

Super Ultra Low Emission System for the Accord SULEV

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ABSTRACT

We developed the Accord SULEV (Super Ultra Low Emissions Vehicle) in order to comply with California's LEV-II SULEV regulations. The emissions system employed is characterized by applying only an under-floor catalyst to attain the super ultra low emissions levels through sophisticated control technology. The improved three-way catalyst achieves both high conversion efficiency and low back pressure while using the same amount of precious metal as was used in the Accord ULEV. ⁽¹⁾

To satisfy SULEV standards using only the under floor catalyst, we developed technologies to increase emissions temperatures by controlling the amount of intake air and the ignition timing before the catalyst is active. This promoted quick catalyst light-off and enabled us to obtain leaner air/fuel ratios when the engine is started than was possible with the previous catalyst system.

Also, in order to further improve the conversion performance of the catalyst once it is active, we developed a New Secondary O₂ Feedback Control System. This is an extremely high precision system that identifies the dynamic changes of the catalyst in real time and utilizes a sliding mode controller mechanism to predict changes in the post-catalyst sensor output.

The implementation of these technologies makes it possible to achieve the most rigorous SULEV standards, with engine output performance equivalent to our ULEV vehicle.

1. Introduction

Worsening air pollution is making it increasingly important to address environmental issues and to find solutions. Automobile emissions are no exception; governments around the world are enacting ever more stringent emission regulations, and the state of California will be enacting the new and more rigorous LEV-II regulations in 2004.

Table 1 indicates emission standards by category as set forth under the LEV-II regulations. Even durability requirements have been revised under the LEV-II regulations so that emissions through 120,000 miles will be regulated.

Fig. 1 indicates the emission standards for NMOG (Non

Methane Organic Gas) under the LEV-I and LEV-II regulations. The new SULEV category has been added in the LEV-II regulations. The SULEV emission standards are extremely strict, being less than 1/5 of the standards under the LEV-I ULEV (Ultra Low Emission Vehicle) regulations, and have been expanded to include emission standards from 50,000 miles up to 120,000 miles. Fig. 2 indicates the NOx emission standards under the LEV-I and LEV-II regulations. Under LEV-II, the NOx standards are more strict, with the

Table 1 LEV-II emission standards (g/mile)

Durability	Category	NMOG	CO	NOx	HCHO
50 kmile	LEV	0.075	3.4	0.05	0.015
	ULEV	0.040	1.7	0.05	0.008
120 kmile	LEV	0.090	4.2	0.07	0.018
	ULEV	0.055	2.1	0.07	0.011
	SULEV	0.010	1.0	0.02	0.004

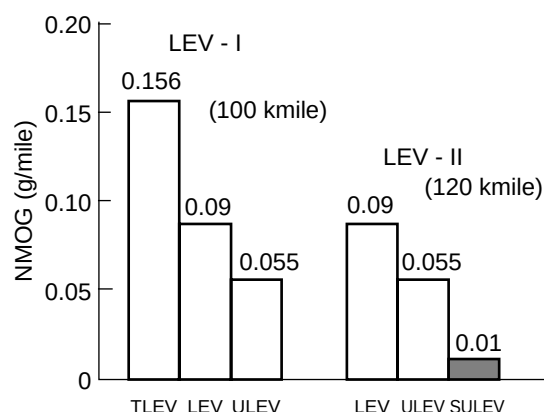


Fig.1 LEV-I and LEV-II NMOG regulations

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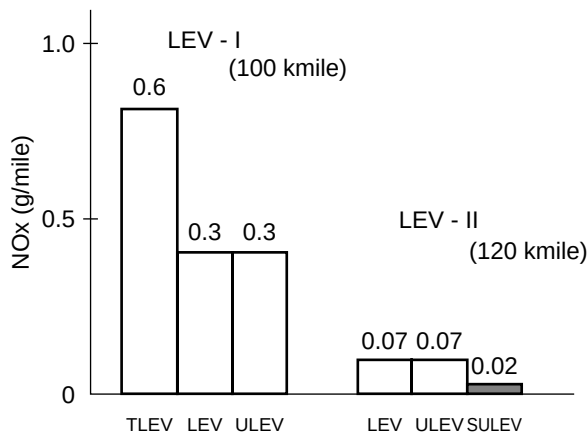


Fig.2 LEV-I and LEV-II NOx regulations

SULEV standard calling for emissions that are less than 1/10 of the standard allowed under LEV-I ULEV.

Honda has developed a Super Ultra Low Emission Vehicle, based on the Accord ULEV, that satisfies the SULEV regulations and has the lowest emissions of gasoline-powered production vehicles in the world. This paper describes the emission system in the Accord SULEV.

2. Technical Concepts Behind the SULEV

As we undertook the development of the SULEV technology, we re-examined the emission performance of the Accord ULEV that is currently being mass produced by Honda, and decided on clear targets for reducing emissions.

