

APPENDIX D

ENGINE EXHAUST TEMPERATURE STUDY

I. Introduction

This study was conducted to evaluate the applicability of passive verified diesel emission control strategies (DECS) for public and utility vehicles to comply with the proposed regulation.

As of September 2005, the majority of the diesel emission control strategy devices verified to achieve greater than 85 percent reduction in diesel particulate matter (PM) are passive diesel particulate filters (DPF). This primary goal was to determine which type of vehicle would be able to use passive DPF by assessing the engine exhaust temperatures.

Secondarily, staff can use the results to evaluate the feasibility of using newer technology, such as flow through filters (FTF), based on the projected requirements for a minimum engine exhaust temperature. Diesel oxidation catalysts (DOC) are also dependent on engine exhaust temperature for successful and efficient operation, however require much lower temperatures and only one such DOC specifies a temperature requirement criteria.

The success of a passive DPF relies on four main components: NO_x to PM ratio, total PM emissions, vehicle space availability for the passive DPF, and engine exhaust temperature. Post-1991 heavy-duty diesel engines are best for achieving the NO_x to PM ratio. The maximum PM emissions the passive DPF can handle are predicted, in part, by the frequency of filter regeneration, which, in turn, is dictated by the engine exhaust temperature profile. For example, the Johnson Matthey's verified CRT requires engine exhaust temperatures of 260 degrees Celsius for at least 40 percent of the duty cycle (ARB 2002a). The Engelhard's verified DPX requires an average of 225 degrees Celsius engine exhaust temperature with temperatures in excess of 300 degrees Celsius for a minimum of ten percent of the duty cycle (ARB 2002b). Table 1 presents a summary of the requirements from the verified devices available in the corresponding web site (ARB 2005).

The main objective of this study was to gather data on exhaust temperature profiles for various vehicles/equipment types that are typically used by municipalities and utilities. The data collected determined the percent of the public and utility fleet vehicles which have the operational characteristics appropriate for aftertreatment retrofits.

Table 1. DECS Temperature Requirements

PM Level	Technology Type	PM Reduction	NOx Reduction	Min. Temp C.	Duration	
Level 3	DPF	85%	25%	260	40%	
	DPF	85%	25%	225	50%*	
	DPF	85%	N/A	225	50%*	
	Lean NOx Cat/ DPF	85%	25%	260	25%	
		DPF	85%	N/A	225	50%*
				and	300	10%
	DPF	85%	N/A	260	40%	
	DPF	85%	N/A	210	40%	
	EGR/DPF	85%	40%	260	40%	
DPF	85%	N/A	280	25%		
Level 2	Flow Through Filter	50%	N/A	300	7%	
	Alternative Fuel	50%	15%			
Level 1	DOC	25%	25%			
	DOC	25%	N/A			
	DOC + crankcase filter	25%	N/A	100<t<550		
	DOC + crankcase filter	25%	n.a			
	DOC	25%	n.a			
	DOC + crankcase filter	25%	n.a	100<t<550		
	DOC + SCR	25%	80%	180	55%	
	DOC	25%	N/A			
	DOC	25%	N/A			

*Average calculated as the 50th percentile

I. Methodology

Public agencies and utilities own and operate a variety of diesel fueled vehicles which are possible candidates for retrofit devices. In order to determine what vehicles are amenable for PM retrofit, staff proposed that the most common vehicle types as determined by the TIAX report (TIAX 2003) be instrumented with dataloggers to determine an average temperature profile for each type. Staff analyzed this engine exhaust temperatures data to determine which percentage of the fleet could possibly use the currently verified passive DPF successfully.

A. Vehicle Selection and Fleet Composition

The study was conducted from November 2003 to September 2004 with an original targeted population of 59 vehicles from public fleets. The vehicle types included dump, flatbed, service and tractor trucks; as well as specialized vehicles such as boom trucks, aerial lifts, cranes, sewer vector vehicles and sweepers. In order to determine what vehicles are amenable for PM retrofit, staff used the most common vehicle types as determined by the TIAX report. Table 2 lists the top ten vehicle types that are diesel-fueled and over 14,000 GVWR used by the municipalities.

