. 1 diesel and (b) ULSD fuel. Average number concentration (dN/dlogDp) and one standard deviation are plotted for each diameter sampled.

In a parallel hybrid design, the internal combustion engine provides primary power to the vehicle with the electric motor assisting only in periods of fast accelerations and hill climbs (Sullivan 1999). Therefore, on the Enfield freeway trip, the diesel engine was essentially powering the vehicle, not the electric motor. This may explain why there was no apparent difference between the diesel and hybrid bus SMPS number distributions for all diameters and fuel types on the Enfield route. The 10 nm diameter concentrations decreased by 51% on the hybrid bus type and 73% on the diesel bus type on average with the fuel switch to ULSD on Enfield, but the 20 nm concentrations were similar between bus and fuel type and the 40 nm concentrations actually increased slightly with the switch to ULSD (Figure 17).

Farmington Route. Number distributions for the stop-and-go Farmington route for different fuel types (No.1 Diesel and ULSD) and bus types (HDE and CD) (Figure 18) were different from the distributions on the Enfield Freeway route (Figure 17). On Farmington, the peak in the distributions occurred at the 10 nm diameter and the number concentrations were much lower at all other diameters. The 40 nm peak concentration on Enfield for all bus and fuel types was higher than the 10 nm peak concentration on Farmington (Figures 17 and 18). In addition, there was a second peak at the 80 and 100 nm diameters for both bus and fuel types. There was noticeable variation in the 80 and 100 nm data for ULSD tests which resulted in major fluctuations in the raw data collected (Appendix A). The large standard deviations for these data points are mostly attributed to the broad range of values of their respective samples under stop-and-go driving conditions. Concentration values varied on a given day for all days used to calculate the averages and standard deviations in Figure 18. As a result, the standard deviations tend to be quite large, especially for 80 and 100 nm on the HDE bus type using ULSD fuel (Figure 18b).

The differences in the Farmington and Enfield distributions suggests that the engine demand and operation on the Farmington route was different than on the Enfield route. The Enfield freeway route, characterized by steady-state driving with high speeds at relatively high loads and little/no acceleration or deceleration, should have produced higher particle number concentrations at all ultrafine diameters (Dp < 100 nm) compared to the Farmington route, characterized by frequent start and stop driving, lower average vehicle speeds and frequent periods of idle (see Tables 7 and 14). At very high engine loads, an increase in elemental carbon formation occurs, which offsets the decrease in nuclei particle precursors (soluble organic fraction, SOF) due to elevated exhaust temperature and more efficient oxidation. As a result, particle number concentrations typically increase with increasing load (Kittleson 1998; Kittleson et al. 2001). Similarly, at high vehicle speeds, particulate matter emissions increase due to high engine load, higher exhaust flow and increased exhaust temperatures (Kittleson et al. 2004).

A large portion of particles emitted at higher vehicle speeds are often derived from the release of particle-associated materials stored in exhaust systems during vehicle operation at low speeds. Furthermore, lower vehicle speeds produce larger particles (accumulation mode particles) and larger aerosol volumes (Kittleson et al. 2004), possibly explaining why the particle concentrations on the Farmington trip were relatively small compared to the Enfield trip and the higher variation in the larger ultrafine diameter (80 nm & 100 nm) particle concentrations on the Farmington trip (low speed, low rpm, low engine load).

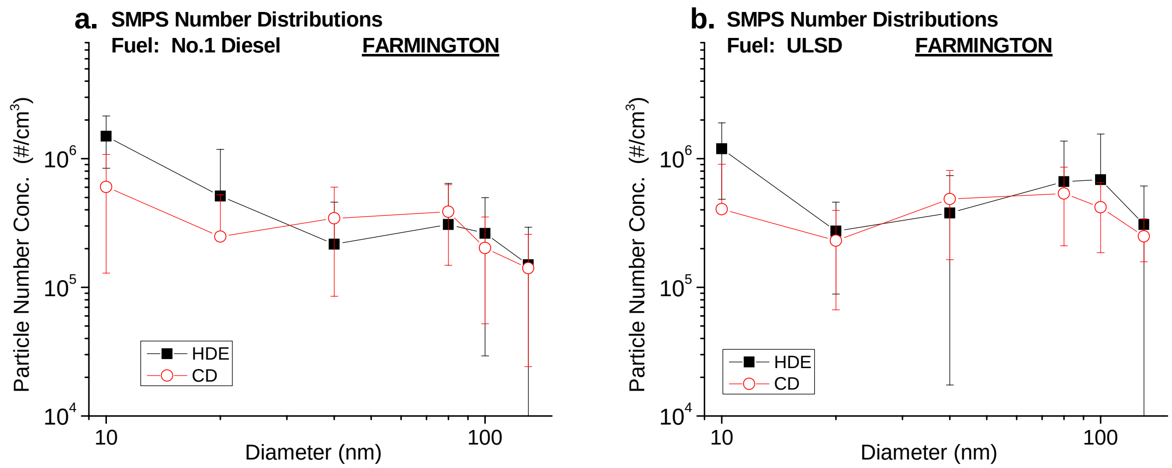

FIGURE 18. Particle number distributions for the Farmington route for (a) No. 1 diesel and (b) ULSD fuel operation. Average number concentration (dN/dlogDp) and one standard deviation are plotted for each diameter sampled.

