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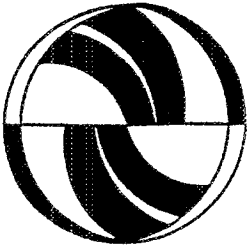
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### Authors

Brodrick, C. J.  
Farshchi, M.  
Dwyer, H. A.  
[et al.](#)

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C J Broderick  
M Farsh-chi  
H A Dwyer  
Daniel Sperling  
S W Grouse  
W Doelling  
J Hoelzer  
M Jackson

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University of California  
Transportation Center

108 Naval Architecture Building  
Berkeley, California 94720  
Tel. 510/643-7378  
FAX. 510/643-5456

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**C.J. Brodrick  
M. Farsh-chi  
H.A. Dwyer  
Daniel Sperling**

Institute of Transportation Studies  
University of California  
Davis, CA 95616

**S.W. Grouse**  
Freightliner Corporation

**W. Doelling**  
Siemens AG

**J. Hoelzer**  
Detroit Diesel Corporation

**M. Jackson**  
ARCADIS, Geraghty, and Miller

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# Urea-SCR System Demonstration and Evaluation for Heavy-Duty Diesel Trucks

**C. J. Brodrick, M. Farsh-chi, H. A. Dwyer and D. Sperling**  
Institute of Transportation Studies, University of California, Davis

**S. W. Gouse**  
Freightliner Corporation

**W. Doelling**  
Siemens AG

**J. Hoelzer**  
Detroit Diesel Corporation

**M. Jackson**  
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## ABSTRACT

The Institute of Transportation Studies at the University of California, Davis (ITS-Davis) has brought together a group of public and industrial partners to demonstrate and evaluate the Siemens-Westinghouse Urea-Selective Catalyst Reduction System (SINOx™). The SINOx System has the potential to generate major reductions in nitrogen oxides (NO<sub>x</sub>) and the volatile organic fraction (VOF) of particulate (PM) from heavy-duty diesel engines, without increasing fuel consumption and carbon dioxide (CO<sub>2</sub>) emissions. This demonstration began with engine bench testing at Detroit Diesel Corporation to calibrate the system to attain 1 g/bhp-hr NO<sub>x</sub> emissions in the transient portion of the US-FTP on a 1999 Series 60 engine that has a 4 g/bhp-hr emission level. The second phase of the project entails an on-highway demonstration of a set of ten, Freightliner Class 8 heavy-duty diesel vehicles. These 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. In addition to emissions and fuel economy testing, a comprehensive study will investigate trucking industry acceptance, infrastructure needs, technical feasibility, and cost-effectiveness of the system. This evaluation is funded by San Joaquin Valley Unified Air Pollution Control District, Sacramento Air Pollution Control District, and California Air Resources Board.

## INTRODUCTION

To address growing concerns about emissions of nitrogen oxides (NO<sub>x</sub>), and particulate matter (PM), the U.S. Environmental Protection Agency (EPA) and the European Community have proposed increasingly strict NO<sub>x</sub> and PM diesel engine emissions standards (1,2). The U.S. EPA estimates that trucks emit approximately 2 million tons/year of NO<sub>x</sub>, not including off-cycle NO<sub>x</sub>, which in 1998 was an additional 1.3 million tons (3). The 2004 NO<sub>x</sub>-HC emission standard of 2.4 g/bhp-hr now scheduled for fifteen months earlier, represents a substantial reduction from the current 4 g/bhp-hr NO<sub>x</sub> standard on the U.S. Federal Test Procedure (FTP) (4). However, some of these emissions reductions will be offset by increases in the number of trucks and vehicle miles traveled. California Air Resources Board (CARB) estimates that between 1990 and 2010, the number of trucks will increase by 70% and vehicle miles traveled will increase by 60% (5).

Some other emissions reduction technologies may be hindered by decreases in fuel economy. The trucking industry is concerned that the engine calibration changes necessary to achieve the NO<sub>x</sub> reduction will increase fuel consumption and costs considerably. Also, fuel economy penalties may be incurred if emissions reduction technologies, such as exhaust gas recirculation (EGR), are adopted to meet future standards.