Table 2. Top Ten Diesel-Fueled Vehicle Types

Vehicle Type	No. of Vehicles	Percent of Fleet
Dump Truck	1,558	22%
Plow & Spreader Truck	1,058	15%
Sweeper	472	7%
Cargo Truck	463	7%
Tractor Truck	350	5%
Sewer Truck	249	4%
Service Truck	238	3%
Flatbed Truck	224	3%
Aerial Lift Truck	205	3%
Crane	153	2%
Total:	4,970	71%

The survey also revealed that the activity level for each vehicle type vary greatly based upon the type of municipality or utility. Fleets were selected to be representative of various municipality or utility types.

1. City of Los Angeles,
2. City of Long Beach,
3. City of Pasadena,
4. Los Angeles Department of Water and Power (DWP),
5. County of Los Angeles,
6. California Department of Transportation (CalTrans),
7. US Marine Corps (USMC), and
8. Southern California Edison (SC Edison).

An average of six of the most common vehicle type by municipality or utility were instrumented in each of the types, for a total of 59 vehicles, for a period of time representative of normal operational activity, for at least five days. Data collection took approximately a year. Staff worked with municipality and utility staff to ensure that vehicles were datalogged for periods of actual operation. Table 3 present the vehicles distribution of vehicles selected for the study. For convenience the number of vehicles with useful data is also presented.

Table 3. Vehicles Selected for Instrumentation.

Vehicle Type	City of LA	City of Long Beach	City of Pasadena	DWP ¹	County of LA	Cal Trans ²	USMC ³	SC Edison ⁴	Total	Vehicles with useful data
Dump Truck	3	2	4	1	2	4	3		19	16
Plow & Spreader Truck						3			3	3
Sweeper	6		3	1		2			12	8
Cargo Truck									0	0
Tractor										
Truck	1			2			2		5	1
Sewer Service Truck	1	2			1	2			6	5
Flatbed Truck		1			2				3	3
Aerial Lift Truck				2					2	2
Crane		1			1	1		2	5	5
		1		2		1			4	2
Total:	11	7	7	8	6	13	5	2	59	45

1. Los Angeles Department of Water and Power.

2. California Department of Transportation,

3. US Marine Corps, and

4. Southern California Edison.

B. Equipment: Engine Exhaust Temperature Dataloggers and Vehicle Characteristics

The dataloggers were four DT500 Series DataTakers purchased by the ARB in 2001. They collect engine exhaust temperature in a second by second basis. In addition to the electronic automated logging, ARB staff recorded the basic information on each vehicle on the data collection sheet presented in Figure 1. The 59 vehicles selected to represent the types and engine makes of the fleets are presented in Table 4 as well as their basic information of their engine manufacturer, engine model, vehicle manufacturer, and model year. The data were collected for a minimum of one work week (five days) on each vehicle, with approximately 100,000 seconds worth of data per vehicle. Although staff installed dataloggers on 59 vehicles, the data of only 45 meet the criteria for inclusion in this report.

Figure 1. Vehicle Data Collection Sheet.

