Predicting smoke

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Internal combustion engines and their requisite stinky emissions will be with us for a long time.

Increasingly stringent emissions requirements and rising fuel costs place an important premium on close control of combustion in internal combustion engines for all applications.

Future technological advances such as infinitely variable valve timing (through camless operation) and direct injection of both gaseous and liquid fuels will allow the spark-ignited (SI) piston engine to be used successfully well into the twenty-first century in automotive applications, possibly as hybrid vehicle power plants.

These engines have the potential to satisfy ever-increasing fuel efficiency and environmental requirements while meeting consumer expectations of power density, reliability, noise, vibration, harshness, and total life-cycle cost. The engines of the future will incorporate significant advances for improved performance, economy, and emissions.

These engines will require the use of more sophisticated and adaptive control systems than those used today. For example, the engine of the future will be camless, use drive-by-wire throttle actuation, and implement load control through exhaust gas recirculation and both intake and exhaust valve actuation with infinitely variable valve timing control.

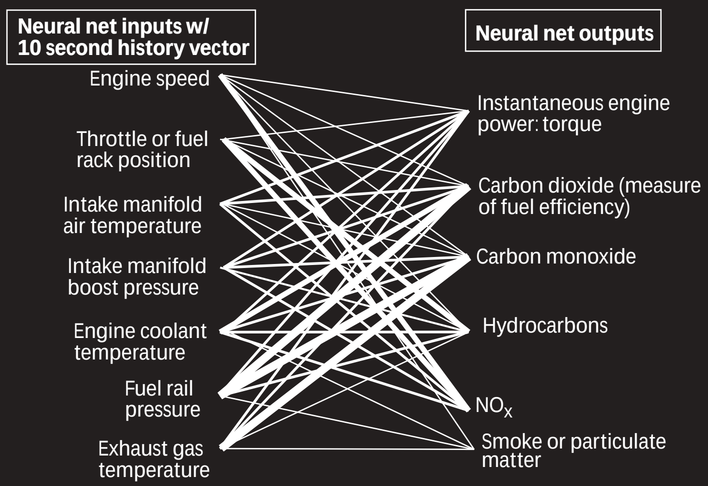
Fuel injection may occur in the intake ports or directly in cylinder, but primary engine control will certainly be effected through fuel delivery control, valve actuation—for load control, reducing throttling losses and increasing rates of exhaust gas recirculation, supercharger, or turbocharger boost—for varying the effective compression ratio and load control and ignition timing control.

For the foreseeable future, compression ignition (CI) piston engines will continue to be used in fuel cost-sensitive applications such as heavy-duty buses and trucks, power generation, locomotives, and off-highway applications. They also have application in hybrid electric vehicles.

Virtual emission sensor

Engine type	10 liter, in line, 6 cylinder
Fuel	Diesel
Compression ratio	15:1
Turbocharger	150-kPa gauge maximum boost
Fuel injection system	Mechanical cam-driven jerk type
Maximum power	300 hp (225 kW) at 2,200 rpm

Virtual sensor description



Virtual sensing computational power requirements for running this neural network model in real time with data rates of 20 Hz is met by the Intel Pentium 100-MHz microprocessor. Running the neural network on a dedicated processor reduces its computational requirements significantly.

Close control of combustion in these engines will be essential to achieve efficiency improvements while meeting increasingly stringent NOx and particulate matter (PM) standards. Future direct injection CI (CIDI) engines will utilize increasingly higher combustion and injection pressures with exhaust gas recirculation, to offset the higher NOx levels produced by the elevated combustion pressures, variable geometry turbocharging, and possibly infinitely variable valve timing, while being truly low emissions and fuel flexible.

Close control of combustion in future engines will be of overriding concern for both

This real-time, neural network–based intelligent performance and emissions prediction system is virtual genius.