To overcome this tradeoff between fuel economy and NO<sub>x</sub>, European Truck manufacturers, DaimlerBenz (now DaimlerChrysler), MAN, and IVECO, set new objectives for themselves in early 1990 minimize fuel consumption, lower CO<sub>2</sub> and PM emissions, while also reducing NO<sub>x</sub> emissions at a reasonable truck operating cost. Urea-SCR technology was found to be the most promising exhaust gas after-treatment technology. The urea-SCR System injects aqueous urea into the exhaust flow. The urea acts as the reducing agent in the catalytic process. A more detailed description of the SINO<sub>x</sub> System is included in the appendix. While aimed primarily at reducing NO<sub>x</sub>, this process also converts some of the volatile organic fraction (VOF) of PM and hydrocarbons (HC). Thus, species identified as air toxics by CARB, such as polycyclic aromatic hydrocarbons (PAH) may be reduced.

After six years of testing and close to \$20 million in research and development, European diesel truck manufacturers, DaimlerChrysler and MAN, asked Siemens-Westinghouse in 1998 to prepare the SINO<sub>x</sub> System for production. Several European and U.S. companies are developing similar technologies, but currently the SINO<sub>x</sub> System is the only system ready for commercialization. This development in Europe has led to testing of the system in Germany, with promising findings. Siemens-Westinghouse has performed laboratory and fleet testing of SINO<sub>x</sub> Systems on approximately 20 European Daimler-Chrysler (Mercedes Benz) and MAN heavy-duty Class 8 vehicles. The following reductions were measured in transient testing (FIGE Transient Test Cycle) in Europe: NO<sub>x</sub> 82%, HC 77%, and PM 18% (6). In addition to the large emissions reduction, the test results suggest that the SINO<sub>x</sub> System will have no effect on fuel economy. The SINO<sub>x</sub> System is expected to be commercially available on Daimler-Chrysler and MAN heavy-duty trucks for the model year 2000.

Due to differences between the U.S. and Europe in diesel fuel quality, truck configurations, design specifications, vehicle operating conditions, and travel distances, it is difficult to estimate the actual emissions and fuel consumption effects of this system in the U.S. Thus, it is important to test this system under operating conditions typical of heavy-duty truck usage in the U.S.

## U.S. DEMONSTRATION PROGRAM

The Institute of Transportation Studies at the University of California, Davis (ITS-Davis) has brought together a group of public and industrial partners to demonstrate and evaluate the Siemens-Westinghouse Urea-SCR System (SINO<sub>x</sub>). The partners in the project include Siemens-Westinghouse Corporation, Detroit Diesel Corporation (DDC), Freightliner Corporation, Valley Material Transport, and ITS-Davis. ARCADIS, Geraghty, and Miller has been subcontracted by ITS-Davis to assist in managing the project. The in-use evaluation of SINO<sub>x</sub>

will be conducted over a period of three years with a set of 10 new Class 8 heavy-duty diesel vehicles operating in California. This study has been designed to test the system under realistic field conditions. Funding and responsibilities are organized to allow for an independent and impartial evaluation that can be used by industry and government to properly plan for the near future.

The primary goal of this project is to quantify the changes in emissions and fuel consumption that can be expected in long haul and local truck operations. General objectives of the program are as follows:

- Demonstrate the technical and operational viability of the SINO<sub>x</sub> Urea-SCR System
- Fully investigate the NO<sub>x</sub>, ammonia, di-nitrogen oxide, PM, and hydrocarbon (HC) emissions quantities, as well as, PM and HC chemical characteristics
- Complete a study of the influence of the SINO<sub>x</sub> technology on engine life and maintenance costs, and compare these results with those of competing technologies, such as EGR
- Carry out a cost-effectiveness study of the SINO<sub>x</sub> System. This study will include the capital cost of the SINO<sub>x</sub> System, urea consumption costs, fuel savings, payback period, and other operating variables. Analysis of infrastructure, system installation, and 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 SINO<sub>x</sub> System
- Evaluate the training 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 SINO<sub>x</sub> 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 will 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 in the U.S.

Conduct research. Perform transient cycle and steady state test analysis of the SINOx Urea-SCR System. Explore the relevant technologies and policy implications of the SINOx Urea-SCR System.

## SCOPE OF THE WORK

Siemens-Westinghouse, Freightliner Corporation, and Detroit Diesel Corporation (DDC), have collaborated on integrating the SINOx System into the Freightliner Argosy. DDC, in cooperation with ITS-Davis and Siemens-Westinghouse, performed steady state and transient baseline engine tests on the SINOx System in late August of this year. DDC documented results of engine performance and optimization tests after installation of a SINOx System. Once the system was optimized, DDC recorded emissions, fuel economy, and emission test results. Engine dynamometer emissions testing was conducted following the EPA 13 Mode Test and the FTP transient test, as well as, on several variable load tests (at constant speeds) and a full load test. However, the data analysis was not completed in time for this publication. Test results will be presented at the SAE 2000 Congress.