		Date:	Init:
1. Fleet Contact Name:			
2. Fleet Business Name:			
3. Fleet Terminal #:			
4. Fleet Terminal Address:			
5. Vehicle Identification No.:			
6. License Plate No.:			Comments:
7. Vehicle Type/Model:			
8. Vehicle Manufacturer:			
9. Vehicle GVWR:		Pounds	
10. Vehicle Model Year:			
11. Estimated mpg:		Mpg	
12. Current Vehicle Mileage:		Miles	
13. Engine Manufacturer:			
14. Engine Model:			
15. Engine Model Year:			
16. Engine Horsepower:			hp
17. Engine Displacement:			in ³ /liters
18. Current Engine Mileage:			miles/hours
19. Engine Mileage at Last Rebuild, Repower, Replacement:			miles/hours
20. Engine Mileage when Next Expect to Rebuild Engine:			miles/hours
21. Fuel Injection:		Yes/No	
22. Aspiration:		Yes/No	
23. Transmission:			
24. Cycle		Two/four	
25. Fuel Sulfur Content:		CARB/15 ppm	
26. Number of teeth on the flywheel:			
27. Emission Certification:			
28. Exhaust Location:			
29. Exhaust Configuration:		Up/down	
30. Exhaust Pipe Diameter:		Single/dual	
31. Underbody Clearance:			mm/inches
32. Currently using DPF?			inches
32. Currently using DPF?		Yes/No	
OIL CONSUMPTION INFORMATION			
33. Current Engine Lubricating Oil Consumption			Qts/Wk
34. What is manufacturer's suggested oil consumption?			____/____
35. Does engine utilize devices that enable less frequent oil changes?		Yes/No	
36. How often is crankcase oil replaced with new oil?			____/____
FUEL DATA			
37. Where do you buy your diesel fuel?			
38. How frequently do you buy your fuel?			per
39. How much do you buy each time?			Gallons
ARB DATA COLLECTION			
40. Smoke opacity test results (attach results strip to this sheet)		1:	4:
		2:	5:
		3:	6:
40. Does the vehicle have access to power source for active DPF?		YES/NO	What:

Table 4. Datalogged Vehicle Description.

Veh#	Vehicle Type	Agency	Engine Manufacturer	Engine Model	Vehicle Manufacturer	Model Year
1	Tractor Truck	LA City	Caterpillar	3406	Peterbilt	1996
2	Dump Truck	Long Beach City	Mack	EC6-265	Mack	1987
3	Dump Truck	LA City	Caterpillar	3306	Peterbilt	1996
4	Sweeper	Pasadena	Cummins	ISB-190	FRHT	1998
4A	Sweeper	Pasadena	Cummins	ISB-190	FRHT	1998
5	Sweeper	LA City	Caterpillar	3126	Freightliner Broombear	2002
6	Dump Truck	Long Beach City	Caterpillar	3306	Freightliner	1988
7	Sweeper	LA City	Caterpillar	3126	5 Star Broom Bear	2002
8	Dump Truck	LA City	Caterpillar	3306	Peterbilt	1997
8A	Dump Truck	LA City	Caterpillar	3306	Peterbilt	1997
9	Sweeper	LA City	Caterpillar	3126	Freightliner	2002
10	Crane	LA DWP	Caterpillar	3126	GMC	1999
11	Crane	LA DWP	Caterpillar	3126	GMC	1999
12	Crane	Cal Trans	Cummins	DT-466-210 BC	International	1987
13	Sweeper	LA City	Caterpillar	3126	5 Star Broom Bear	2002
14	Dump Truck	USMC	Caterpillar	C-12	Navistar	2000
15	Dump Truck	USMC	Caterpillar	C-12	Navistar	2000
16	Dump Truck	Pasadena	Caterpillar	3116	GMC	1997
17	Lift Knuckle Boom	Cal Trans	Navistar	E-210	Navistar	1991
18	Sweeper	Pasadena	Caterpillar	3116	GMC	1997
19	Dump Truck	Cal Trans	Caterpillar	3126	Freightliner	2001
20	Lift Aerial Boom	LA County Public Works	Navistar	D-210C	Navistar	1989
21	Sweeper	Cal Trans	Cummins	ISD-205	Elgin Sweeper	2002
22	Dump Truck	Pasadena	Caterpillar	3116	GMC	1997
23	Dump Truck	USMC	Navistar	C-12	Caterpillar	2001
24	Sweeper	Cal Trans	Cummins	ISD-205	Elgin Sweeper	2003
25	Sewer Vactor	LA County Public Works	Caterpillar	C-10	International Harvester	2002
26	Sewer Vactor	Long Beach City	Caterpillar	3116	GMC	1998
27	Sewer Vactor	Long Beach City	Cummins	8.3-C	Ford	1997
28	Dump Truck	Pasadena	Caterpillar	3116	GMC	1997

Table 4. Datalogged Vehicle Description (continued).

