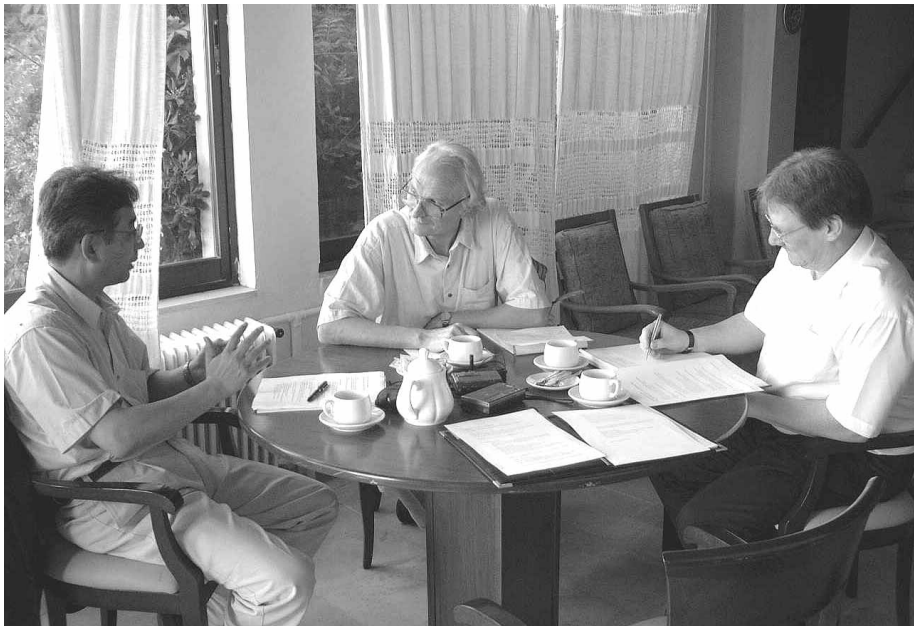
INTERVIEW

Diesel Engine and PM Measurement



Prof. Dr. Jiro Senda
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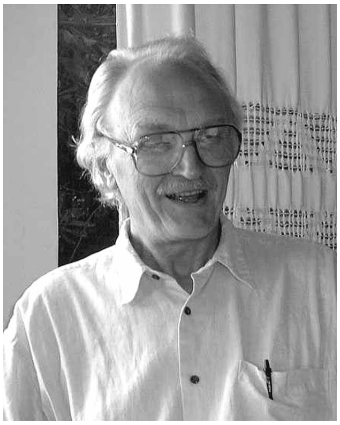
Wishing to achieve the simple goal of creating a convenient, enjoyable automobile that can also coexist with a Wishing to achieve the simple goal of creating a convenient, enjoyable automobile that can also coexist with a pleasant natural environment, scientists and engineers around the world are working night and day in various research efforts. One thing that is getting considerable attention in this type of research is the efficient diesel engine. Of course, there is also the important matter of reducing PM, which is said to adversely affect human health. Recently, an interview was held with Prof. David B. Kittelson of Minnesota University, one of the world's leading authorities on internal combustion engines, and Prof. Jiro Senda of Doshisha University, about the current conditions of and future outlook for diesel engines and PM measurement. The interview covered a wide range of topics, from the conditions of various types of engine development, such as direct injection engines and fuel cell engines, to the subject of PM measurement. The interview itself was conducted this past May in Greece by Dr. Masayuki Adachi of and Mr. Les Hill of Horiba Ltd.



Prof. David B. Kittelson

Director of the Center for Diesel Research,
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Diesel Engine, Direct-Injection Gasoline Engine, and Fuel Cell

Hill How do you view the diesel engine technology today and its long-term future automotive applications, in comparison to other types of engines?

Kittelson I'm sort of a diesel optimist. In the near-term, the diesel certainly has the best prospect as a low CO_2 emitter. I also think that global pollution issues are more important than some of the local issues but most of the concerns about the diesel, especially in the United States, are very narrowly-focused without taking into the global issues into account.
I do think, of course, that you have challenges on NOx and particulate matter. To me, NOx is a harder problem than particulate matter. The combination of particle traps and low-sulfur fuel, coupled with some kind of oxidizing catalyst, will allow us to solve both the solid and the volatile, nano-particle problems. The nano-particle problem is basically about volatile material and the combination of the low sulfur fuel and oxidation catalyst is an effective solution.