The conventional diesel bus mean particle concentrations were often lower than the hybrid bus particle concentrations especially for the 10 and 20 nm diameters on the Farmington route (60% lower for 10 nm; 52% lower for 20 nm) for No. 1 diesel fuel and were 66 and 16% lower on 10 nm and 20 nm, respectively when operating on ULSD (Figure 18, Table 15). Hybrid technology is designed to offer fuel economy and emissions improvements when the vehicle operates under short trips, periods of fast acceleration and grade inclines (Sullivan 1999); most of which occur in the Farmington route, especially the rapid accelerations from periods of idle at the numerous stops. However, the hybrid bus type did not perform significantly better than the conventional diesel bus type on the Farmington route in terms of number concentrations for ultrafine particles. <u>This surprising result contradicts the benefits typically attributed to hybrid-electric vehicle design and suggests that the Allison Transmission parallel hybrid drive control systems on the buses used in this study were optimized for performance rather than significant emission reductions. Alternatively, one could surmise that all the previous studies documenting significant PM emissions benefits due to hybrid technology can really be attributed to the use of diesel particulate filter aftertreatment, not any overall PM emissions benefits due directly to the hybrid design.</u>

The parallel hybrid design utilizes the combustion engine when high power demand and constant speed are required (like the Enfield Route) and the electric motor provides power at lower speeds and start and stops (e.g., Farmington Route). Furthermore, the parallel design uses both sources to work together during accelerations, including accelerations from idle. Apparently, on the Farmington route in this study, the diesel engine may still have been working equally hard on the hybrid bus type as on the diesel bus type with little help provided from the battery. Thus, the Allison Transmission parallel design configuration studied may be the main reason for no noticeable improvement in particle number concentrations on the Farmington route between the CD and HDE bus types.

Table 14. Percent difference in mean SMPS concentrations by route (%).

Dp (nm)	Enfield	Farmington	Avon	AvonUP	AvonDOWN
No. 1 Diesel (Phase 1)					
10	48	60	-4	-118	*NA*
20	2	52	36	-104	-46
40	-17	-59	11	*NA*	35
80	7	-26	53	51	60
100	-93	23	38	*NA*	*NA*
130	18	6	44	28	83
ULSD (Phase 2)					
Dp (nm)	**Enfield**	**Farmington**	**Avon**	**AvonUP**	**AvonDOWN**
10	75	66	48	49	72
20	23	16	12	23	43
40	-15	-29	37	58	71
80	-30	19	27	26	79
100	4	39	28	18	50
130	-2	19	32	-15	85
ULSD + DPF (Phase 3)					
Dp (nm)	**Enfield**	**Farmington**	**Avon**	**AvonUP**	**AvonDOWN**
10	3	-2120	-7	-318	14
20	-80	-61	-117	6	-127
40	-45	-94	-192	17	-313
80	65	-166	2	79	-37
100	20	-109	25	63	*NA*
130	25	42	25	67	-149

NA = Not available due to missing data. Percent difference calculated as 100* (C_{HDE}-C_{CD})/C_{HDE} where C_i is SMPS mean concentration for given bus type *i*, for given route and fuel.

Avon Route. Similar to the Enfield and Farmington routes, the Avon route SMPS distributions (Figure 19) showed no significant differences in ultrafine particle emissions between the hybrid and diesel bus types on both No.1 diesel and ULSD fuels. Number distributions for the upgrade and downgrade portions of the Talcott Mountain sections of the Avon route, however, had dramatically different number concentrations from each other. Figure 19 shows the average number distributions for the entire trip on the Avon route; including the steep uphill and downhill portions, the sections of N. Main Street and Route 44 before Talcott Mt. and the portion on Route 44 prior to arriving at Marshalls (on Avon Outbound). The full Avon distributions are bimodal, showing elevated 10 nm concentrations and a broad peak between 40 – 100 nm.

The grade of a route is directly proportional to the load placed on the engine. At high loads (and low air/fuel ratios) and high speeds, the exhaust temperature increases as does the particle number concentration (Kittleson 1998; Kittleson et al. 2004). Thus, the Avon upgrade route is an ideal driving situation to promote high ultrafine particle number emissions from diesel vehicles and is examined in more detail below. There was no apparent relationship between % load and any other engine parameter, or any other engine parameter and particle concentration.

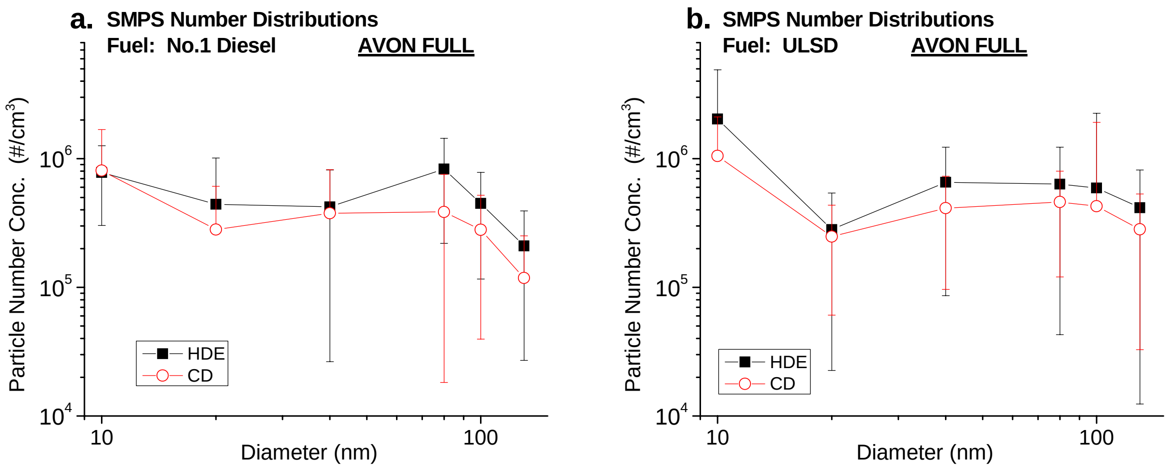

FIGURE 19. SMPS Particle number distribution for the full Avon route when using (a) No. 1 diesel and (b) ULSD fuel. Average number concentration (dN/dlogDp) and one standard deviation are plotted for each diameter sampled. Data from which these plots were derived came from: 27 Feb, 21 Apr, 27 Feb, 29 Jun, 27 May, 28 Apr, 29 July, 3 Aug, 4 Aug, 06 Aug, 10 Aug, 25 Aug, 26 Aug, 23 Apr, 6 Aug, 20 Sept, & 21 Sept.

