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Urea-SCR System Demonstration and Evaluation for Heavy-Duty Diesel Trucks: Phase I, Preliminary Emissions Test Results and Cost-Effectiveness Analysis

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Abstract - As Phase I of a urea selective catalyst reduction (urea-SCR) demonstration and evaluation project, the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) has conducted engine dynamometer emissions tests on the Siemens-Westinghouse urea-SCR system, SINOx™. ITS-Davis also conducted a preliminary cost-effectiveness estimate for urea-SCR technology, in general. ITS-Davis and its partners Freightliner Corporation, Detroit Diesel Corporation, and Siemens-Westinghouse conducted engine dynamometer testing of the SINOx System on the Federal Test Procedure (FTP) using certification diesel fuel. The SINOx System achieved 1.0 g/bhp-hr NOx emissions on the FTP on a 1999 DDC Series 60 engine. The system achieved a 73% reduction from the engine baseline emissions of 3.67 g/bhp-hr on the FTP. There was no measurable effect on fuel economy. Probable limitations of the current generation SINOx demonstration system include size, weight, and the potential for tampering. The cost-effectiveness of SCR technology for 2000 model year HDDVs is estimated at less than $2,000 per ton of NOx removed for new vehicle applications. ITS-Davis is currently evaluating potential barriers to SCR implementation including fleet resistance to adding an additional fluid (urea) and the need for special urea fueling infrastructure. Phase II of the SCR demonstration and evaluation project, scheduled to begin in January 2000, will address durability, consumer acceptance, tampering, catalyst effect on PM size distribution, cost, and on-road emissions levels.

INTRODUCTION

Heavy-duty diesel trucks and buses are major contributors to the oxides of nitrogen (NOx) emissions inventory. Heavy-duty diesel trucks contribute 30 percent of NOx from on-road vehicles in the State of California, even though these vehicles comprise approximately 2 percent of California's on-road vehicle fleet and accumulate 4 percent of the vehicle miles traveled (*1*). Heavy-duty diesel vehicles (HDDVs) will continue to be major contributors of NOx emissions. California Air Resources Board (ARB) estimates that between 1990 and 2010, the number of trucks will increase by 70% and vehicle miles traveled will increase by 60% (*2*). ARB will use a combination of lower emissions standards for new HDDVs and reduced emissions from in-use HDDVs to meet NOx attainment. Research by the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) indicates that urea selective catalyst reduction systems (urea-SCR) have the potential to meet increasingly stringent future HD emissions certification standards for new vehicles. An analysis of the retrofit potential of the systems is on-going. This paper presents the results of Phase I of ITS-Davis' urea-SCR demonstration and evaluation: engine dynamometer emissions test results, a technical assessment, and a cost-effectiveness estimate.

BACKGROUND

Diesel Aftertreatment

In addition to SCR, there are three other aftertreatment technologies to significantly reduce NOx emissions from HDDVs: lean NOx catalysts, NOx adsorbers, and plasma catalysts. SCR systems and NOx adsorbers have the greatest NOx emissions reduction potential of 60-90%. (*3, 4, 5*). SCR systems have the potential of 70-90% reduction with certification diesel fuel (*5*). NOx adsorber systems have the potential of 70-90% NOx reduction when fuel sulfur is less than 50 ppm (*3*). However, sulfur levels less than 10 ppm may be necessary to lengthen the service life of the catalyst. It is not possible to use NOx absorbers with the current diesel fuel since the rhodium catalyst increases sulfate PM at high temperature, and the sulfur poisons the catalyst.

Due to similar limitations, lean NOx catalysts require low sulfur fuel. Furthermore, the NOx reduction potential of lean NOx catalysts is low to begin with - in the 15-30% range (*4*). Plasma catalysts are a potential NOx reduction option, but a relatively new application. Preliminary results indicate their efficiency will be less than 50% and the energy consumption is a minimum of 5% of fuel consumption (*6*), thus making plasma catalysts inferior to NOx adsorbers and SCR. With current diesel sulfur levels for on-road in the U.S. in the range of 350-500 ppm, SCR is very promising for meeting the more stringent standards proposed for the future.