Adachi You say you are optimistic for the diesel's future. Does this include the use of diesel for passenger cars? What size of vehicle?

Kittelson Yes. I think it depends on what part of the world you are talking about. Obviously, in Europe the diesel passenger car is a reality and I think this will continue. In the U.S., I'm not really certain. The problem in the U.S. is that we have, I think, a very ill-conceived energy policy in that we have extremely low fuel prices and that doesn't give much incentive for diesel passenger cars. On the other hand, the Department of Energy in the United States has a major commitment to try to introduce the diesel into sports utility vehicles. That can have an enormous impact on American energy consumption and I really hope it happens. Again, the barriers are NOx and PM. And so, if NOx and PM control technologies develop the way I think they will, I'm fairly optimistic that we will have sports utility diesels.

Adachi If you think about the competitor for diesel engines, I think the biggest competitor is direct-injection gasoline engines which also have discussions with NOx and PM.

Kittelson I think in the United States if a direct-injection gasoline passenger car is introduced, it will have to meet the same standards as diesel. When you put a PM trap and other control technologies on a stratified charge GDI, you really have a convergence of the gasoline and diesel direct injection engines and will really finish up being quite similar.
Alternatively, homogeneous or early-injection direct-injection gasoline engines, with variable valve actuation could probably come into the U.S. and wouldn't need to have a particle trap because they are running, essentially, Lambda 1. This would be a passenger car alternative in the U.S. and probably a fairly likely one. But if you

go stratified, and need the PM trap, then I don't see that it has an advantage over diesel, and diesel probably is then more attractive.
All of these things are sort of near-term prospects – the next 10 to 15 years. I think in the long term, it's likely that fuel cells are going to be very important. But they are further off than many people think, certainly further off than the politicians think.

Adachi So you think that the fuel cell is really coming in the long-term future?

Kittelson Yes but I do think we will probably end up with some kind of mix for a long time. I asked the question about operability of fuel cell vehicles in extreme climates and the fuel cell people were fairly optimistic about it but I remain to be convinced. I think any kind of electrochemical device that has a lot of liquid water has disadvantages in extreme climates. So we may find that we have conventional engines persisting for longer in certain parts of the world. A diesel engine or a gasoline engine runs as a total energy system, as a cogeneration system, in cold weather. It's a very effective system – then you're capturing all the waste heat, or a significant fraction. When you look at the overall efficiency that is very important.

Hill How do you view the diesel and gasoline?

Senda Firstly, when we consider power density, diesel and gasoline engines have a very high potential compared to fuel cells. The power density of the fuel cell is very much lower than diesel or gasoline engine systems, so it a very important point to continue to use them.
The next point I want to mention is efficiency and emissions from engines. As you know, the diesel engine has a highest thermal efficiency, however, we are subject to some kind of emissions. We also have very severe regulations, as well as the E.U. and the U.S. So to clear the future regulations in Japan, we have some limitation in the engine improvement. So we have to use some kind of fuel reformulation or we need an after-treatment system, for instance the NOx reduction catalyst and DPF system. So we need some kind of research relating to after-treatment and fuel reformulation.
When we consider the diesel engine hybrid, this is the best candidate for the future engine system, because according to results of the life-cycle assessment, it is well known that the potential of systems with diesel engines is highest, at a comparable level to the fuel cell using hydrogen.
When we use the fuel cell with the reformulation system of gasoline or methanol, the potential should be lower. The fuel cell system with reformulation has not so high potential compared to the hybrid system.

Prof. Dr. Jiro Senda

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The Coexistence of Fun to Drive and Environmental Conservation

Senda Third point is that, in the future, within twenty or thirty years, we have to consider a new type of transportation system inside the city. For example, car sharing or TDM (Transportation Demand Management) and so on. Battery power could be used for short trips, for shopping and so on. And then in suburban area, we can use the fuel cell EVs. Further, outside the fuel cell zone, we should use the hybrid system with high-efficiency gasoline or diesel engines. Finally, we need to use the heavy-duty diesel engine for long-distance transportation. So my opinion is that the best treatment or the optimum use of several types of engine systems should be provided, including diesel, gasoline, fuel cell, and hybrid systems. Also ultimately, fuels should be optimized and targeted.