Veh#	Vehicle Type	Agency	Engine Manufacturer	Engine Model	Vehicle Manufacturer	Model Year
29	Dump Truck	Pasadena	Caterpillar	3116	GMC	1997
30	Lift Boom Truck	Long Beach City	Caterpillar	3116	GMC	1992
31	Service Truck	Long Beach City	Navistar	7.3 Power-stroke	Ford	2000
32	Crane Boom Truck	Long Beach City	Caterpillar	3126	FRHT	2001
33	Dump Truck 10-wheeler	LA County Public Works	Caterpillar	C-15	FRHT	2002
34	Dump Truck / Tandem Axle	LA County Public Works	Caterpillar	C-15	FRHT	2002
35	Dump Truck/ 5500-6X4	LA DWP	Cummins	ISM-400V	International	2002
36	Sweeper Trk	LA DWP	Caterpillar	3126	5 Star-Freightliner	2002
37	Sevice Crew Cab	LA County Public Works	International	Power Stroke Diesel	Ford	2001
38	Sevice Crew Cab	LA County Public Works	Navistar	Power Stroke Diesel	Ford	2001
39	Flatbed Truck	LA DPW	Cummins	ISM-320V	Kenworth/T800B	2002
40	Sewer Vactor	Cal Trans	Caterpillar	C-12	International	2001
41	Sweeper	LA City	Caterpillar	3126	5 Star-Freightliner	2003
42	Dump Truck	Cal Trans	Cummins	ISM	Volvo	2001
43	Flatbed Truck	LA DPW	Cummins	ISM-320V	Kenworth/T800B	2002
44	Dump Truck	Cal Trans	Cummins	ISM	International	2001
45	Dump Truck	Cal Trans	Cummins	ISM	Volvo	2001
46	Sewer Vactor	LA City	Caterpillar	3126	Sterling/Ford	2002
47	Sewer Vactor	Cal Trans	Caterpillar	C-12	International	2001
48	Sweeper	LA City	Caterpillar	3126	Freightliner	2002
49	Lift Aerial Truck	SC Edison	Navistar	DT-466 HT	Navistar	1995
50	Lift Aerial Truck	SC Edison	Navistar	DT-466 HT	Navistar	1996
51	Dump/Plow Trk	Cal Trans	Navistar	DT-466 HT	Navistar	1992
52	Dump/Plow Trk	Cal Trans	Cummins	ISM 370	Volvo	2001
53	Dump/Plow Trk	Cal Trans	Cummins	ISM 370	Volvo	2001
54	Tractor Truck	LA DWP	Cummins	NTC-400-BG3	International	1985
55	Tractor Truck	LA DWP	Cummins	NTC-400-BG3	International	1984
56	Tractor Truck	USMC	Caterpillar	C-12	International	2003
57	Tractor Truck	USMC	Caterpillar	C-12	International	2003

II. Results and Discussion

A. Engine Exhaust Temperatures

Engine exhaust temperatures were collected and analyzed for the applicability of mainly two types of passive DPFs or one type of FTF. ARB Staff assessed a range of conditions that the diverse suppliers required for minimum engine exhaust temperatures and frequency distributions. The conditions ranged from temperatures equal or above 210 C for more than 40% to 300 C for more than 10% of the operation of the vehicle's engine or a combination of the conditions. For the case of one DOC the conditions require temperatures between 100 C to 500 C. Table 5 presents the range of condition evaluated. More vehicles were able to meet the engine exhaust temperature requirements of the FTF than either passive DPF.