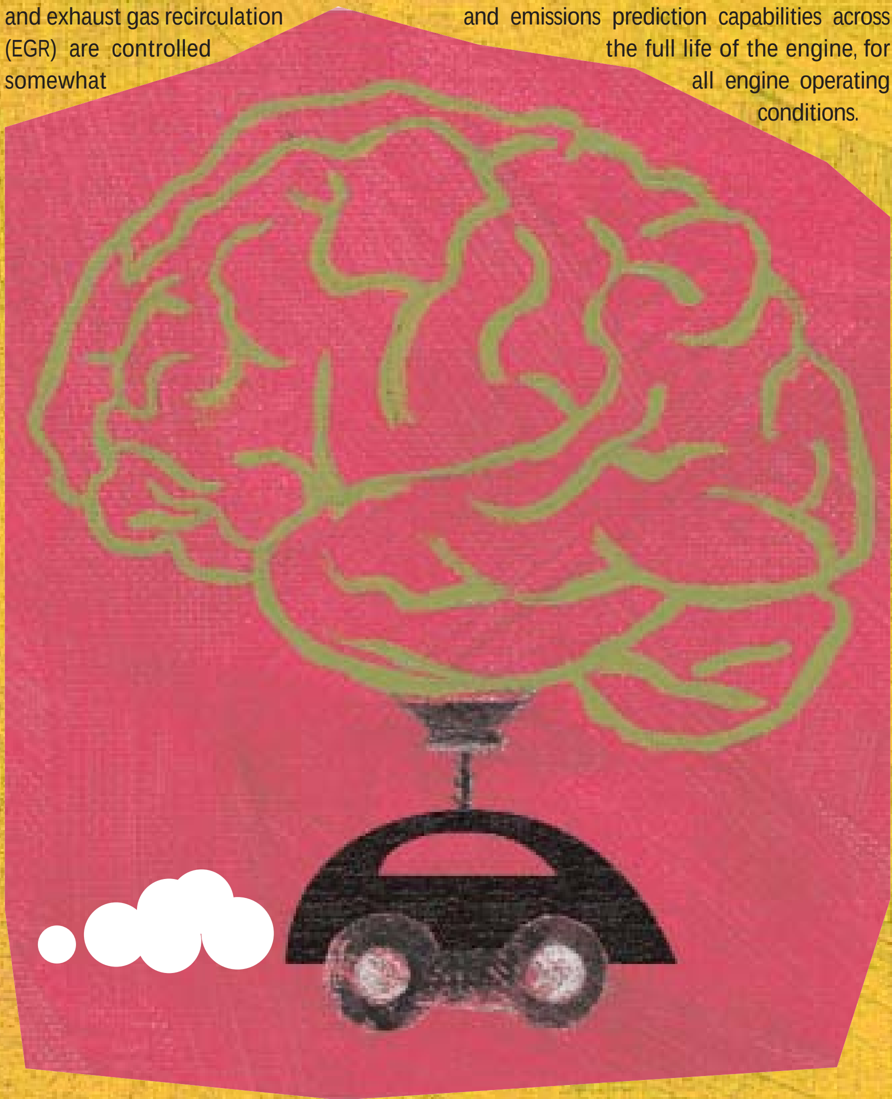
efficiency and emissions. In an ultralow emissions vehicle, for instance, operation through one day with a failed engine sensor or control system may well produce a higher contribution to the emissions inventory than operation for a year with a fully functional system.

Advanced onboard diagnostic capability and the ability to reconfigure control "on the fly" following fault detection will be an indisputable requisite in the future.

These engines of the future will require significantly more complex control, having many more degrees of freedom than engines today. Standard, classical one-dimensional or map-based control, in which fueling, ignition, and exhaust gas recirculation (EGR) are controlled somewhat independently, will prove woefully inadequate in dealing with the multiple independent degrees of freedom presented by wide-range fuel, EGR, ignition, boost, and valve control in future SI engines or fuel injection rate shaping, EGR, boost, and valve control in future CIDI engines.

Moreover, the costs, time, and complexity associated with engine development, performance mapping, and control system development and calibration are increasing significantly.

What is required is a truly multidimensional, adaptive, learning control system that does not require the laborious development of an engine model but has excellent performance and emissions prediction capabilities across the full life of the engine, for all engine operating conditions.



Neural network–based virtual sensing offers all of these capabilities. The excellent generalization capabilities that are achieved through online learning means the engine control system designer need make no assumptions about the governing equations dictating the engine performance and combustion characteristics.

The virtual sensing system automatically develops the engine control laws by learning the engine behavior over time. This allows a truly optimized and adaptive engine control system to develop with a minimum of effort.