Kittelson Yes. I think that's related to my comment that we're going to see a distribution of different types of vehicles for different climates. As we evolve systems, we will probably have somewhat different vehicles for northern climates, for example, than for moderate climates, where electric and other concepts work better.
I really like your idea about this sort of stratification of vehicles; a different sort of approach to urban centers than that used for long distance travel. And all of this becomes very feasible when you have GPS systems and so on. I think the intelligent transportation system is going to play an increasing role.
For example, if you have a hybrid vehicle using GPS, you know what terrain is coming. You could set the storage levels in the energy system in your hybrid. Even if not a full hybrid, when you are approaching a hill, you could start the engine operation at the right time to minimize emissions. There are all kinds of things you can do if you have a little bit of anticipation. Because the emissions are so much higher on transients. If you can minimize those transient effects, you could have a big advantage! GPS offers enormous potentials there.

Senda So, as you said, in the case of GPS, all driving processes might be controlled to optimize emissions and fuel economy. In this case, I have to consider "fun to drive". This is a very important point for people. We already have the "fun to drive"using the hyper density engines such as diesel or gasoline. So I think we (will) never take away these kind of high power density engines. When we use the next generation powertrains with low power density, we don't have the "fun to drive". So from this point of view, diesel and gasoline (engines) should survive.

Hill Right. I like that second point about the intelligent use, you can still have a vehicle which, in the right location, is fun to drive but can be restricted during the time when it is in the cities as the control can be adapted for the location.

Kittelson You know, in terms of "fun to drive", I suspect that the user interface and the user 'feel' of driving will be much nicer on a mild hybrid than a true hybrid. On a true hybrid, you have this disconnection between the engine and what the vehicle is doing. And there's something about driving where you're dealing with your

engine and so on, and you could get that with an electric assist, with the mild hybrid system, you would still maintain … in fact you could have very high performance with that kind of a parallel hybrid. But if you go to a full series hybrid there's a big disconnection between what the engine is doing and what you want the car to do. I don't know if the hybrid manufacturers have looked at that but I wonder what kind of driver feedback they are getting. I know personally, I refuse to have automatic transmissions because I like to shift – I like to feel the way the engine responds. And, you know, you could do that with mild hybrids, but not with full hybrids.

Hill What is interesting is the way that the public perception of diesel has changed in the last three years, at least in Europe. Nowadays people are specifying diesel engines in luxury cars because of that unique sensation of high torque. This gives tremendous acceleration without "revving" the engine.

Kittelson Well that could be the thing that brings the diesel passenger car into the United States because we don't have the fuel cost incentive. If the public perceives the diesel as being a luxury, high-performance vehicle, then it will sell.

Logical Discussion Based on the Measured Data

Adachi How do we think about the diesel engine emissions in the "Real World" terms?

Kittelson Again we have this difference between Europe and the United States. Certainly in Europe, there is no doubt that diesel engines are associated with the soiling of buildings and with some impact on visibility. These are unambiguous environmental effects you can attribute to the diesel but the other health effects are still debatable. Certainly there's a correlation between particulate matter and health effects. I don't doubt the "Six City" and other studies, but the exact contribution of the diesel is not clear. It was mentioned the other day that a city like Paris should have very high respiratory disease rates given the high use of diesel but I don't think the statistics bear that out.
Now, in the U.S. we have an interesting situation because we have 99% spark ignition passenger cars. And despite the fact that the diesel gets the attention in terms of particulate matter, there are some studies, for example the Amtrak study in Colorado, that suggested that two thirds of the fine PM associated with vehicles in the U.S. comes from spark ignition. So spark ignition, especially, off-cycle and "old", – maybe not old, but worn in one way or another – those vehicles are significant particle emitters and are definitely a problem. And of course, spark ignition, in terms of CO_2 is much worse than diesel.