Avon Upgrade and Downgrade (Talcott Mt.). Extracting only the upgrade portions of Avon Inbound and Outbound from the entire Avon route resulted in higher average particle concentrations on all diameters compared to the distributions over the full Avon route (compare Figure 20a,b to Figure 19). Uphill particle concentrations for all diameters were also much higher than those measured for either the Enfield or Farmington routes. The overall shape of the number distribution for the upgrade route was similar to that for the Farmington route, with a peak at 10 nm for ULSD operation and 20 nm for No. 1 diesel fuel. The number concentrations for larger diameters were much lower than those for 10 and 20 nm and their average concentrations were similar to one another (Figure 20). There was missing data at 40 and 100 nm diameters for the hybrid – No.1 diesel fuel configuration, but the hybrid bus type emitted much lower particle concentrations for the nuclei mode particles compared to the conventional diesel (10 and 20 nm, Figure 20a); whereas the diesel bus type emitted fewer nuclei mode particles under ULSD fuel operation on the Avon upgrade route (Figure 20b).

Particle number concentrations for the downgrade portion of Talcott Mountain in Avon (Figure 20c,d) are plotted on the same scale as the upgrade portion to indicate the much lower concentrations measured during the downhill coast, as one would expect. Surprisingly, the downgrade distribution shape was similar to that of the upgrade portion with a peak at 10 nm for all bus and fuel types (there was no downgrade data collected for the 10 and 100 nm diameters for HDE buses on No. 1 diesel fuel).

The Avon uphill route is characterized by a relatively constant speed and high load on the vehicle (Table 15). The typical speed for the Avon upgrade route was considerably lower than the Enfield route and the engine demand (% load) was slightly higher, while the engine speed values for these routes were relatively close to each other. In comparison to the Farmington route, the Avon uphill section had much higher % load and engine speed operation. The mean vehicle speed for the Avon uphill route was higher than the Farmington trip as well, only because the Avon uphill trip is a constant incline with no stops, whereas the Farmington trip has many periods of idling that reduce the average vehicle speed. With the exception of the load on the engine, the vehicles were operating under the same conditions going uphill as going downhill on Talcott Mountain (Table 15).

When operating over large changes in road grade (i.e., Avon Outbound uphill portion), which affect engine power demand, the observed particle concentration range will increase. Therefore, the large standard deviation in Figure 20b for HDE/ULSD operation can be attributed to the variation in road grade and corresponding engine load from the bottom to the top of Talcott Mountain. Figure 20a shows a somewhat bimodal distribution where local maxima occur at 10 nm and over the 40 – 80 nm diameter range for both bus types. It is difficult to tell if the same trend presents itself in Figure 20b due to missing data, although the complete distribution of the diesel bus type data does not show a bimodal trend when going uphill on No.1 diesel fuel.

Table 15. Typical vehicle and engine parameters for Enfield, Farmington and Talcott Mt. in Avon (uphill and downhill portions only) routes based on August 4th scantool data.

	Enfield	Farmington	Avon Upgrade	Avon Downgrade
Vehicle Speed (mph)	60	11.75	35.14	37.5
Engine Load (%)	82	28	95	1.18
Engine Speed (rpm)	1779	1008	1838	1814

The average downgrade particle concentrations (Figure 20c, d) were much lower than the average Avon upgrade concentrations. The diesel bus type had a 90% -97% reduction in particle concentration for all diameters between the upgrade and downgrade portions of the route. In contrast, the hybrid bus type ranged between 60% - 90% reduction from the upgrade to the downgrade subroutes, much lower than that observed for the conventional buses. A recent study showed a similar percent reduction (66 – 95% reduction) between uphill and downhill driving (Brown et al. 2002). There was much less engine power demand going downhill compared to uphill so one expects lower particle concentrations in the exhaust under downhill coasting conditions. The HDE bus type appears to have lower concentrations at most diameters on both the Avon upgrade and downgrade sections compared to the conventional diesel bus type. In particular, the HDE appears to be much cleaner than the CD under steep grade using No. 1 diesel fuel for nanoparticles (10, 20 and 40 nm) (Figure 20a). Recovery of prior regenerative braking energy gain may best explain why the hybrid bus type has lower nanoparticle concentrations than the conventional diesel when traveling uphill and using No. 1 diesel fuel. Regenerative braking should provide the greatest benefit on the downgrade portion of the Avon trip due to frequent braking, however the SMPS data do not support this conclusion for the 7-9% grade encountered on Talcott Mountain (i.e., friction and exhaust brakes were necessary to keep the vehicle under control).