1. Passive Diesel Particulate Filters and Flow Through Filters

In general, the vehicles experienced low engine exhaust temperatures. About 56 percent of the tested vehicles meet the criteria of a level 3 DPF device that required equal or above 210 C for more than 40% of the time. The criteria for the level 2 FTF device were met by 67% of the tested vehicles. The engine exhaust criteria was for a temperature of 300 C for more than 7% of the time.

a. Analysis By Vehicle Type

The results analyzed by vehicle type illustrate which vehicle duty cycles appear to be more severe when compared to the others. For convenience a summary of the results by type, engine manufacturer, and model year is presented in Table 5. This table list eight different temperatures and temperature frequencies criteria reported by the DECS manufacturers from T1 to T7 found in Table 1. The temperature stated has to be reached or surpassed for the percent of the time stated. The control levels are stated at the top of the columns. The column labeled T2&T7 is for a level 3 device that has to meet both temperature and frequency criteria.

In most cases, relative to the DPF, the FTF engine exhaust temperature requirements were easier to meet. With the exception of the sewer vector vehicles where the FTF requirements were meet at a lower percentage. The pattern showed by the DPF and FTF are presented in Figure 2. Dump/plow and flatbed trucks duty cycles were most amenable to the use of these passive DPFs, followed by sweepers and service trucks with 50% to 67% of the vehicles achieving the regeneration temperatures. Aerial lifts and cranes showed the lowest feasibility to use retrofit devices along with tractor trucks, although there was only one of the later.

Table 5. Summary Results.

No. of Veh	Lev.	3	3	3	3	3	2		3	1
	Required minimum temperatures and frequencies									Min
	C	T1	T2	T3	T4	T5	T6	T7	T2&T7	Max
	%	210	225	260	260	280	300	300	100	500
		40	50	25	40	25	7	10		
By Vehicle Type										
Dump Truck	16	56%	6%	31%	6%	19%	81%	56%	6%	100%
Dump/Plow Truck	3	100%	100%	100%	33%	100%	100%	100%	100%	67%
Sweeper	8	63%	50%	63%	38%	38%	63%	50%	50%	100%
Tractor Truck	1	0%	0%	0%	0%	0%	0%	0%	0%	100%
Sewer Vactor	5	60%	0%	40%	0%	20%	40%	40%	0%	100%
Service Truck	3	67%	67%	67%	33%	67%	67%	67%	67%	100%
Flatbed Truck	2	100%	100%	100%	100%	100%	100%	100%	100%	100%
Aerial Lift Truck	5	20%	20%	20%	20%	20%	60%	60%	20%	80%
Crane	2	0%	0%	0%	0%	0%	0%	0%	0%	100%
By Engine Manufacturer										
Caterpillar	25	60%	20%	40%	16%	24%	64%	44%	20%	100%
Cummins	11	45%	36%	55%	18%	45%	64%	64%	36%	100%
International	1	100%	100%	100%	0%	100%	100%	100%	100%	100%
Navistar	8	50%	38%	38%	38%	38%	75%	75%	38%	75%
By Model Year										
1988-1993	5	40%	40%	40%	40%	40%	60%	60%	40%	80%
1994-2002	38	58%	26%	45%	16%	32%	68%	55%	26%	97%
2002-2006	2	50%	50%	50%	50%	50%	50%	50%	50%	100%
All the vehicles										
% meeting conditions	45	56%	29%	44%	20%	33%	67%	56%	29%	96%

