THE DIESEL ENGINE'S CHALLENGE IN THE NEW MILLENIUM

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Diesel engines are the dominant propulsion engine of choice for most of the commercial surface transportation applications in the world. Consider agricultural uses: Diesel engine power is used to prepare the soil, transport the bulk seed or seedlings, pump irrigation water, and spray fertilizers, mechanically harvest some crops and distribute the produce to market. Diesel engines power virtually all of the off-highway construction equipment. Deep water commercial freighters or containerships are almost all diesel engine powered. The passenger ships are primarily either diesel or a combination of diesel and gas turbine, referred to as CODAG or CODOG. The fuel economy, low maintenance costs, and reliability of diesel propulsion has lead to major retrofits so the ships could be operationally cost competitive. The Queen Elizabeth II, or QE II, was built in the mid-fifties with a state- of-the art steam plant that moved the ship 22 feet per gallon of fuel burned. This steam turbine was replaced in the late 80's with diesel engines that provided over 40 feet per gallon. The Larkspur commuter ferries that run between San Francisco and Sausalito/Tiburon were originally fitted out with gas turbine propulsion engines. Maintenance problems plagued these ferries resulting in many canceled runs and very high operating costs. The four Larkspur ferries were retrofitted with diesel engines resulting in an over 40 percent improvement in fuel economy and 75 percent reduction in maintenance costs while compiling a near perfect record of providing scheduled sailings. Considerable amounts of commodities are carried in barges along our inland water-ways, virtually all moved by diesel engine powered tugs or tow boats. Diesel-electric engine locomotives power essentially all freight trains and non-electrified passenger trains in the US.

Heavy duty trucks carry about 3,745,000,000 tons of cargo per year. These trucks are mostly diesel engine powered. Why is the diesel engine the dominant choice for these applications? The diesel engine produces far more useful torque per rated horsepower than spark ignition (Sl) gasoline engines or gas turbines. Diesel engines are much more efficient, durable and reliable than any other heat engine. US diesel engine manufacturers warranty their Class 7 & 8 heavy-duty truck engines for 500,000 miles! In other words, the diesel engine powered vehicles are the most economical to own and operate.

So what's the problem with diesel engines? Will the diesel engine be replaced in the next 20 years or so by a "perhapsatron"? Should the diesel engine become a significant propulsion engine for personal autos and light trucks (sports utility vehicles, pick-up trucks and mini-vans)? Should new transit buses be fitted with diesel engines or natural gas engines? The problem with diesel engines is their emissions: principally oxides of nitrogen (NO_x) and particulate matter (PM). There is no real competitor on the technical horizon to the diesel engine for the heavy-duty truck, rail, or marine propulsion where high torque is required and most of the rated horsepower can used continuously. A possible exception might be the diesel hybrids. There is considerable activity involving greater use of electric motors with diesel engines for accessory drives, as well as regenerative braking and the new very high efficiency "pancake" alternators that also incorporate the starter and damper functions. Additional electric power will be generated by an alternator/ motor installed between the turbocharger's turbine and compressor. This technology may or may not wind up in the hybrid category. However, this technology or a variant of it, has a very high probability of commercial introduction in this decade with both diesel and gasoline engines. Another exhaust gas utilization technology that looks attractive is quantum well thermoelectrics. These devices can either be used to convert heat to electricity at a 30 percent level between surfaces at 3000C and 5000C or to heat/cool at similar efficiencies. The rapidly emerging computer aided design and manufacture are particularly beneficial to the diesel engine's efficiency and durability.

Thus this 102 year old diesel engine concept has considerable potential for further improvement although currently it is the most efficient and durable heat engine by a large margin. The problem is the level of diesel engine emissions and their perceived effects on health. Concerns are amplified by the clouds of black smoke emitted by pre-'94 busses and trucks during accelerations. These clouds of smoke look unhealthy and smell bad. However the greater threat to human health comes from the <2.5 micron particles that the human eye can't detect, but the human body can. Many of these particles are inhaled but not all are exhaled. The smaller the particle, the higher the probability that it could be retained in the human respiratory system. The greater concern should be with the nanoparticles, which are defined as less than 50 nano meters in diameter. or roughly 1/1000 the diameter of a human hair. The 0.1 to 10 micron diameter particles typically can stay in the atmosphere for about a week. The human respiratory system ingests particulates of <10 microns in diameter. The larger particles are removed from the atmosphere by settling quickly. The residence for the 10 nanometer diameter particles is only about 15 minutes as they coagulate with the 0.1 to 1.0 micron particles (1). While the smaller particles are the greater human health hazard, the EPA standards are still based on mass measurements. Some of the engines developed to meet the particulate mass standards did so but significantly increased the number of nanoparticles in the process. In the combustion process, toxins attach to carbon particle surfaces. However, when these carbon particles are oxidized, the toxins are destroyed. The AEA Technology group in the UK have measured 24 toxins on the EPA's diesel exhaust list before and after their non-thermal plasma device for particulate reduction was activated in diesel engine exhaust. Measurements of these toxins typically went from substantial in the no aftertreatment case to near zero or below the threshold of measurement when the non-thermal plasma device was turned on. Similar results should be obtained with the catalytic particulate traps that oxidize carbon particulate. Thus the regulatory agencies should develop standards based on particle size and numbers rather than mass. Easier said than done.