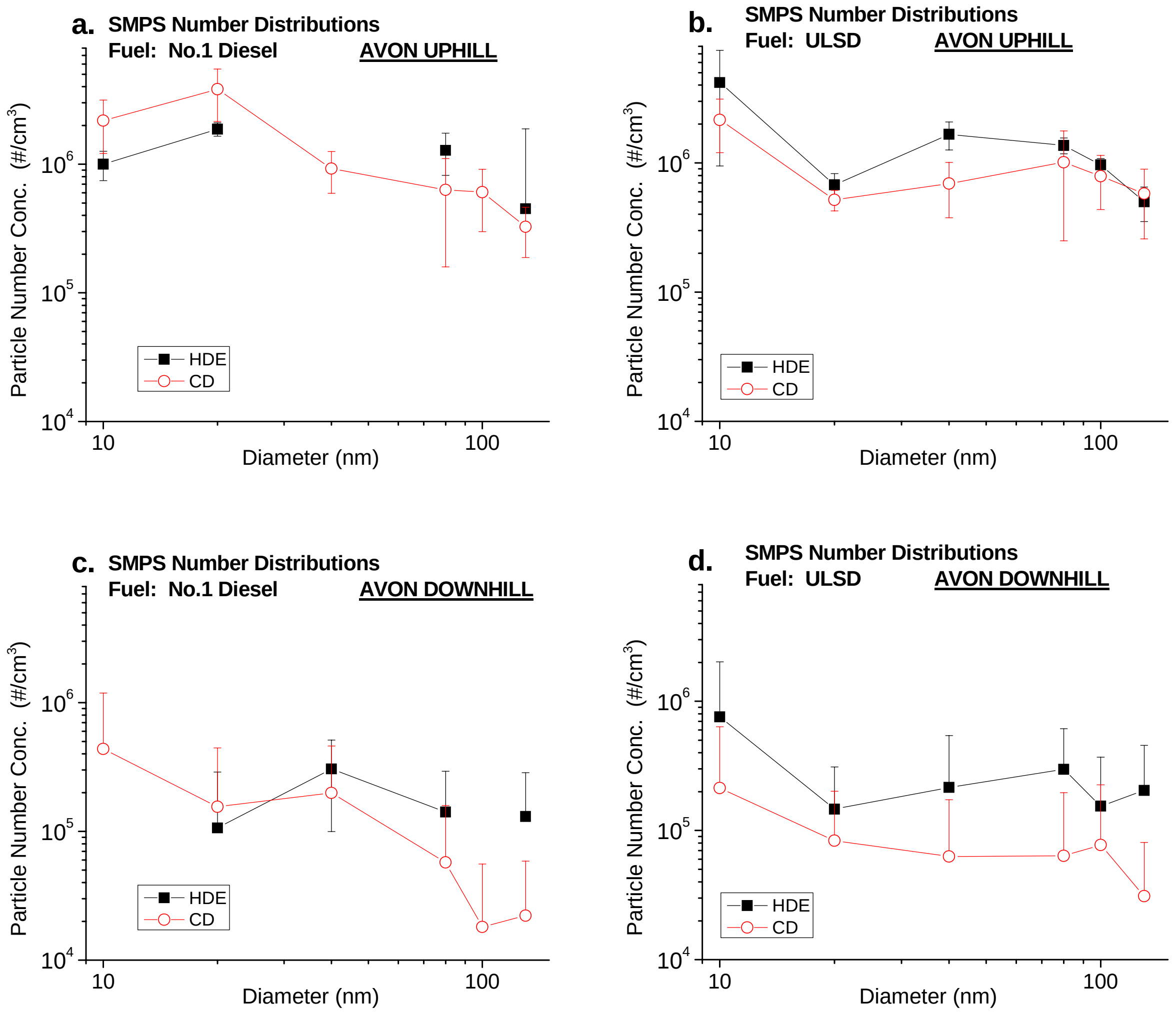

FIGURE 20. Particle number distribution for the *upgrade* (a,b) and downgrade (c,d) sections of Talcott Mt. portion of Avon route using (a,c) No. 1 diesel fuel and (b,d) ULSD fuel. Average number concentration (dN/dlogDp) and one standard deviation are plotted for each diameter sampled. The y-axis scale is identical in all four panels.

Dwyer et al. (Dwyer et al. 2002) examined the effect of grade on emissions and fuel economy with application to travel in San Francisco, California and concluded that at very large grades (10-19%), the fuel economy of most bus types (hybrid electric, conventional diesel, and compressed natural gas) drops well below 0.5 miles per gallon and that emissions are increased by a factor of fifty (compared to the CDB test cycle). Dwyer et al. (2002) also noted variability in particulate mass emission by bus type and retrofit application: CD and HDE buses, when fitted with particulate traps had considerably lower PM mass emissions (approximately 0.25 and 0.18 g/mi PM, respectively) at high grade (19% grade) than the CD bus on the same grade without a particulate trap (5.5 g/mi PM). It is important to note that these authors also found that the hybrid with trap emitted more PM *mass* than the conventional diesel bus with trap at high grade;

similar to the results of this study in terms of particle number concentration on Avon Upgrade-ULSD and Farmington with either fuel type (Figures 18 and 20).

It is frequently noted that the number concentration for particles from diesel engines increases with increasing engine load (Kittleson 1998; Brown et al. 2002; Dwyer et al. 2002; Kittelson and W. F. Watts 2002; Kean et al. 2003). As load is increased, the exhaust temperature increases as well and the SOF (soluble organic fraction) in the exhaust particulate phase is more effectively oxidized. As a result, the SOF contribution to the particle number concentration is decreased substantially. However, a simultaneous increase in elemental carbon formation takes place with increasing load and can offset the SOF decrease to result in an overall increase in the number concentration of particles. Furthermore, under high load conditions, engines typically operate fuel-rich (Kean et al. 2003). This phenomena may explain why there was no noticeable decrease in nanoparticle concentration between the Avon and Enfield routes (both had high load operation).

Fuel Sulfur Content Effects. The concentration of exhaust nanoparticles, primarily comprised of sulfates (Kittleson 1998), should decrease with the implementation of ULSD fuel because most of the sulfur in the fuel that contributes to those smaller nucleation particles is removed. For the SMPS measurements made in this study using on-road sampling, there was only a subset of vehicle route-bus-particle diameter conditions that showed the expected reduction in route-average particle number concentrations with the ~10x reduction in fuel sulfur content. These cases are shown in Table 16. Reductions between 15 and 85% in the number concentration of particles with diameters less than 40 nm were observed, but only for operating conditions that can best be described as relatively high load. Note also that the highest reductions were seen for the conventional diesel (CD) buses, not the hybrids, and larger reductions were observed for the smaller diameters (i.e., 10 nm decreased more than 40 nm).

Table 16. Percent reduction in SMPS number concentrations between operation on No. 1 diesel fuel and ULSD.

Route	Diameter	HDE	CD
Avon Uphill only	20 nm	63%	86%
	40 nm	--	25%
Farmington	10 nm	20%	32%
	20 nm	46%	--
Enfield	10 nm	52%	73%
	40 nm	--	15%

Diesel Particulate Filter Emissions. The addition of the DPF dramatically reduced particle number concentrations compared to operating on ULSD and a diesel oxidation catalyst (Table 17 and Figure 22). DPF type and make were different for each bus type (Johnson-Matthey CRT for HDE buses and Engelhard DPX for the CD buses), however number concentrations for all diameters, regardless of bus type and route, were reduced by 95% - 99% (Table 17). Figure 22 visually represents the number concentrations by diameter for all three phases of the study. The DPF number distributions typically had the same distribution shape as the ULSD and No. 1 data, just at much lower concentrations. It should be noted that the raw SMPS data used to calculate the plotted DPF averages and standard deviations in Figure 22 were not greater than the specified quantitation limit of the CPC (3 x HEPA data collected before and after sampling each day) or three times greater than tunnel blank data. Therefore, the number concentrations and calculated percent reductions are only approximate. We can definitively state that the effect of the DPF was consistent across all SMPS diameters, routes and bus types and an over 95% removal occurred. Only on the Enfield route for 10 nm for both bus types did the least efficient (~ 95%) removal of particles occur (Table 17). These removal efficiencies are in agreement with previous studies (Wayne et. al., 2003; Lanni et al., 2001; see Table 3 references).