Currently, an in-field pilot test is being conducted on one vehicle. The external catalyst designs are being finalized based on the pilot testing. In January 2000, the 10 fleet trucks will be fitted with the catalyst at Freightliner's Oregon factory.

Prior to delivery of the retrofit trucks, Hydro Corporation, the urea supplier in the European demonstration, will supply the urea, and Stockton Service Supply will supply the urea infrastructure for this demonstration. The urea will be supplied to the fleet depot. The urea supply system will be integrated into the fleet's current fuel island. Special handling of the urea is not required since it is a non-hazardous organic salt solution commonly used in agriculture as a fertilizer. The urea used in this application is dissolved in demineralized water (based on industrial specifications) resulting in a 32.5% urea solution.

ITS-Davis, Freightliner, and Siemens-Westinghouse will jointly conduct training of the operators in the use of the SINOx Systems. ITS-Davis will design the training for the fleet operators, conduct routine quality assurance checks, and assess the responses to training. ITS-Davis will also establish a diesel and urea fueling protocol, monitor proper system usage, and create procedures and forms for completing fleet logs. ITS-Davis will evaluate the ease of use by the trucking personnel, barriers, and costs.

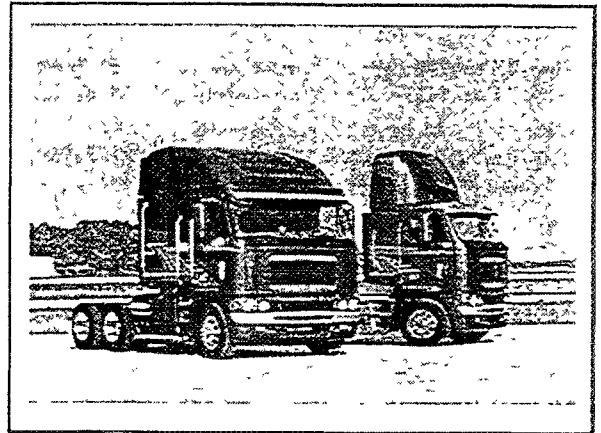
ITS-Davis will have the primary responsibility for emissions testing and field demonstration of the SINOx equipped trucks over a three-year period. The majority

of testing will take place the first year and a half of operation. Deterioration testing will be conducted every six months for the remaining year and a half of the demonstration. 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 low fuel consumption for heavy-duty diesel engines in mobile on-road applications in California. This includes the cost effectiveness, comparison with competing technologies, and analysis of urea infrastructure supply issues and costs.

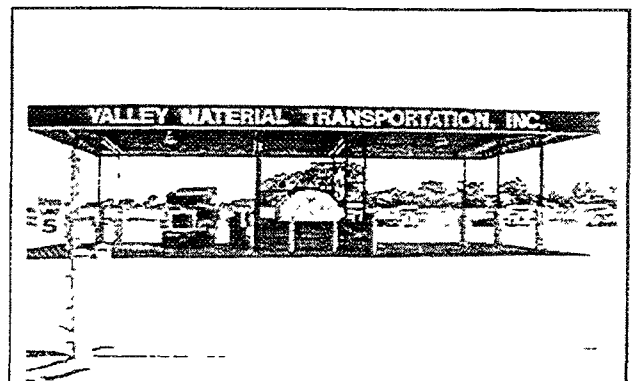
## TEST FLEET

Valley Material Transport operates out of French Camp (Stockton), California carrying construction materials primarily along the I-5 corridor in California and Oregon. The portion of the fleet that will be used for this test consists of 2000 model year Freightliner Argosy trucks with 1999 DDC Series 60 engines (Picture 1). The 10 trucks equipped with the SINOx catalyst as well as 5 control vehicles will travel 120,000 to 220,000 miles per year. The majority of operation is within the San Joaquin Valley Unified Air Pollution Control District, Sacramento Air Pollution Control District, and South Coast Air Quality Management District.