The South Coast Air Quality Management District is a strong advocate of natural gas powered transit buses while trying to prevent new diesel busses from being purchased by California transit systems. Their position is based on health effects considerations as they interpret them. If they are comparing older in-service transit buses with natural gas (CNG) buses, they have a valid point. Recent data, such as reported by the Swedish consulting group, Ecotraffic, measured emissions from transit buses in field trials running on diesel fuel, ethanol, natural gas (CNG), and bio-fuels. They report that the lowest level of particulate and possible cancer causing toxins were from diesel engines with particulate traps operating on Swedish Class 1 Diesel Fuel (Sulfur level of 10 PPM). This study also determined that from both a fuel and a vehicle perspective CNG causes higher greenhouse gases. This is because there are high levels of methane released in fuel production and methane has 20 times the greenhouse gas activity as $C0_2$ (2). The largest transit bus organization in the US, New York City Municipal Transit, reports similar results. This is important as CNG buses cost about $50,000 more than similar diesel powered vehicles, require a dedicated fueling station that costs well over a million dollars, and require significant modifications to stopage facilities to insure no gas build up.

There are primarily four aftertreatment systems that are being developed for NO_x reduction. These are the Urea systems that develop ammonia (NH3), NO_x adsorber catalysts, nonthermal plasma systems, and lean NO_x catalysts, cooled exhaust gas recirculating (EGR) with microprocessor control being used as a diluent that very effectively reduces NO_x generation during the combustion process, but EGR is not considered aftertreatment. Urea is a source of ammonia (NH_3) that is introduced into the engine exhaust such that it will reduce NO_x to molecular N_2 and H_20 with trace amounts of nitrous oxide (N_20) form. This reaction requires a temperature of about 1400 F, which requires a device of some sort to increase the exhaust temperature, or an SCR catalyst which reduces the reaction temperature to around 700 F or the introduction of hydrogen which also lowers the reaction temperature. Hydrogen for this purpose can be derived from diesel fuel or from the NH_3. This urea approach presents major challenges for enforcement. NO_x adsorber catalysts work well until the catalysts are poisoned by sulfur. Even 15 P.M. may be too much sulfur and a sulfur trap may be necessary to achieve desired lifetimes with NO_x adsorber catalysts. Lean NO_x catalysts have been in development for over 20 years. The results are essentially shown in Figure 1. Either heat the exhaust to around the copper zeolite type catalyst maximum efficiency temperature or cool it to the more efficient thermal range of the platinum catalysts. At least one European organization is pursuing the latter approach. The better non-thermal plasma devices are getting up to 70 percent NO_x reduction when using diesel and propene fuel respectively as the reductant.

Reduction of particulate (PM) is less difficult than NO_x reduction. All diesel engine manufacturers are heavily involved in the development of particulate filters/traps. Wall flow filters effectively remove particulate from the exhaust gas. However, they require relatively high temperatures to regenerate or oxidize the particulate. Catalyzing filters are used to lower the regeneration temperature to enable light-off. A competitive design uses an oxidizing catalyst to convert NO to $N0_2$, which is a better reductant at the front of the fillter. These systems are being tested primarily on transit buses in service. Another approach close to commercial introduction involves a thin coating of Silicon Carbide on a trapping filter and using periodic microwave transmission to regenerate the accumulated particulates. The goal of the non-thermal plasma programs is to simulataneously reduce NO_x and particulate.

AEA Technology is using non-thermal plasma to only reduce particulate and is using London Taxis as their test vehicles. Their device is essentially independent of temperature or fuel sulfur levels. Early results indicate the plasma keeps the catalytic surfaces clean, suggesting minimal catalyst aging, but this is yet to be validated by long term testing. As previously noted, AEA testing indicated that poly-aromatic hydrocarbons, identified by the EPA as toxins, were reduced to minuscule levels or were below the threshold of measurement when the carbon particles (soot) were oxidized! This should be the case for any aftertreatment system that oxidizes particulates in diesel exhaust.