Urea-SCR Technology

Urea-SCR systems have been used to control NOx in stationary power plants since the mid-1970's. In the late 1980's, European Truck manufacturers, DaimlerBenz (now DaimlerChrysler), MAN, and IVECO began pursuing urea-SCR as an exhaust gas after-treatment strategy for trucks. A urea-SCR system was demonstrated on a light-duty diesel vehicle in 1995 (*7*). At the same time, TNO conducted heavy-duty diesel engine urea-SCR system tests in the Netherlands (*8*). In 1999, Siemens-Westinghouse reported on a 3 years on-road demonstration with heavy-duty diesel truck in commercial operation in Europe (*9*). Several companies, such as Siemens-Westinghouse, Johnson

Matthey, Engelhardt and others are currently investigating heavy-duty truck applications in the U.S. and Europe (*5, 9, 12*).

UREA-SCR SYSTEM PERFORMANCE

Emissions Reductions

SCR technologies utilize ammonia (NH_3) to reduce NOx to nitrogen and water in the presence of a metal oxide catalyst that is not sensitive to sulfur. Since ammonia is toxic and flammable, the urea-SCR systems commonly uses aqueous urea ($CO(NH_2)2$) to obtain the ammonia. Urea is non-toxic and non-flammable. The urea is injected into the exhaust gas of the engine, where the urea forms ammonia and carbon dioxide through hydrolysis. Next, the exhaust passes through the catalyst where the ammonia and the NO_x react to molecular nitrogen (N_2) and water vapors (H_2O). Injection into the exhaust is managed with an electronic control unit that is connected to the electronic engine management system.

Urea injection must be controlled to correspond with the amount of NOx in the exhaust at a given time. It is possible to inject excess urea to assure maximum NOx conversion; however, this results in unreacted ammonia being released. This excess ammonia is referred to as "slip". Since ammonia is toxic and limits are placed on human exposure, it is essential to minimize slip. In stationary, indoor applications, the acceptable level of exposure for an 8 hour workday is 50 ppm of ammonia. Acceptable levels of slip from SCR systems are being evaluated by regulators, but the maximum, based on ITS-Davis discussions with California Air Resources Board, will likely be somewhere between 50-30 ppm on the Federal Test Procedure (FTP).

Urea-SCR technologies have been demonstrated to reduce NOx emission from 4 g/bhp-hr NOx on a 1998 engine to between 1.2-1.5 g/bhp-hr on the FTP transient cycle using certification diesel fuel (*10*). This is approximately a 66% reduction. A greater than 70% emissions reduction was measured for off-cycle emissions reductions using a 13 Mode test (*10*). A combination oxidation catalyst, particulate filter, SCR catalyst configuration has achieved 0.7 g/bhp-hr NOx on the FTP with a 1999 DDC Series 50 engine. However, this requires low sulfur fuel (*12*).

To date, the Siemens-Westinghouse urea-SCR system is the first SCR system reported to achieve less than 1 g/bhp-hr NOx emissions on the FTP using certification diesel fuel. Using a 1999 Detroit Diesel Series 60 HD diesel engine equipped with a 1999 SINOx system, a Siemens-Westinghouse, Detroit Diesel Corporation, ITS-Davis Team conducted engine dynamometer testing on the Federal Test Procedure (FTP) using certification diesel fuel. With the exception of the FTP cold start test, each test was replicated three times to assure consistency in the data. Table 1 presents the exhaust emission results for the engine baseline FTP runs and their average values. Seven pollutant measurements were conducted for FTP tests: NOx, hydrocarbons (HC), particulate matter (PM), the volatile organic fraction of particulate matter (VOF PM), carbon monoxide (CO), carbon dioxide (CO_2), and NH_3. Table 2 presents the exhaust emission results for the one cold and three hot FTP runs with the optimized SINOx calibration and certification fuel. Table 3 presents the Composite FTP results. The optimized SINOx after treatment system is capable of reducing NOx by more than 73% on the FTP cycle and the target of less than 1.0 g/bhp-hr of NOx is achieved with an average of 4.4 ppm of ammonia slip per cycle.