Picture 1 Freightliner Argosy Trucks



Picture 2 Valley Material Transport, Inc



The Valley Material Transport trucks will be identical to the control trucks with the exception of addition of the SINOx System and a urea fuel tank. The urea tank will be approximately 30 gallons and will be split added behind one of the diesel tanks. The specific urea consumption amounts depend on the NOx emissions at specific operating conditions of the diesel engine and may vary from 3-5% of fuel consumption (by volume). Thus, approximately 1 gallon of urea is consumed for every 20 gallons of diesel. The Valley Material Transport trucks have two 100 gallon tanks, so the 30 gallons urea capacity allows for urea to be refilled during every other diesel refueling.

Urea refueling will occur at a single central location, the fleet's French Camp headquarters (Picture 2). The urea fuel supply and pump will be located on the fleet's fueling island adjacent to the diesel pumps. The additional urea tank will be monitored closely to prevent misfueling and assure proper usage. Urea fueling will be controlled with key cards using the same system the fleet has for diesel fuel. A special nozzle has been selected which will prevent diesel from being pumped into the urea tank and vice versa. Urea fuel flow sensors on the truck will allow ITS-Davis to verify that urea is flowing when the trucks are running.

## EMISSION TESTING AND FIELD DEMONSTRATION

ITS-Davis will measure emissions from the test fleet while in operation along their normal routes, as well as on traditional chassis dynamometer cycles. The chassis testing will take place at the California Truck Testing Facility (CaTTS) in Richmond, CA, on a sample of trucks at the beginning and middle of the demonstration. In-use testing is planned using EPA's emissions test trailer, a full emissions measurement laboratory that is housed in a tractor-trailer. During both types (dynamometer and on-road) of testing, vehicle operation parameters will be simultaneously monitored. All of the trucks will be equipped with an 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, injection timing, and barometric pressure. These data will be used for evaluating truck operation as well as developing emissions models.

Chassis dynamometer testing will measure in-use emissions of NO<sub>x</sub>, PM, HC, N<sub>2</sub>O, ammonia, and particle composition. A sample of trucks will be tested for the above pollutants at the beginning of the trial as well as at the completion of the trial.

In-use testing using EPA's trailer will include real-time PM mass and PM sizing. Real-time particulate mass measurements are planned following integration of a Tapered Element Oscillating Microbalance (TEOM) into the trailer. Electrical Low Pressure Impactors (ELPi) will be used for real-time particle sizing before and after catalyst. NOx emissions will also be monitored.

## CONCLUSION

The major goals and contributions of this project can be summarized as follows:

1. Performance of the Siemens-Westinghouse SINOx System will be tested under realistic on-road operating conditions. The analysis of the results will be independently evaluated by ITS-Davis, and the merits of the system will be documented. In addition, concerns of the California Air Resources Board and U.S. EPA regarding issues such as system tampering and urea fueling infrastructure will be addressed.

2. The SINOx System will be introduced and demonstrated to U.S. manufacturers and government agencies using actual California truck fleets. This type of demonstration project is useful in helping industrial companies and government agencies make the decisions necessary to implement new equipment and emission regulations on a rational basis. It will allow government agencies to evaluate the potential emission reduction of Urea-SCR technology in other applications, including marine, railroad, and portable diesel powered equipment currently in use in Europe.

3. The data generated by this project will be reduced and analyzed to form the basis of the project report. The project report will focus on the possible improvements in emissions, and the potential to utilize the Urea-SCR technology in the state of California and the U.S. The report will be distributed and made available to a wide spectrum of government agencies and vehicle/engine manufacturing companies. It will also be posted on the ITS-Davis website.