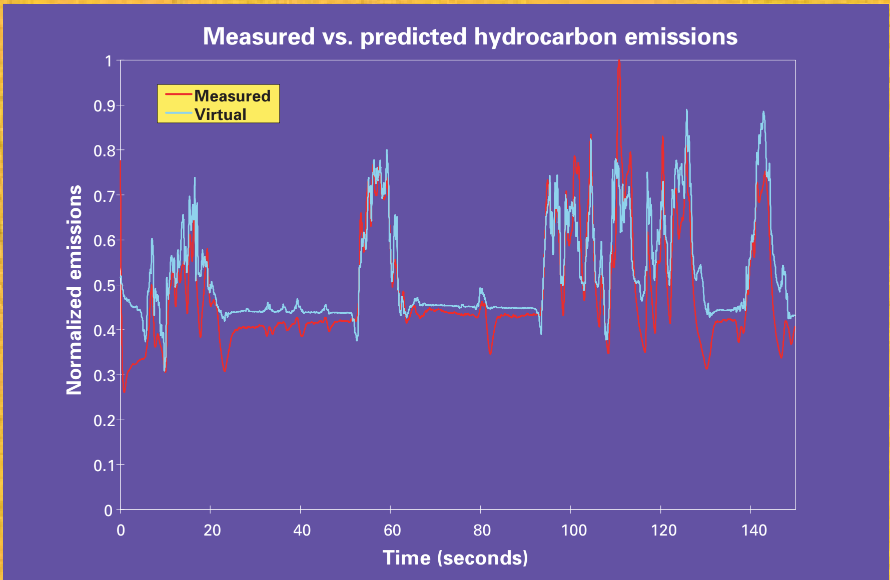
VIRTUAL SENSING SYSTEM

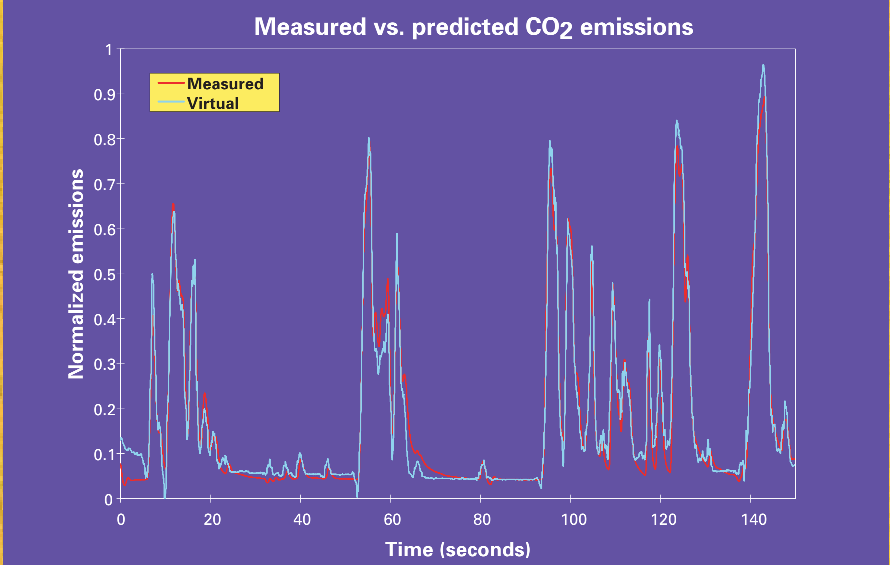
This NeuroDyne-developed sensing system has these immediate applications:

- Engine control, whereby the neural network model provides real-time values of unmeasured or difficult to measure parameters such as NOx emissions or PM emissions for diesel engines
- Oboard diagnostics, in which the neural network model can be used as a virtual emissions sensor for the real-time measurement or prediction of NOx and others
- Real-time prediction of emissions from engines for continuous emissions measurement purposes
- Engine, engine control, and fuel combustion modeling
- Engine and control system mapping for emissions compliance or control system design and development

The system is a predictive engine model that runs on a microprocessor in parallel with the engine in real time. It takes input signals from the same sensors as the engine itself. In SI engines, the neural network model uses manifold air pressure and temperature; engine speed; fuel injection pulse width; EGR valve setting; exhaust gas oxygen concentration; exhaust gas temperature; engine coolant temperature; throttle position; and ignition timing advance.

The neural network model of the engine is able to make highly complex, nonlinear, and multidimensional associations between select-





ed input parameters and outputs in real time to allow accurate predictions of engine performance (real-time torque output), engine emissions (unburned hydrocarbons, carbon monoxide, and oxides of nitrogen), and fuel consumption (as demonstrated by carbon dioxide emissions) across the full range of engine operation.

LEARNING ON THE FLY

The neural network model learns in real time and on the fly the precise relationship between all designated inputs and outputs. The neural network model assigns global or general weights between all designated inputs (engine operating parameters) and corresponding outputs (torque, fuel consumption, and regulated emissions) on the basis of results learned during engine dynamometer testing.

A further local set of weights exists and varies in time across the life of the engine. This provides a true learning and adaptive prediction system. As a result, the neural network model provides the driver with a smart diagnostic system or an engine controller, both of which are the results of a virtual suite of sensors.

These virtual sensor results may be either unmeasured or unmeasurable engine parameters or a duplicate estimation of already measured variables. One immediate application is in the virtual measurement of engine-out NOx emissions for onboard diagnostics in both spark-ignited and compression ignition engines.