TABLE 1. Engine Baseline Emissions on the Hot FTP

	NOx g/bhp-hr	HC g/bhp-hr	PM g/bhp-hr	PM VOF g/bhp-hr	CO g/bhp-hr	CO_2 g/bhp-hr
Baseline Hot 1	3.68	0.236	0.0882	0.0208	1.105	604
Baseline Hot 2	3.67	0.231	0.0836	0.0224	1.093	604
Baseline Hot 3	3.68	0.238	0.0833	0.0229	1.072	605
Average Hot Baseline	3.67	0.235	0.0850	0.0220	1.090	604

TABLE 2 Engine Emissions on the Cold and the Hot FTP with the SINOx System

	NOx g/bhp-hr	HC g/bhp-hr	PM g/bhp-hr	PM VOF g/bhp-hr	CO g/bhp-hr	CO_2 g/bhp-hr	NH_3 ppm/cycle
Cold FTP 1	1.47	0.0416	0.0817	0.0074	1.75	588	13.7
Hot FTP 1	0.898	0.0225	0.0672	0.0073	1.31	586	2.8
Hot FTP 2	0.827	0.0016	0.0663	0.0069	1.30	584	2.9
Hot FTP 3	0.847	0.0224	0.0662	0.0069	1.29	584	2.9

TABLE 3 Engine Emissions on the Composite FTP

	NOx g/bhp-hr	HC g/bhp-hr	PM g/bhp-hr	PM VOF g/bhp-hr	CO g/bhp-hr	CO_2 g/bhp-hr	NH_3 ppm/cycle
Composite FTP	0.980	0.0252	0.0693	0.0073	1.37	586	4.4

Although NOx emissions reductions were the primary goal of the SINOx system, the system also reduces PM and HC. On the hot-FTP, the SINOx system achieved greater than 20% reduction in total particulate and a greater than 60% reduction in the VOF of PM. A hydrocarbon reduction of greater than 90% was observed on the hot FTP. During dynamometer tests there was occasional urea injector clogging. Evaluation of this will be conducted during the demonstration of the field-ready systems.

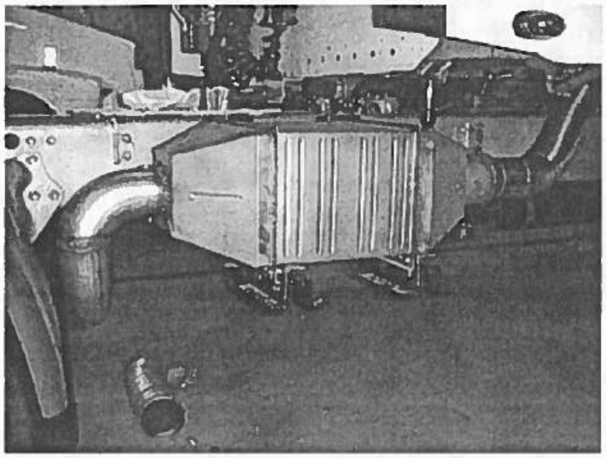
Limitations

As can be seen from the bench test results, the SCR system achieves less reduction on the FTP cold start tests. This is because SCR catalyst light-off temperatures are around 200 C (*5*). Some engines have exhaust temperatures below this at certain low load operations, such as idling. This is not a problem for modern, long-haul trucking vehicle applications, but it could be a difficulty for other applications.

The weight and size of the catalyst system are additional factors to consider when evaluating this technology. Weight of the catalyst system is dependent upon the catalyst size, composition, fuel tank parameters, and amount of urea fuel. The SINOx catalyst which achieved the reductions discussed above is shown in Figure 1 on the Freightliner Pilot Test Truck being used by ITS-Davis for on-road emissions and durability testing. The truck is equipped with two 100 gallon diesel tanks. A split diesel-urea fuel tank (not pictured) is used on one side, with the diesel tank remaining 100 gallons, and the urea portion of the tank being 20 gallons. Since urea consumption is estimated at 4 to 5% of diesel consumption for the SINOx system, this tank is sufficient for approximately 400 gallons of diesel usage. This allows the trucker to replenish urea during every other diesel refueling, and hence could require less urea refueling infrastructure. For the 1999 model year, Class 8 vehicle with 20 gallon urea tank the SINOx system weight (including the system, fuel tank, and fuel) is between 250-200 lbs.

As opposed to technical limitations, infrastructure and consumer acceptance issues are often regarded as the main impediments to urea-SCR usage. Phase II of the project, scheduled to begin in January 2000, will address infrastructure requirements, durability, consumer acceptance, tampering, catalyst effect on PM size distribution, and on-road emissions levels. Details of Phase II are discussed later in the paper.