Table 17. Percent reduction in route-average SMPS number concentrations between operation on ULSD diesel fuel with and without a diesel particulate filter (DPF).

Conventional Diesel (CD) -- Engelhard DPX				
Dp (nm)	**Enfield**	**Farmington**	**AvonUP**	**AvonDOWN**
10	95.8	98.2	99.6	99.5
20	99.5	99.9	99.7	99.2
40	99.6	99.7	99.3	95.5
80	99.8	99.6	99.9	99.2
100	99.7	99.6	99.9	NA
130	99.8	99.9	99.9	97.5
Hybrid Diesel-Electric (HDE) -- Johnson Matthey CRT				
Dp (nm)	**Enfield**	**Farmington**	**AvonUP**	**AvonDOWN**
10	98.9	100.0	100.0	100.0
20	99.8	99.9	99.8	99.8
40	99.7	99.8	99.6	99.6
80	99.4	99.9	99.6	99.6
100	99.7	99.9	99.7	99.7
130	99.8	99.9	99.7	99.7

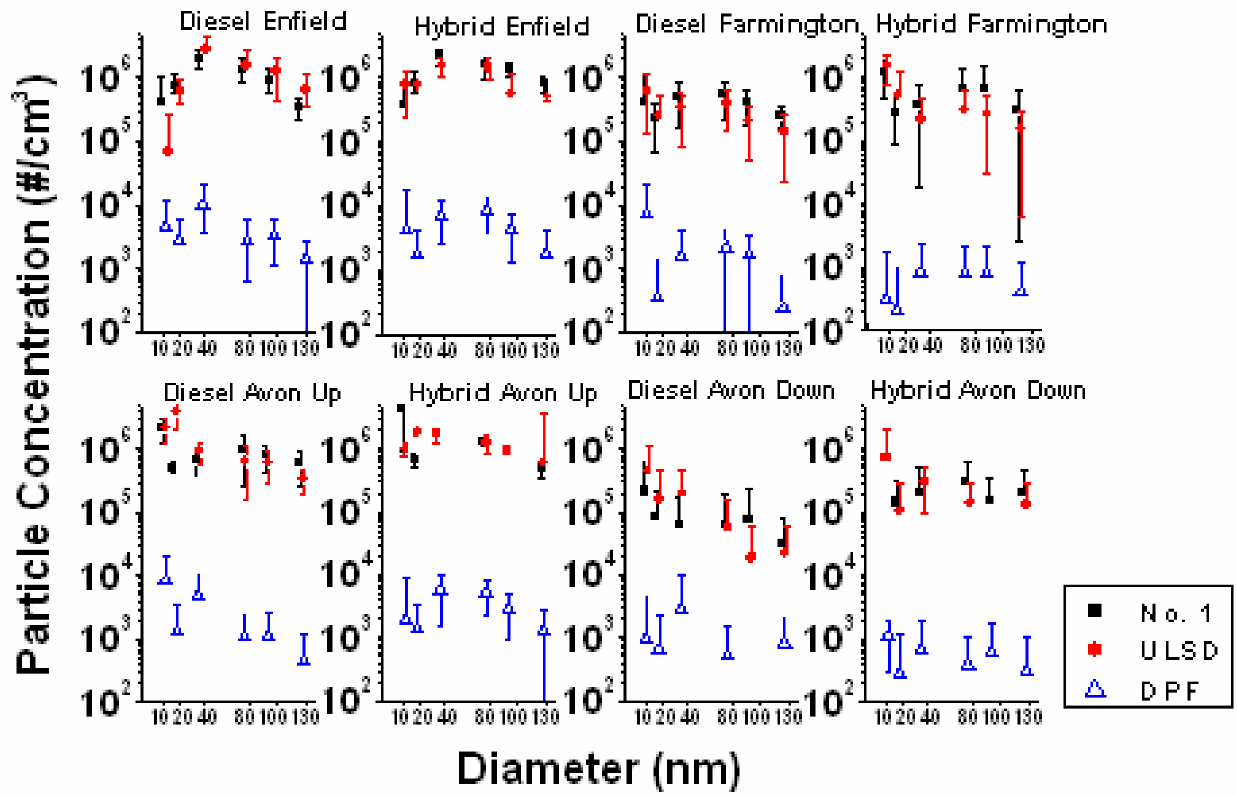

FIGURE 22. SMPS particle number distributions for all fuel and exhaust aftertreatment configurations. Number concentrations (dN/dlogDp) are plotted on a log y-scale. X-axis is on linear scale. Particle concentrations are plotted by diameter for the same bus type on a given driving route.

Total Particle Number Concentration and Size Distributions (ELPI).

The ELPI second-by-second data were summed over all 12 ELPI channels to compute the total particle number (TPN) concentration (dN; #/cm^3) for each subroute for each day of sampling. Particle number *distributions* were determined as averages over all one-second distributions collected on a given subroute on a given sampling day. The TPN raw data are plotted in Appendix B along with the size distributions (dN/dlogDp; #/cm^3) for each bus on each route for individual sampling days and the time series plots of the raw ELPI particle concentrations (dN; #/cm^3) on each subroute.