There is considerable controversy concerning the level of sulfur in diesel fuel and when very low sulfur fuel be available. Sulfur poisons catalysts and is especially harmful to the Barium type NO_x adsorbers. Sulfur in diesel fuel results in sulfur dioxide ($S0_2$) in the exhaust gas. Roughly 2 percent of this $S0_2$ further oxidizes to $S0_3$ which condenses with the water in the exhaust to form sulfuric acid. This sulfuric acid is absorbed by the carbon particulates thereby increasing the mass of particulate emissions. These oxides of sulfur have further reactions in the atmosphere resulting in problems including acid rain. The EPA appears to be leaning to 15 PPM sulfur in diesel fuel by 2007. The California Air Resources Board is considering requiring the ultra-low sulfur diesel fuel by 2004. This could lead to the early availability of this fuel but possibly in insufficient quantities to meet the demand. It is interesting to note that several major oil companies in Europe are providing 10 PPM sulfur diesel fuel in quantity. Texaco is currently providing 10 PPM sulfur fuel in Germany and the Scandinavian countries, and will shortly provide it in the UK and France. This was achieved by the countries involved designing tax reduction motivation to help defray the very expensive refinery modification costs (3). The most definitive effect of various sulfur level diesel fuels on diesel engine emissions is the Diesel Engine Comparative Sulfur Effects, or DECSE Program, managed by DOE's National Renewable Energy Laboratory. At this point in time, it appears that diesel fuel with around 15 PPM sulfur will be necessary to meet the Tier 2 Standards.

Particulates from diesel engines have been taking the rap for the exponential increase in asthma over the last 25 years on both sides of the Atlantic. Many agree that parts of dead cockroaches, their feces, dust mites, and the like cause asthma. The concern is what might exasperate this respiratory disorder. While diesel particulates are a candidate, particulate emissions from heavy-duty trucks and buses have been reduced by 90 percent over the last 25 years. This inverse relationship suggests another culprit/culprits. Consider what happened about 25 years ago. The catalytic converter was introduced on gasoline engine powered automobiles and the AIDS disease was detected. In a paper presented at the National Academy of Sciences this Spring it was reported that an Italian medical group had made a correlation between very small quantities of platinum and enhanced susceptibility to asthma (3). In response to the AIDS epidemic, there is an incredible expansion in the use of Latex gloves that give off allergens that could play a role in asthma.

Enough speculation. The Health Effects Institute is initiating a major program to sort out the asthma situation. While, several Environmental groups are blatantly anti-dirty diesel, some appear just anti-diesel. Representatives from the Environmental Community have been invited to the last four DEER Workshops and there has been an Environmentalist Panel Session in the last two DEER Workshops. Our objective was to provide information with respect to the technological advances in diesel engine emission reduction recently achieved and further advances in various stages of development. While there is some commonality in goals of the Environmentalists and the Diesel Engine Community, there are also major differences. However, mutual respect emerged between the two groups as the dialogue developed. There are some other Environmentalists who are trying to eliminate diesel engines in highway use based more on emotion than science, as illustrated by the cover of a pamphlet handed out during a recent meeting to discuss the Washington, DC Metro acquisition of a large number of transit buses shown as figure 2.

Diesel engineers have to worry about meeting very stringent emission standards with reliable and durable devices that are economically viable. Impending EPA Regulations will require emissions reduction systems to work for

435,000 miles on Class 7 & 8 trucks. There will be onboard diagnostics to tell how well they are complying with the emission regulations. The biggest challenge is for the light-truck clean diesel engine manufacturers to meet the Tier 2 Standards by 2007. Vehicle manufacturers will probably want some engine test data that shows Tier 2 can be achieved before they commit to a production contract. The advantages for the diesel engine demonstrated at this Workshop, including acceleration, noise, and all around performance, are competitive with comparable gasoline engines in the same vehicle except for fuel economy and greenhouse gas emissions (GHG). Both the Cummins and the DDC Light Truck Clean Diesel Engines provided at least a 62 percent advantage in combined city/highway fuel consumption and this diesel fuel economy advantage can be increased to over 70 percent in urban traffic! These diesel engines would produce about 25 percent less $C0_2$, the primary GHG, per mile than comparable gasoline engines. Diesel engines produce a small fraction of the CO emitted from a gasoline engine. For example, if a diesel car or light truck were in a garage with the garage door shut and the engine running, there wouldn't be enough CO emitted to cause serious health problems; whereas the gasoline engine under the same conditions would produce enough CO to kill a person in a matter of minutes. In fact, there are about 2800 people killed each year, accidental or suicidal, by CO emitted from gasoline engines. The low volatility of diesel fuel means that in a collision between 2 diesel cars the probability of fire is far less than it would be with gasoline powered vehicles. The fuel economy advantage of diesel engines extended to the light-truck market could significantly affect our balance of payments.