FIGURE 1 Catalyst on Freightliner Pilot Truck, a 1999 Century Class



Future Development

The SINOx electronic control unit is referred to as "open loop" because it receives engine sensor output such as speed, torque, and temperature, from the engine management system. A "mapping" processor then correlates these engine sensor values with corresponding emission values. Algorithms are used to relate the predictive emission monitoring system (PEMS) values from the "map" to the required reducing agent quantity. PEMS control is dependent on receiving all variable parameters influencing the NOx mass flow in transient and steady-state information. Currently, all this information is not available on the data bus.

Potential SCR improvement strategies that would optimally reduce NOx, regardless of engine operating condition, include improving the urea injection system by integrating the urea injection controller with the engine control unit. Several companies are investigating NOx and ammonia sensors. These could be used to create a closed loop system that would control urea injection based on measured NOx and ammonia values. Integrating the urea injection control into the engine controller would likely further improve NOx reduction.

Retrofit of open-looped systems to in-use trucks is challenging because it would be necessary to calibrate the SINOx system for each specific engine model. However, emissions reductions for in-use vehicles are not likely to be as demanding as the 1 g/bhp-hr target used for this study. Addition of an oxidation catalyst to reduce excess ammonia emissions, is one possibility that is being investigated (*12*). Disadvantages include the formation of sulfates, potential of NO_2 formation, additional backpressure, cost, and weight. As with new engine applications, development of NOx and ammonia sensors for a closed-loop system could greatly enhance performance of the SCR system in retrofit applications. A retrofit study is part of ITS-Davis Phase II of testing.

COST-EFFECTIVENESS

Cost-effectiveness of urea-SCR systems depends on factors such as NOx-reduction performance, catalyst lifetime, component materials, and largely the production volume. Data for the cost-effectiveness estimate were obtained from catalyst manufacturers as well as testing overseen by ITS-Davis. All cost estimates are conducted for Class 8 (Gross Vehicle Weight of 33,000 to 80,000) HDDVs. This class of truck was chose because Class 8 trucks account for half of all new HD truck and bus sales (*14*). Because Class 8 trucks are predominantly line-haul trucks, they accumulate the most mileage of any class of truck. Class 8 also includes buses, which contribute considerably to urban air pollution.

Table 4 presents a preliminary cost-effectiveness calculation for application of urea-SCR to new 1999 Class 8 vehicles that accumulate 120,000 miles per year. The assumptions made in this analysis are footnoted. Shaded values in the table represent calculated, as opposed to assumed, values.

TABLE 4 Cost-Effectiveness Estimate for Application of Urea-SCR Systems to 1999 Model Year Heavy-Duty Diesel Vehicles

Scenario	Units	FTP Operation
1999 engine NOx emissions [a]	g/bhp-hr	4.00
Conversion [b]	bhp-hr/gal	14.30
NOx emissions	g/gal	57
Annual Miles driven [c]	mi/yr	120,000

Specific fuel economy highway [d]	mi/gal	5.5
Annual fuel consumption	gal/yr	21,818
Annual NOx emissions	g/yr	1,248,000
Specific diesel fuel cost [e]	$/gal	1.05
Annual fuel operating cost	$/yr	22,909
Fuel cost per mile	$/mi	0.191
Aqueous urea consumption as percent of fuel consumption [f]	%	4
Annual aqueous urea consumption	gal/yr	873
Specific aqueous urea cost [g]	$/gal	1
Annual Urea Cost	$/yr	872.73
Specific aqueous urea economy	mi/gal	137.50
Urea cost per mile	$/mi	0.007
Typical NOx-reduction for Highway Operation [h]	%	73
Controlled specific NOx emission, highway operation	g/bhp-hr	1.08
Annual controlled NOx emission	g/yr	336960
Annual NOx reduction	g/yr	911040
Useful life/ minimum design performance lifetime [i]	miles	500,000
Calculated lifetime in years based on 500,000 mile performance	years	4.17
HD truck urea SCR system capital cost [j]	$	2,000
Reducing agent cost over useful life	$	3,636
Cost of operation & maintenance, labor, wear & tear, spares over useful life [k]	$	1,500
Installation cost [k]	$	500
Total cost over useful life	$	7,636
Total NOx reduction over useful life	US tons	4.18
NOx-reduction cost effectiveness	$/ ton	1825