Senda In Japan, the diesel engine is used in trucks and buses, resulting in intensive emissions of particulate material, especially in the city area. In Tokyo they proposed a severe rule demanding the installation of DPF systems in the older trucks and buses. In the modern diesel engines, there is no severe particle emissions because of the use of the common rail injection system. So the problem is the older type diesel engines which can be solved with the retro-fit DPF system.

Kittelson One important issue is the old versus new, because as you said, the older vehicles are the problem and these need to be retrofitted. They're the ones that really hurt the image. And unfortunately, all the health studies are based on older technology engines. Even today, in the health studies that are being made, the exposures are not at levels that are really comparable to what you have in the real world. To make things happen in a reasonable time they have to use these elevated levels, but you always have to ask, is this a realistic way to test the affects of PM exposure?

Hill Perhaps the governments could use tax incentives to get users to upgrade their vehicles, engines or to retrofit DPFs. As Europe has a high tax policy for fuel and vehicles, they can afford the incentives.

Senda The Governor of Tokyo made a powerful image by showing PM in bottle on TV.

Kittelson It's easy to point the finger at a vehicle emitting a visible smoke cloud. If you have lots of tiny invisible nano-particles coming out, you can't point your finger at that and, in fact, it becomes quite an academic topic to describe at all. So I think that's part of the difficulty and if it turns out that the extremely tiny particles are more dangerous and we have to focus even more on spark ignition then I don't think it will be so easy for politicians to do this, because the image isn't there. What you can't see, people tend not to get excited about.
You know there's one thing that Dr. Joe Maderdly from the Lovelace Inhalation Toxicology Research Institute always gives this example to put exposure to particles into perspective. He makes a comparison between the dose to your lung if you live in a city where the concentration of particles is right at the ambient standard, which is high, to somebody who smokes one pack of cigarettes a day. There's a difference of two orders of magnitude! You've got two orders of magnitude more dose to your lung if you just smoke one pack a day, compared to living in a highly polluted city. And think about of how long people argued about the health effects of cigarettes!

Senda We need an effort to advertise the exact information relating to the diesel engine. As you said, gasoline also emits particles. Ultrafine PM is very focused, but Ultrafine PM is coming from not only the the diesel engine. So a famous person, as you, should appeal that point to the general public.

Kittelson I think all of us who are in the scientific and academic communities have that kind of responsibility, but the interesting thing is that it's so hard to have the visibility if you present a reasonable case, compared to someone who presents an extreme case, but, I think you have to continue. A lot of small impacts one could hope would add up to offset some of the more extreme impacts. People do take these very extreme positions. Unfortunately, in television, for example, they give you 30 seconds. If you have a complex issue, 30 seconds doesn't work very well.

Versatile Measurement and it's Analysis are Important in order to Deduce the PM

Hill Let us look at the developments of emissions regulations and measurement technology in the future.

Kittelson There is one thing I wish people would do when they plot emission regulations as a function of time is to use a semi-log scale. You find that the emission standards look like an exponential decay function. We're going to be seeing a sort of continuing percentage decrease each year, on average. I don't what it is, it's probably five or six percent per year. When we looked at Minnesota air pollution trends, we looked at carbon monoxide and we looked at the decay and compared that decay rate with the target emissions standards on new cars. Both were following that exponential decay. However the decay rate of atmospheric pollution isn't as steep as the emissions standards, and that has to do with the fact that you have noncompliance and also off-cycle emissions. But I think we're going to see this continuing exponential decay. I feel uncomfortable when people talk about zero emissions, but certainly a decreasing trend, I think, that can continue indefinitely. I think we have to face that it will continue indefinitely.
The issues, more and more, are going to be off-cycle emissions and associated with regions where the traffic patterns are such that you have a build up of local pollution. We've found that storage and release of PM is a big issue. In other words, you store PM material in your exhaust system when engines are idling and running at light load, and then when you go to high load, you release the PM. Recent work has found a similar observation from spark ignition engines; if you run a vehicle at low speed, and then you speed it up, you get a significant release of nano-particles which then gradually decay.

Senda Previously in Japan we had very severe regulations for NOx but not for PM. In future, PM will be severely regulated as well. So in order to use diesel engines in other applications, and to improve the diesel image, we need to meet these kinds of regulations and research into fuel and developments of existing emission treatment will be required.