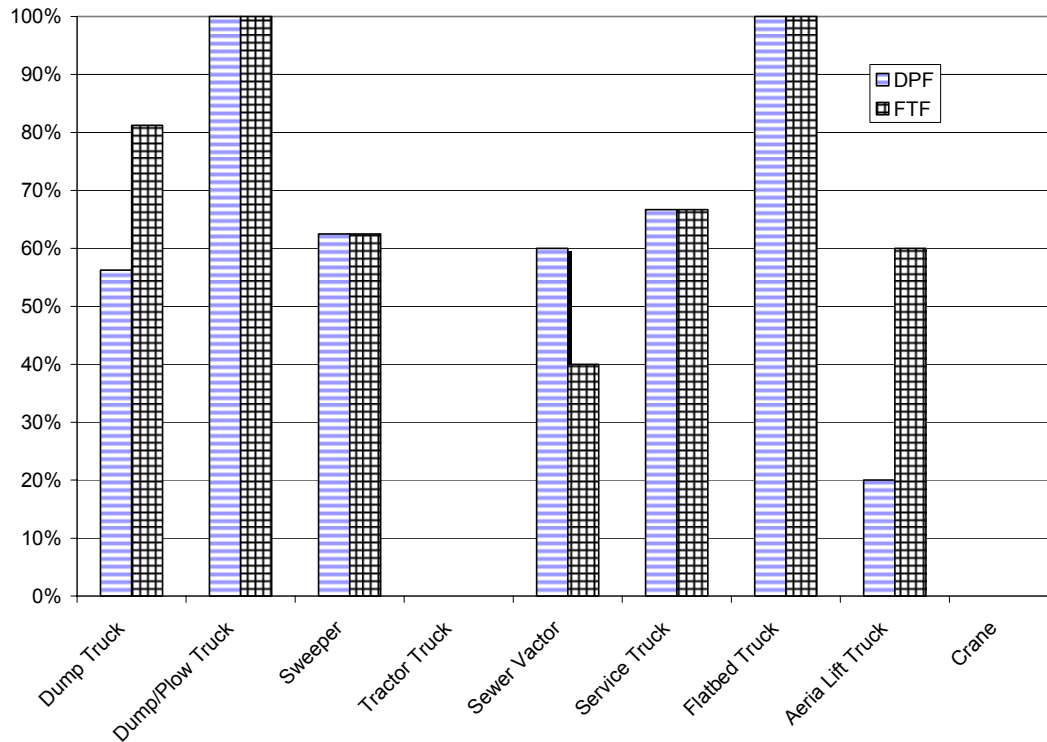


Figure 2. Results by Vehicle Type.

b. Analysis By Engine Type and By Model Year

Cummins and Caterpillar engines comprise the greatest percent of test vehicles. Out of 45 vehicles with useful data, 36 had Cummins or Caterpillar engines. Of the Caterpillar engines, 60% achieved the DPF engine exhaust temperature requirements followed by the Cummins engines with 55% and the Navistar engines with 50%. The single International engine achieved almost all the requirements studied with the exception of one of them at 260 C. The majority of the engines achieved the conditions required for the FTF (Table 5).

The majority of the vehicles were in the group 1994 to 2002 which indicated that a DPF could be utilized in 58% of the vehicles, and an FTF could be utilized in 68% of the vehicles. Vehicles from 1988 to 1993 showed similarities for DPF technologies at 40%, whereas the group of two newer sweepers from 2003 was split by half, one achieving all the requirements and the other not. The majority of the vehicles could use the FTF.

The results from the 45 individual vehicles with useful data that meet the specific thresholds of required temperature parameters are presented in Table 6.

B. Implications for Public and Utility Vehicle Fleet Retrofit Feasibility

The results suggest DPFs may not be able to be used on the full number of vehicles in the verified engine families without significant assistance in increasing the engine exhaust temperature through greater catalysis, using pipe insulation, or locating the DPF closer to the engine. For the FTF technology, the data indicate that this technology may be feasible for a much higher percentage of vehicles, as high as 67 percent. Dump, dump/plow, service, and flatbed trucks, as well as specialized vehicles like sweepers appear to be most suitable to application of either the passive DPF or FTF. Active DPFs where an external heat source is used to regenerate the DPF may be the choice for public and utility vehicles when the exhaust do not generate enough heat to use passive DPFs.

III. References

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TIAX LLC, California Public Fleet Heavy-Duty Vehicle and Equipment Inventory, a report to the California Air Resources Board. March 17, 2003

Table 6. Vehicle Results.