[a] The pre-aftertreatment, baseline NOx emissions level of 4.0 g/bhp-hr emissions is used for the FTP. Actual on-road NOx emissions have been found to be much higher than 4.0 g/bhp-hr due to many 1990-1998 HD engines being programmed to optimize for fuel economy when operating on-road and due to on-road operation differing from FTP operation (*18*). However, since the emissions levels for the SCR systems are determined from Federal Test Procedure testing, the baseline emissions used in this cost-effectiveness estimate were chosen to be consistent with actual baseline engine emissions measurements on the two tests. One assumption made is that the baseline emissions as well as the emissions reduction are assumed constant for the life of the catalyst. Realistically, we expect to see some degradation in the SCR emissions reduction over 5 years. Degradation in baseline emissions is also anticipated, but it is not included due to insufficient data.

[b] The bhp-hr/gal conversion factors were based on Carl Moyer Program, California's heavy-duty NOx reduction incentive program, guidelines. To obtain the bhp-hr/gal conversion, the fuel economy of the truck is multiplied by the factor of 2.6 bhp-hr per mile. This 2.6 g/bhp-hr was developed by ARB specifically for heavy-duty trucks based on their driving cycle. The 3.5 bhp-hr/mi conversion factor traditionally used by the Environmental Protection Agency was developed from limited testing of a bus and three trucks. Comparison of the EPA conversion factor with those determined at Colorado School of Mines indicate that conversion factors should be developed for a variety of trucks and from in-use as opposed to new vehicles (*19*).

[c] Based on data from the fleet ITS-Davis is working with, the average annual mileage for long-haul vehicles is approximately 120,000 mi/yr for the first four years. This is slightly higher than the 100,000 mile per year average for newer long-haul trucks found in the 1992 Truck Inventory and Use Survey (TIUS) (*15*).

[d] Fuel economy for 1999 model year trucks was determined from the Freightliner Corporation and the test fleet used for this study (*20*). Average fuel economy for 1999 vehicles being tested was reported as 5.5 miles per gallon.

[e] A diesel fuel cost of $1.05 per gallon was assumed.

[f] An average urea consumption level of 4% of the diesel was measured when the system was demonstrated in Europe (*9*).

[g] The urea cost estimate is based on the current cost of SCR grade urea (this requires a higher level of purity than does fertilizer grade urea), and would likely decrease if used in greater quantity. Hydro and Carhill Corporation have supplied the urea for SCR trials at $1.00 per gallon. The Manufacturers of Emissions Controls Association (MECA) estimates that the market cost of urea for wide-spread use would be $0.75 per gallon (*10*).

[h] NOx emissions reduction estimates are based on Phase I testing conducted by Detroit Diesel Corporation, Siemens-Westinghouse, and ITS-Davis. The emissions reduction is effected largely by the driving cycle and the calibration of the SINOx control unit. A 73% reduction was measured on the FTP test when the SINOx controller was calibrated for optimal performance on this test.

[i] The design life of a SINOx catalyst is 500,000 miles. The SINOx catalysts have thus far accumulated over 300,000 miles in Germany. The 500,000 miles is the same catalyst life estimated by the MECA as well as Siemens Westinghouse (*10*).

[j] The $2000 capital cost of system is estimated from the MECA study (*10*). This is for an annual supply of 26,000 systems and an industry-wide production volume of 220,000 systems. This is within 75% of the Engine, Fuels, and Emissions (EFEE) estimate for EPA (*5*).

[k] Maintenance and installation cost estimates were made by ITS-Davis.

DISCUSSION OF COST-EFFECTIVENESS

From Table 4, the cost-effectiveness of the system is in the range of approximately $1800 per ton of NOx removed on the FTP. This is well within the guidelines for Carl Moyer Program, California's heavy-duty NOx reduction incentive program, which requires a cost-effectiveness of $12,000 per ton of NOx removed using a baseline NOx emissions level of 6.0 g/bhp-hr. On-road emissions test will be conducted to quantify the baseline emissions and emissions reductions achieved in realistic operation of long-haul trucks.

The estimate does not, however, include the additional cost of the urea infrastructure. Based on estimates from several service supply companies, the cost of adding urea supply infrastructure for this demonstration project is estimated at $19,000. This includes adding a urea pump, 5000 gallon double-walled urea storage tank, piping and electronics, and an electronic key-card access controller to the existing fuel island. For a 50 truck fleet, with 3 tons emissions reduction per truck over the life of the catalyst, this cost is an additional $126 per ton of NOx removed. It should also be noted that the maintenance and repair costs are estimates from research and development programs, and need to be confirmed for U.S. operation of 500,000 miles.