Virtual sensing also offers an added level of protection against existing engine sensor failure, as in the case of wide-range exhaust oxygen sensing in lean-burn engines.

VIRTUAL SENSING ACCURACY

Given approximately 30 minutes of highly transient hot engine dynamometer training, the virtual sensor prediction model predicts engine performance and emissions parameters to within 1% to 3% of their instantaneous values.

In the case of the engine emissions, the prediction accuracy is equal to that of emissions analyzers that provide the training data.

For the studied diesel engine, it was not necessary to vary all input parameters individually in a multidimensional test matrix but rather to merely exercise the engine (as a system) through a wide cross section of its expected performance envelope.

The neural network–based system has excellent generalization capabilities, provided a wide range of representative engine performance training date is available. Modeling of cold-start engine performance and emissions is quite feasible using data from several cold starts at various initial engine and air temperatures.

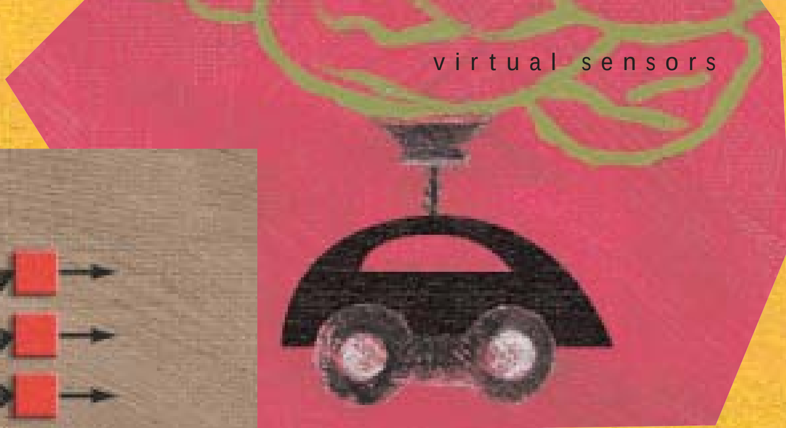
The neural network architecture is a *partially recurrent net*, which has more accurate mapping than a *multihidden layer* net. The input vector includes instantaneous engine parameter values as well as a receding history window of 5–10 seconds of the same data.

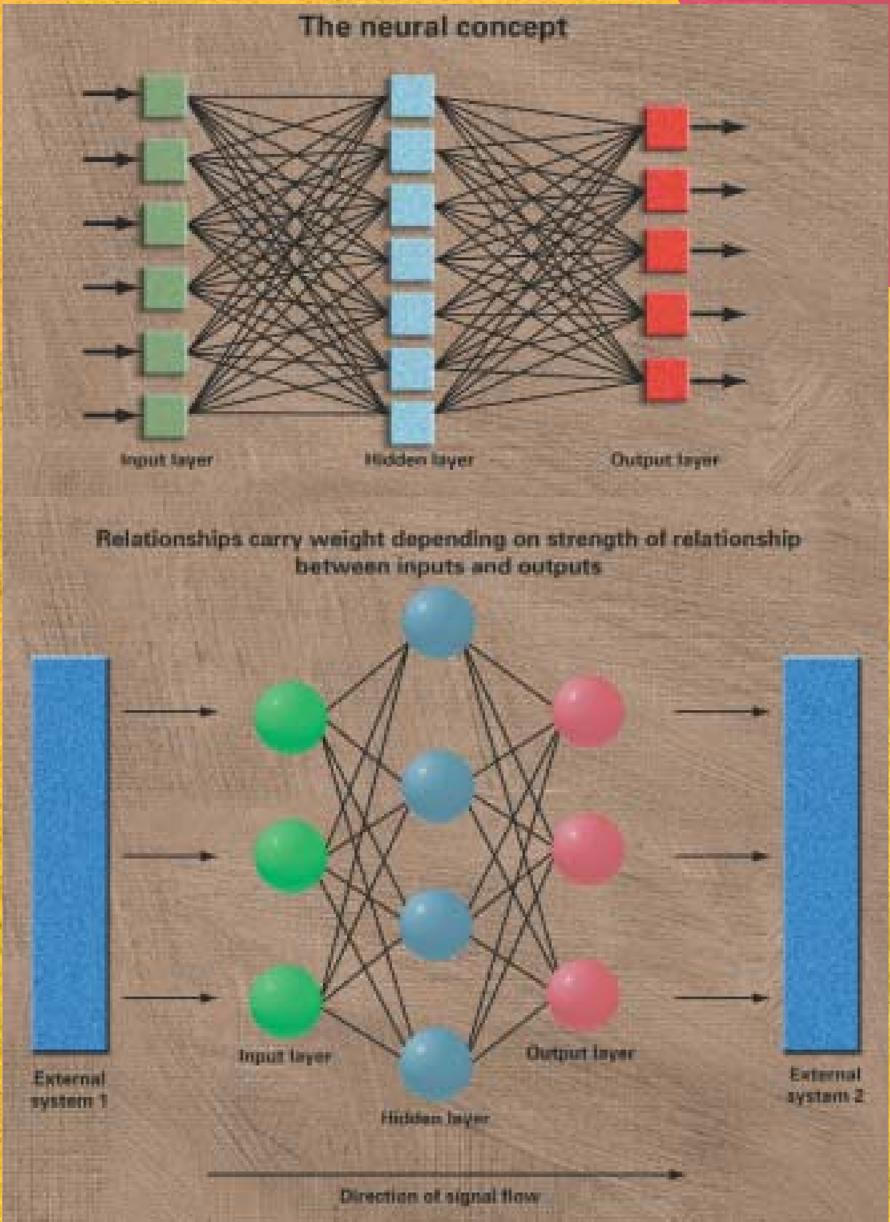
Including this sliding window is necessary to capture the full dynamics of diesel engine operation, including turbocharger spool up and the emissions arising from transient fueling variations. All raw engine measurements, obtained from either a fully instrumented engine on a dynamometer during training or an engine in the field during normal operation, register at a 20-Hz data sampling rate.