Vehicle Type	Model Year	Required minimum temperatures and frequencies									Min
		T0	T1	T2	T3	T4	T5	T6	T7	T2&T7	Max
		C %	180 55	210 40	225 50	260 25	260 40	280 25	300 7	300 10	100 500
Tractor Truck	1996	0	0	0	0	0	0	0	0	0	1
Dump Truck	1988	1	1	1	1	1	1	1	1	1	1
Dump Truck	1997	0	0	0	0	0	0	1	0	0	1
Sweeper	2002	1	0	0	0	0	0	0	0	0	1
Crane	1999	1	0	0	0	0	0	0	0	0	1
Sweeper	2002	1	1	1	1	0	0	1	1	1	1
Dump Truck	2000	1	1	0	0	0	0	1	0	0	1
Dump Truck	2000	1	1	0	0	0	0	1	1	0	1
Dump Truck	1997	0	0	0	0	0	0	0	0	0	1
Knuckle Boom	1991	0	0	0	0	0	0	0	0	0	1
Sweeper	1997	1	1	0	1	0	0	1	0	0	1
Dump Truck	2001	1	1	0	0	0	0	1	1	0	1
Lift Aerial Boom	1989	1	0	0	0	0	0	1	1	0	1
Sweeper	2002	0	0	0	0	0	0	0	0	0	1
Dump Truck	1997	1	1	0	1	0	1	1	1	0	1
Dump Truck	2001	1	1	0	0	0	0	1	1	0	1
Sweeper	2003	0	0	0	0	0	0	0	0	0	1
Sewer Vactor	2002	0	1	0	1	0	0	1	1	0	1
Sewer Vactor	1998	1	1	0	0	0	0	0	0	0	1
Sewer Vactor	1997	1	0	0	0	0	0	0	0	0	1
Dump Truck	1997	1	1	0	0	0	0	1	0	0	1
Dump Truck	1997	1	1	0	1	0	0	1	1	0	1
Lift Boom Truck	1992	0	0	0	0	0	0	0	0	0	1
Service Truck	2000	0	0	0	0	0	0	0	0	0	1
Boom Truck	2001	0	0	0	0	0	0	0	0	0	1
Dump Truck	2002	0	0	0	0	0	0	1	0	0	1
Dump Truck	2002	0	0	0	0	0	0	0	0	0	1
Dump Truck	2002	1	1	0	1	0	1	1	1	0	1
Sweeper	2002	1	1	1	1	1	1	1	1	1	1
Sevice Crew Cab	2001	1	1	1	1	0	1	1	1	1	1
Sevice Crew Cab	2001	1	1	1	1	1	1	1	1	1	1
Flatbed Truck	2002	1	1	1	1	1	1	1	1	1	1
Sweeper	2003	1	1	1	1	1	1	1	1	1	1
Dump Truck	2001	1	0	0	1	0	0	1	1	0	1
Flatbed Truck	2002	1	1	1	1	1	1	1	1	1	1

Table 6. Vehicle Results (continued).

Vehicle Type	Model Year	Required minimum temperatures and frequencies									Min
		T0	T1	T2	T3	T4	T5	T6	T7	T2&T7	Max
		C	C	C	C	C	C	C	C	C	C
		180	210	225	260	260	280	300	300		100
		55	40	50	25	40	25	7	10		500
Dump Truck	2001	0	0	0	0	0	0	1	1	0	1
Dump Truck	2001	0	0	0	0	0	0	0	0	0	1
Sewer Vactor	2002	1	1	0	1	0	1	1	1	0	1
Sewer Vactor	2001	0	0	0	0	0	0	0	0	0	1
Sweeper	2002	1	1	1	1	1	1	1	1	1	1
Lift Aerial Truck	1995	0	0	0	0	0	0	1	1	0	1
Lift Aerial Truck	1996	1	1	1	1	1	1	1	1	1	0
Dump/Plow Trk	1992	1	1	1	1	1	1	1	1	1	0
Dump/Plow Trk	2001	1	1	1	1	0	1	1	1	1	1
Dump/Plow Trk	2001	1	1	1	1	0	1	1	1	1	1
% meeting conditions		64%	56%	29%	44%	20%	33%	67%	56%	29%	96%