Adachi In all regulations, the PM mass concentration is limited. Which other parameter is the more important, the number density or the size?

Kittelson I don't think anyone knows. I have seen studies that suggest that number density is associated with allergies and asthma. I have seen studies that show when you dose little animals, rats or other animals, with different size particles, that surface area is the most relevant in terms of determining respiratory response. On the other hand, the "Six City" studies suggest that it is really is fine particle mass, less than two and a half microns. There's evidence for these different weightings and I don't think we're going to know very soon which is the most appropriate. One important point is that the instrumentation used for number and surface area is generally more sensitive and will give better resolution with very clean engines than mass measurements. When you get down to the 2007 U.S. heavy-duty standards,

which are 0.01 grams per horsepower-hour, the mass emissions you are measuring are stretching the ability to make accurate filter measurements. The EPA has worked extraordinarily hard coming up with special filter holders that don't shed material, ultra-precise balances and methods for neutralizing electrical charge on the filters but measurements must still be made very carefully. The standards will continue to get tighter and I don't think mass is necessarily the easiest or most accurate parameter to measure.

If I look at number concentration using a condensation particle counter, you could almost say it has an infinite dynamic range, because it can count down to individual particles. One problem, using these extremely sensitive instruments is that the background dilution air becomes an issue. If you look at SMPS data, for example, after a engine particle trap, often what they are measuring is at the tunnel background level. So the issue becomes one of system as opposed to instrument accuracy.

Another open issue is that of transient testing. I think although the standards are written in terms of an integrated measurement, it is becoming more important for diagnostics and R&D to discover where PM and NOx emissions are being produced in the test cycle. Of course you can do it with NOx, but in terms of PM it's not so easy. However, there could be some interesting combinations of instruments; for example diffusion chargers give you what is called a Fuchs or kinetic surface area and can have a response time in the order of one second. The condensation particle counter also has a time response at the same level and now if you take the ratio of those two signals, the surface to number, you can get the diameter of average surface. So you can measure on transients how particle size, or at least an average size, is changing.

Adachi So in order to be a practical regulation procedure, it must be some kind of easy technology, stable and repeatable.

Kittelson Now there is one reason why the regulatory agencies like mass measurements is that is because it is easy to define a standard using weights. Currently, there is no standard on number, there is no standard on surface area. You can't go and buy a bottle of certified particles. You can calibrate in terms of PSL beads but there isn't a standard way of generating them. This is something that hasn't been agreed on and this is something we really need to do. In fact in the E.U. "Fifth Framework" particulate program, we've been talking about the standards. On the CRC 483 program we have a quality assurance plan that basically looks at how we calibrate instruments and we have established some standard protocols.

Hill Are there any other issues that will be important in the future?

Kittelson I think we have to also talk about oil formulation. Whenever you have a very lean-burn system that is basically not making carbon, it still is going to produce an oil aerosol and that oil aerosol is going to have to be removed in some way. If you have a very lean system, the exhaust temperature may be too low for good catalytic removal, so then you are going to have some kind of particle treatment or else you're going to have to look very carefully at oil consumption and

oil formulation. So this is an issue that hasn't been looked at.
Every time I see another diesel bus in California converted to natural gas because of pollution reduction, you know that there is a likely nano-particle emission problem as the diesel conversions have relatively high oil consumption. I've talked to people from most of the major diesel companies that do these conversions and they confirm that the engine has not been optimized and will have a relatively high oil consumption because of the engine vacuum.

Senda I also think that fuel formulation is a very big and important program, especially in the future if we can make some kind of high value liquid fuel from bio-mass material. The problem is the cost and the production system. Bio-diesel will be more effective in the future because it is renewable and so we need to concentrate with a cost-effective production system.

Kittelson When I left the US for this trip, the Minnesota legislature was about to pass a law mandating that all diesel fuel sold in Minnesota has two percent bio-diesel content. This is the low-cost bio-diesel that does not come from plants but from waste oils like McDonalds and that kind of thing. But it turns out you can produce it relatively economically.

Hill One benefit about fuel formulation strategies is that they can be effectively targeted to sensitive areas such as cities. Thank you all very much.

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