This rate can be increased or decreased, depending on the balance between desired accuracy and computational effort required. The data flows through an infinite impulse response filter for conditioning. It maintains its integrity. The virtual sensor accounts for the transport delays and finite response times inherent in the existing engine sensors.

ENGINE DIAGNOSTICS PAYBACK

The value of having onboard virtual power and fuel consumption sensors is that the driver has real-time knowledge of abnormal or dangerous engine operating conditions and can take action.





The predicted engine emissions results are useful to vary an engine control strategy in real time to minimize emissions from the vehicle as it operates through its driving cycle.

The value in predicting exhaust gas temperature (EGT), as well as measuring it, lies in the fact that the difference between the measured and predicted values can further refine the weights that the neural network model assigns to the relationships between individual model inputs and outputs. In essence, the EGT prediction becomes an onboard engine dynamometer and a key component of the engine diagnostic system.

The addition of further exhaust emissions sensing devices would serve to strengthen the prediction capabilities of the virtual sensing system. The virtual sensor suite thus provides a true learning capability and could enable reconfigurable control in the event of sensor or engine component failure.

Virtual sensor prediction also provides a high level of redundancy, albeit without additional sensor cost or hardware complexity. As an example, the instantaneous fuel consumption of the diesel engine is calculated by the neural network based on the engine speed, rack position, manifold boost pressure and temperature, engine temperature, and (perhaps) measured air flow rate into the engine.

The fact that several input parameters are interrelated and dependent on one another provides a significant level of in-built redundancy if one of the engine sensors in that set fails.

This innovative system has immediate application in engine control, onboard diagnostics, and emissions measurement for light- and heavy-duty vehicles, stationary engines, and marine, off-highway, and locomotive diesels. Future potential applications include emissions monitoring for turboprop engines and gas turbines for propulsion and power. IT

Terminology

Virtual sensor: Microprocessor that uses equations and data from a process to sense other data about that system. For instance, if a virtual sensor knows the temperature and pressure of a vessel containing water, it can deduce what percentage of the gas phase in the tank is water because the processor knows laws and equations and has tables describing the physical behavior of gas liquid systems over a wide range of conditions.

Neural network: A type of artificial intelligence that attempts to imitate the way a human brain works. Rather than using a digital model, in which computations manipulate zeros and ones, a neural network creates connections among processing elements. The organization and weights of the connections determine the output. They are effective for predicting events when the networks have a large database of prior examples to draw on. Neural networks are working in voice recognition, image recognition, industrial robotics, medical imaging, data mining, and aerospace applications.

Drive-by-wire system: A system whereby computerized electric circuits replace mechanical and hydraulic linkages to the steering, brakes, shifter, and throttle.

Behind the byline

Chris Atkinson has a Sc.D. in mechanical engineering, **Theresa Long** a Ph.D. in mechanical engineering, and **Emil Hanzevack a** Ph.D. in chemical engineering. They are cofounders of Calico Systems Inc. (www.calicosystemsinc.com), a high-tech company focused on control, calibration, diagnostics, and virtual sensing, primarily in automotive applications. **Michael Traver** has a Ph.D. and works at Automotive Testing Laboratories, Inc., where he specializes in engine and vehicle testing and development.