The benefits of diesel engines are substantial and so is the degree of difficulty meeting the emerging diesel engine emission standards. This Workshop is organized to assist development of the necessary technology to enable compliance with these standards.

References

1. Kittleson,D and Abdul-Khalek, 1. "Nano-particle Formation during Exhaust Dilution "2nd ETH Workshop on Nanoparticle Measurement," Zurich, Switzerland, August, 1998

2. AhIvik, P. and Brandberg, A: " Relative Impact on Environment and Health from the Introduction of Low Emission City Buses in Sweden", SAE 2000-01-1882, presented at SAE Fuels and Lubes, Paris, France June 19-22, 2000

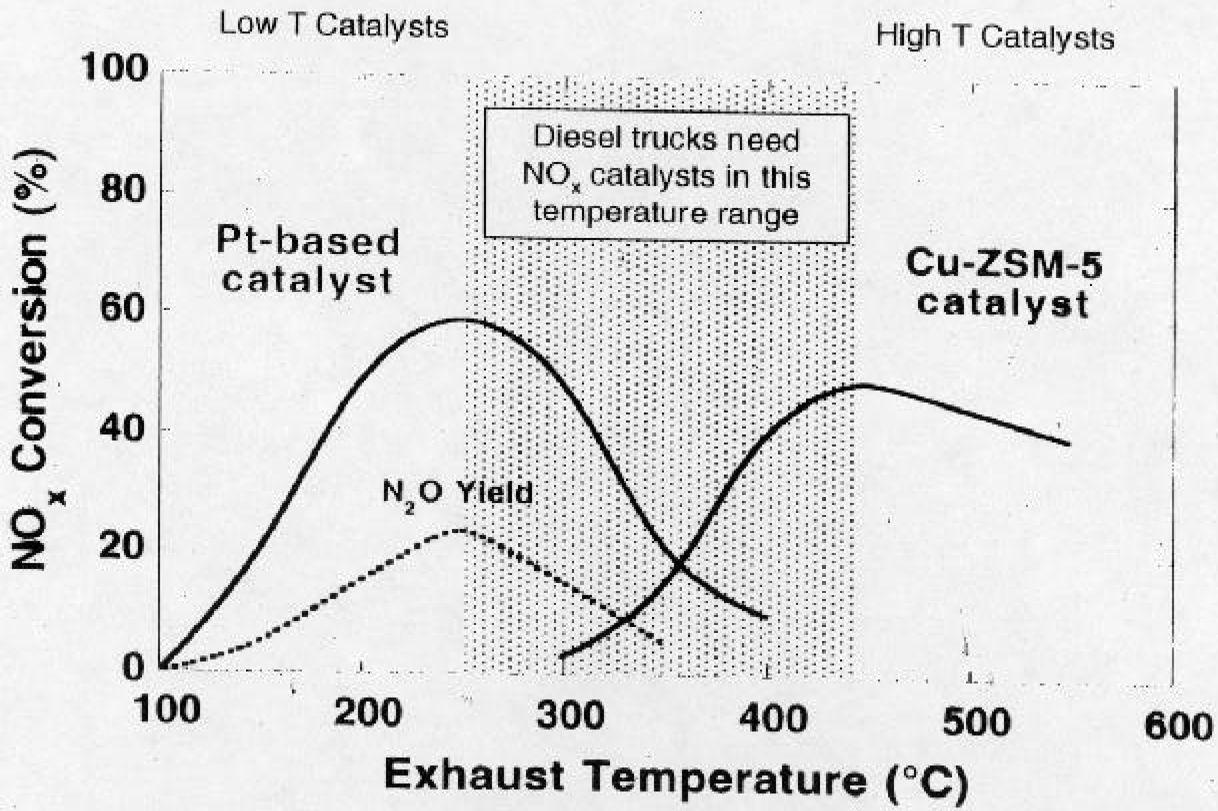
3. Personal Communication with Dr. Alfred Jung, June 14, 2000

Figures

1. Lean NO_x Catalysts in Diesel Engine Exhaust

2. Pamphlet Cover handed out by the Sierra Club

Lean-NO_x Catalysts



[R.M. Heck and R.J. Farrauto, *Catalytic Air Pollution Control: Commercial Technology* (1995)]

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