QA/QC Data. For the ELPI HEPA and tunnel blank tests, data were collected at all four instrument gain settings ("ranges") so that all ranges of instrument operation encountered over the day could be evaluated. The ELPI raw data collected during operation with the HEPA on the inlet typically had counts close to zero for all stages for all instrument gain ranges with little variation between days (see plots in Appendix B). For the ELPI tunnel blank tests, data were also collected at all four instrument ranges and typically resulted in counts slightly greater than the HEPA data as expected due to background particles in ambient air. Note that the tunnel blanks were always collected in the parking lot in front of CTTRANSIT's maintenance building, so the level of ambient diesel particles was detectable. During Phase 3 of the study, when exhaust concentrations were low due to DPF aftertreatment, an additional tunnel blank was collected at the end of the Avon route, in the Marshall's parking lot, where ambient diesel particulate levels were expected to be lower.

Total Particle Number (TPN) Concentrations. There was no significant difference in the mean total particle number concentration measured by ELPI between the individual buses when operating on both ULSD and No. 1 diesel fuel for all six driving subroutes, but TPN values were ~two orders of magnitude lower for operation with the DPF (Figure 23).

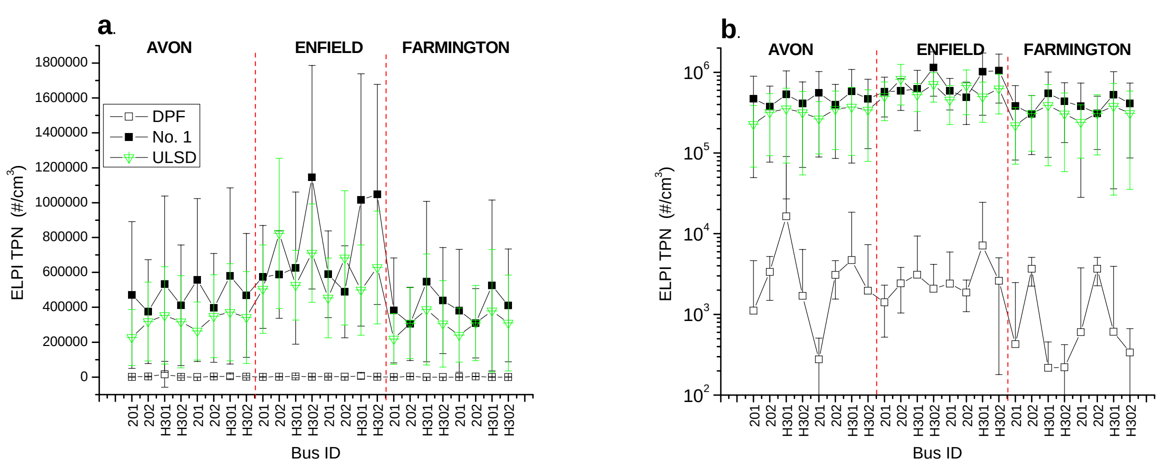

FIGURE 23. ELPI total particle number concentrations for individual buses by subroute. Inbound and Outbound subroutes are plotted separately in each route section of the plots. (a) has a linear y-scale and (b) has a log y-scale.

Particle Number Distributions. There was no observable difference in the mean particle size distributions measured by ELPI between the individual buses when operating on both ULSD and No. 1 diesel fuel for all six driving subroutes (Figure 24). The similarity in average size distributions between the HDE and CD buses likely reflects the fact that the two bus types had similar engine types in terms of model year and performance specifications (peak torque and power, see Table 4). The lack of difference in particle number emissions when operating on fuels with different sulfur content was surprising because fuel sulfur content is thought to contribute to exhaust nanoparticle emissions, as discussed above in detail. These results may indicate that these MY2002/2003 diesel engines are not as sensitive to fuel sulfur content as were earlier model year diesel engines. Alternatively, the source of nanoparticle precursor species may not originate in the diesel fuel for these vehicles, but may come from the high sulfur content in the lubrication oil which was identical for all four buses throughout the project (Exxon XD-3 15W-40; estimated 2300 ppm S based on the lubrication oil phosphorus content because sulfur is added as zinc dialkyldithiophosphate). This alternative is plausible because both of the diesel engines operated with blowby (see Table 4, vehicle specifications).

The size distribution plots (Figure 24) also indicate generally higher variability in the measured emissions when operating on ULSD with DPF aftertreatment, but it should be kept in mind that the particle counts were close to background levels (but well above three times the HEPA and TB measurements, in contrast to the SMPS data) with the DPF, so some of the variability in Figure 24 can be attributed to the difficulty of accurately quantifying the low particle number concentrations measured with the ELPI during Phase 3 of the study. Note also that the measured ELPI concentrations were also more variable when operating on No.1 diesel fuel compared to the variability under ULSD operation. This observation contrasts with that made above for the PM mass measurement and may reflect the different biases of the two different PM measurement techniques (gravimetric mass is biased towards larger particles and the ELPI is better suited for measuring particles between 10 nm and ~500 nm for diesel exhaust).

It is important to recognize that the size resolution possible with the ELPI is much coarser than that measured by the SMPS. For example, both the 10nm and 20 nm SMPS diameters are lumped into ELPI Stage 1. Thus, some of the conclusions drawn in terms of differences between routes and bus types may be different for the SMPS and ELPI datasets. The lower size resolution of the ELPI is one possible explanation for the lack of significant differences in number distribution shape between routes that was observed in the SMPS data. Comparison plots between the SMPS and corresponding ELPI stage particle concentrations are presented in Appendix C (Table C-17 and Figures C-1 to C-5) for some of the sampling days during Phase 2. The plots show reasonably good correspondences between the two instruments, especially given the different measurement techniques and variation in range of particle diameters measured by each instrument.