PHASE II

The second phase of the project entails a three year on-highway demonstration of a set of ten, Freightliner Class 8 heavy-duty diesel vehicles. ITS-Davis' main purpose is to conduct an independent and objective evaluation of the potential of the SINOx Urea-SCR System to achieve extremely low emissions while maintaining good fuel economy for heavy-duty diesel engines in mobile on-road applications in California. The test vehicles are part of the Valley Material Transport fleet based in French Camp, California. Performance of the SINOx System will be tested under realistic on-road operating conditions, using on-road emissions measurement techniques as well as traditional dynamometer testing. All of the trucks will be equipped with advanced data-loggers that will provide second-by-second fuel flow, urea flow, air mass flow rate, vehicle speed, engine speed, engine torque, manifold inlet temperature, air inlet (ambient) temperature, and barometric pressure. These data will be used for evaluating truck operation as well as developing emissions models. Chassis dynamometer testing will be conducted at the California Truck Testing Service (CaTTs) in Richmond, California, and on-road testing will be conducted by the Environmental Protection Agency using their trailer-based continuous emissions test facility.

In addition to emissions and fuel economy testing, ITS-Davis' comprehensive study will investigate trucking industry acceptance, infrastructure needs, technical feasibility, cost-effectiveness, a comparison with competing technologies, and an analysis of urea infrastructure supply issues and costs. The general objectives of Phase II of the program are as follows:

- Evaluate the technical and operational viability of the SINOx Urea-SCR System.

- Fully investigate the NO_x, ammonia, N_2O, PM, and hydrocarbon (HC) emissions quantities, as well as, PM and HC chemical characteristics.

- Complete a study of the influence of the SINOx technology on engine life and maintenance costs.

- Carry out a cost-effectiveness study of the SINOx System. This study will include the capital cost of the SINOx System, urea consumption costs, fuel savings, payback period, and other operating variables. Analysis of infrastructure, system installation, urea consumption costs versus fuel savings, and the benefits of emission regulation compliance will determine the timeline for the net benefit of the urea system.

- Assess the system's adaptability to U.S. trucks, as well as, its reliability and durability.

- Conduct a safety and risk analysis of preventive measures associated with tampering of the SINOx System.

- Evaluate the training needs and acceptance of vehicle operators and fleet personnel. In-person training and interviews will be done prior to installation of the systems, and focus groups will be conducted after the SINOx System is in place to add to information on the commercial viability and market acceptance of the systems. Feedback can reveal difficulties and complications in system utilization that could be addressed prior to introduction of the system to the market.

- Verify and quantify the emission reductions and fuel savings that were obtained in the European tests, and ascertain that similar reductions are possible for U.S. operation.

- Conduct research. Perform transient cycle and steady state test analysis of the SINOx Urea-SCR System. Model emissions formation in the modern HDD vehicle. Explore the relevant technologies and policy implications of the SINOx Urea-SCR System.

Further details of the planned testing can be found in a Society of Automotive Engineers Paper, 1999-01-3722 (*11*).

CONCLUSIONS

The advantage of urea-SCR systems over competing aftertreatment technologies, is that urea-SCR does not require low sulfur fuel. The Siemens-Westinghouse urea-SCR system, SINOx, achieved 1.0 g/bhp-hr NOx emissions on the FTP on a 1999 DDC Series 60 engine. Significant hydrocarbon and particulate emissions reductions were also measured. This indicates the SINOx system in combination with the DDC Series 60 would likely meet tougher, more stringent NOx emissions standards in the future; however, in-use performance is still under evaluation. Factors such as size, weight, and resistance to tampering will likely be factors in the commercialization of these SCR systems. The likely obstacles to implementation of any SCR system are fleet resistance to adding yet another fluid (urea) and the need for special urea fueling infrastructure. Excluding infrastructure costs, the cost-effectiveness of SCR technology for 2000 model year HDDVs is estimated at under $1800 per ton of NOx removed for new vehicle applications. Phase II of ITS-Davis' SCR demonstration and evaluation project, scheduled to begin in January 2000, will address durability, infrastructure needs, consumer opinion, tampering, catalyst effect on PM size distribution, and on-road emissions levels.

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