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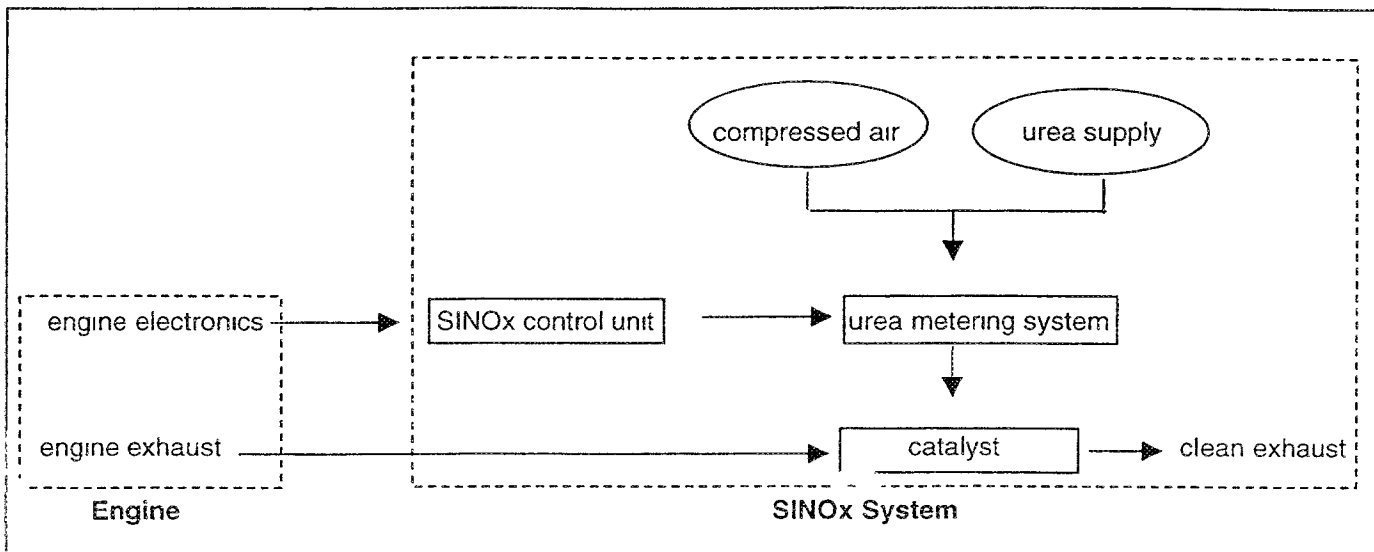
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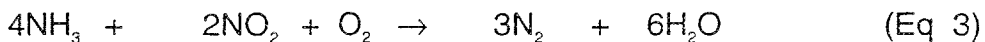
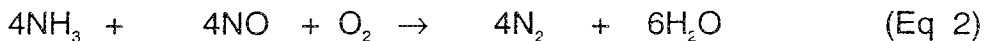
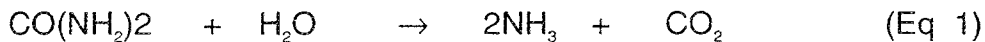
## APPENDIX

The SINOx-System schematic is shown in Figure A1. The system injects the reducing agent ammonia (NH<sub>3</sub>) into the tractor's exhaust in the presence of the SCR catalyst. Nitrogen oxides (NO<sub>x</sub>) are reduced to molecular nitrogen (N<sub>2</sub>) and water vapor (H<sub>2</sub>O). Since NH<sub>3</sub> is toxic and flammable, the SINOx System uses aqueous urea to obtain the ammonia. Urea is a non-toxic, non-flammable, non-hazardous material. Injection is managed with an electronic control unit that is connected to the electronic engine management system. A detailed description of this process is included below.

Figure A1 Schematic of the SINOx System



The reducing agent is injected into the exhaust gas of the engine, where the urea forms ammonia NH<sub>3</sub> and CO<sub>2</sub> through hydrolysis, which then passes the catalyst, where the NH<sub>3</sub> and the NO<sub>x</sub> react to molecular nitrogen (N<sub>2</sub>) and water vapors (H<sub>2</sub>O). The injection of the reducing agent is supported by compressed air. The atomized reducing agent is mixed homogeneously upstream of the (SCR) catalyst, assisted by a static mixer in the exhaust pipe.



The SCR catalyst consists of titanium dioxide, tungsten oxide and vanadium pentoxide and is extruded to a honeycomb catalyst without any additional coating. This homogeneous extruded catalyst does not show the shortcomings of coated ceramic or corrugated stainless steel substrates, such as delaminations, clogging, reactivity loss, etc. Investigations on coating thickness showed a minimum requirement regarding the thickness of the active catalytic material.

The reducing agent metering system has to respond to rapid changes in exhaust gas flow, temperature, and emission concentration. An electronic control unit governs the metering system. The SINOx electronic control unit receives engine sensor data such as speed, torque, temperature, etc. from the engine management system. A "mapping" processor then uses these sensor values and corresponding emission values. These values are used to relate the

predictive emission monitoring system (PEMS) values from the "map" to the required reducing agent quantity. This allows the system to achieve the specified  $\text{NO}_x$  reduction with minimum excess  $\text{NH}_3$  injection ("slip")