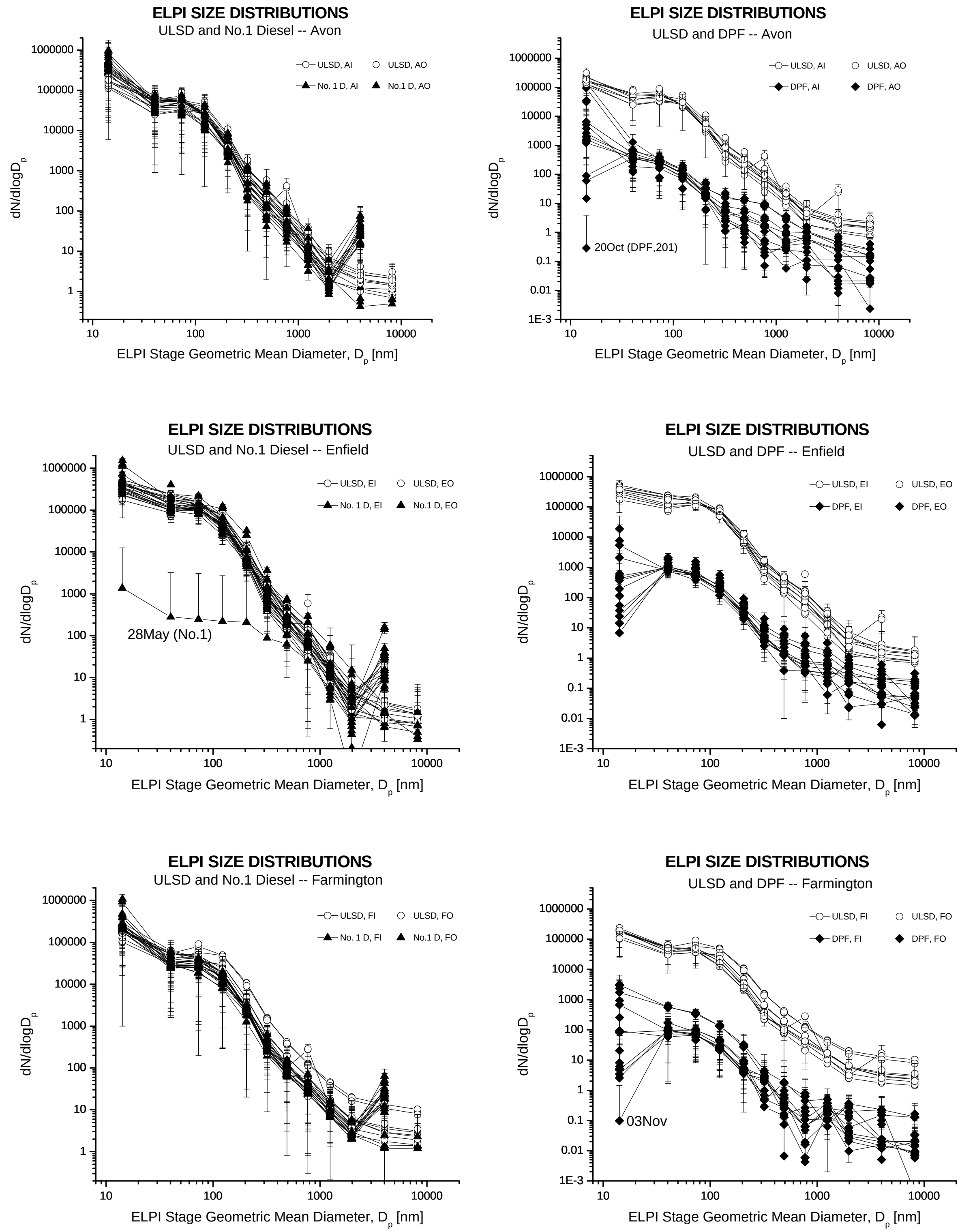

FIGURE 24. Daily average subroute ELPI particle size distributions as a function of fuel/ aftertreatment. Left panels compare average distributions measured for ULSD and No. 1 diesel fuel operation. Right panels compare ULSD operation with and without a DPF. Open symbols in all plots represent emissions during operation on ULSD without a DPF.

CONCLUSIONS & RECOMMENDATIONS

The general trends in the particle emissions for the HDE and CD transit buses as measured by three separate instruments/ techniques were similar:

(1) Particle mass and number emissions for these 2002/2003 model year diesel transit buses were not sensitive to diesel fuel sulfur content. This observation did not vary with driving route or bus type and was confirmed for data collected on PM filters, the SMPS and the ELPI.

(2) Different buses of the same type (HDE or CD) did not have statistically different particle emissions when operating under the same fuel and aftertreatment configurations.

(3) Particle mass and number emissions were reduced to instrument background levels when the buses were outfitted with DPFs and the percent reductions were similar for the CD and HDE buses.

(4) Particle number *distributions*, based on averaging data collected at each SMPS diameter over multiple days on a single type of bus for a given driving route, varied depending on the driving route (see **Figure 25**, below). The Enfield route, characterized by steady-state freeway driving at high speed, had a particle number distribution that peaked around the 40 nm range for both bus types and fuel types. The peak for the Farmington trip, classified by significant start and stop driving with high accelerations and long periods of idle, shifted away from the 40 nm peak and was closer to 10 nm. The upgrade and downgrade portions of the Avon route had a similar particle number distributions to those seen for Farmington with a peak at 10 nm. The maximum particle concentrations occurred on the Avon upgrade route for the CD-ULSD configuration and the lowest particle concentrations occurred on the downhill route for both bus types and fuel types.

(5) Road grade and corresponding power load requirements on the diesel engine was a more important determinant of ultrafine particle emissions than any other parameter. This observation is based on the comparison of SMPS number concentrations at individual diameters between routes.

(6) Fuel sulfur content did affect the variability in PM mass measurements and SMPS number concentrations differently. Variability was highest for PM mass measurements during Phase 2 (ULSD) whereas the SMPS number concentrations were most variable when operating on No. 1 Diesel fuel during Phase 1 testing.

(7) Measured PM mass emissions ranged from 0.02 to 0.5 g/mi for operation in Phases 1 and 2 (without the DPF) and were less than 0.10 g/mi for operation with a DPF. The on-board measured values are similar to literature values for diesel buses based on laboratory dynamometer tests. This observation is encouraging because it implies that new (MY 2002/2003) diesel buses such as those studied here practically meet the 2007 MY emission standards for PM (0.01 g/bhp-hr; assuming a conversion factor of

4.6 bhp-hr/mi for transit buses (EPA 2002) this translates into a 0.046 g/mi standard) when outfitted with a diesel particulate filter.

(8) Although the make and manufacturer of the diesel particulate filters were different, both resulted in greater than 95% reduction in particle number emissions and brought PM mass emission rates to near ambient levels.

(9) On-board testing of in-service transit buses is feasible, both for gas and particulate emissions measurement, but demands for data collection are labor-intensive and therefore costly.

(10) Interpretation of the emissions data would have been facilitated by cooperation of the hybrid bus manufacturer so that time-resolved data could be interpreted in more detail as a function of engine/electric motor parameters.

These observations lead to the following **recommendations**:

- The Allison hybrid buses, in their current control configuration, do not have any significant emission benefits over the conventional diesel buses, but may have other fuel economy and maintenance benefits that are not addressed by this study. CTTRANSIT should investigate whether a series hybrid design will offer more emissions benefits without sacrificing other advantages of the hybrid bus such as lower noise, smoother rides and performance characteristics comparable to conventional diesel transit buses on freeway commuter routes and routes with high grade (up to 9% in this study).

- While operation on ULSD did not lower PM emissions relative to No.1 diesel for the buses tested, operation on ULSD does enable the use of diesel particulate filter aftertreatment. The use of DPFs on older engine buses in the CTTRANSIT fleet should be a targeted goal for CTTRANSIT over the next 5-10 years to cover the gap as the current fleet is replaced by newer technologies.

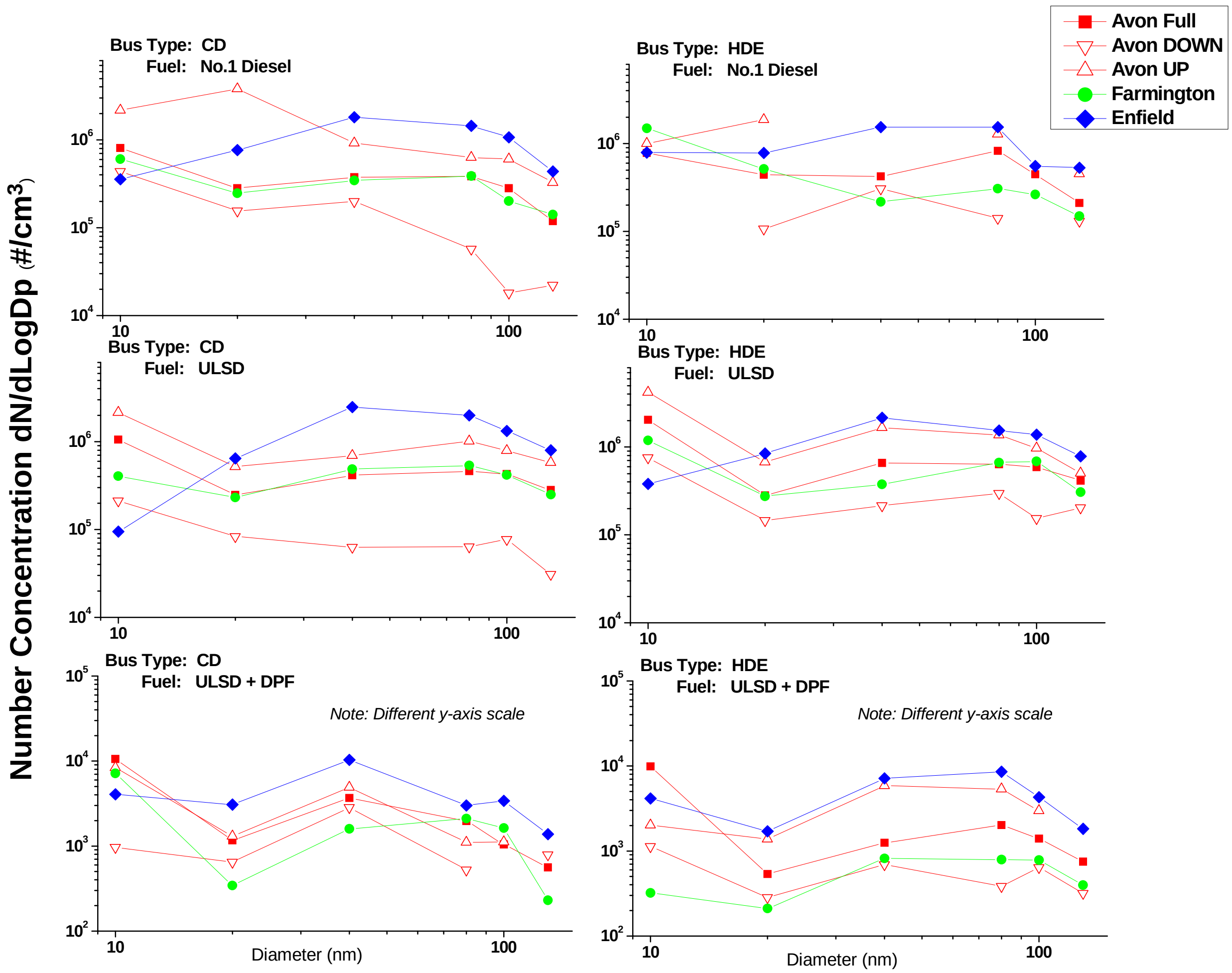

FIGURE 25. Grouped SMPS number distributions for each phase of the study. Note that the y-axis scale is over two orders of magnitude smaller for the two bottom plots of emissions during operation on ULSD + DPF. No standard deviations are graphed to allow for best visual representation of estimated number distribution. The X axis is plotted on a log scale.

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APPENDICES

Appendix A. Plots of SMPS Single-Diameter Raw Data

Appendix B. Plots of ELPI Raw Data

Appendix C. Experimental Methods Detail

Appendix D. Digital Photographs

The four appendix documents are posted as PDF files on the *Connecticut Cooperative Highway Research Program* page of the Connecticut Transportation Institute website: http://www.cti.uconn.edu/

1. From the *Connecticut Cooperative Highway Research Program* homepage http://www.engr.uconn.edu/ti/Research/crp_home.html

2. Follow the “Completed Projects” link to Project 03-8: http://www.engr.uconn.edu/ti/Research/crp_completed.html

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