Fig. 3 shows the measured emissions from an Accord ULEV, with the FTP (Federal Test Procedure) cycle broken down into three periods. Period A extends from engine startup to the start of driving, period B extends from the end of period A until the engine stops at the end of the LA-4 driving cycle, and period C extends from restart after the hot soak until the end of the test.

In period A, the measured emissions of NMHC (Non Methane Hydrocarbon) and NOx were both twice the level allowed under the SULEV regulations. This period encompasses a cold start and warm-up of the catalyst. Since the catalyst is not fully active during this period, a technology that reduces the engine emissions during this time and that rapidly raises the catalyst temperature for early light-off are both needed. In period B, NMHC emissions were below the SULEV standard, but NOx emissions were at roughly the same level as the SULEV standard. It became clear that in order to satisfy the SULEV regulations, it would be necessary to reduce NMHC and NOx emissions not only in period A but also in period B. Since the catalyst is fully active in this period, the problem at hand was to develop new control technology that would further increase the catalyst conversion efficiency.

The engine is already warmed up in period C, so any technology that can reduce emissions in periods A and B would also be able to reduce emissions in period C.

Although there are a variety of approaches⁽²⁾ available for solving the problem at hand, "simplicity" had been stipulated as one of the basic principles behind the

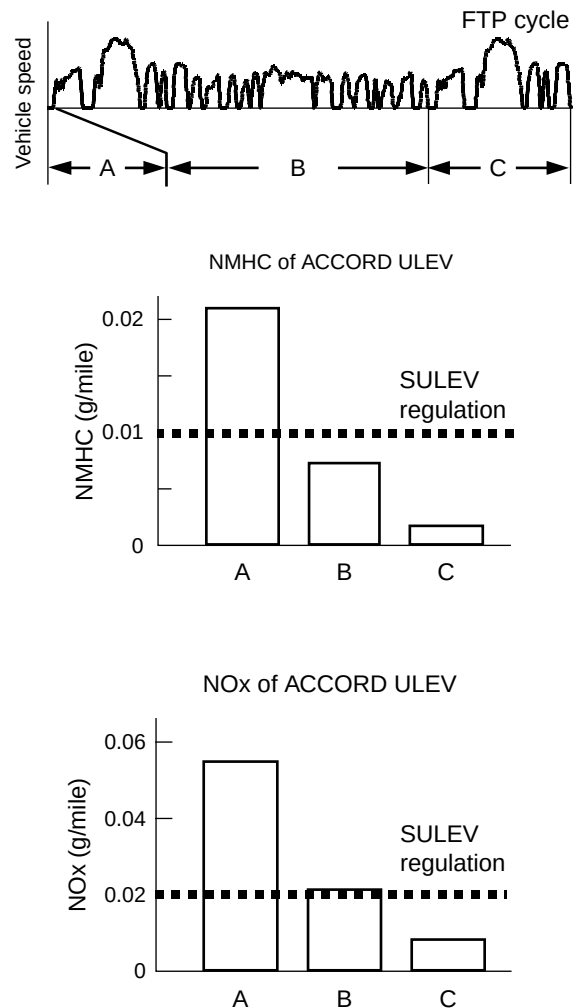


Fig.3 ACCORD ULEV Emissions at A-C period

development of the Accord SULEV. This emphasis on simplicity as a system concept had been carried over from the development of the Accord ULEV, a gasoline-powered car designed by Honda to satisfy California's LEV-I ULEV regulations of September 1997. The Accord ULEV system configuration manifested this simplicity, since the system was built around VTEC-E and a high-precision air-fuel ratio control system, and it utilized only an underfloor three-way catalyst.

In order to meet the stringent SULEV emission regulations, we considered means such as using a close-coupled catalyst or hydrocarbon trap, but there was concern that such means would raise costs and reduce engine output. By utilizing only an underfloor three-way catalyst that could achieve early light-off and provide high conversion efficiency as the result of a high cell density and thin walls, and by developing control technology that could obtain maximum performance from the catalyst, we were able to achieve a low-cost system with low back pressure.

Fig. 4 shows the overall configuration of the system designed to meet the SULEV regulations. The current Accord ULEV system comprises components (a) through (h).

The new technologies that were adopted in the Accord

SULEV system are as follows:

- A catalyst with high cell density and thin walls (1200-cell, 2.0-mil, the precious metal content being equivalent to that of the catalyst used in the Accord ULEV)
- A quick catalyst warm-up control system to achieve early light-off of the catalyst
- Improved AAI (Air Assisted Injector) that boosts the assist air pressure
- Lean burn control after startup that produces an air/fuel ratio that is even leaner than that achieved in the Accord ULEV
- New secondary oxygen feedback control (PRISM: Prediction and Identification type Sliding Mode Control) that maximizes the conversion performance of the catalyst

3. Three-way Catalyst with High Cell Density and Thinner Walls

It is already known that increasing the cell density and reducing the wall thickness effectively improves the conversion performance of a catalyst.

Fig. 5 shows the relationships between the cell density of the newly developed 1200-cell, 2.0-mil catalyst and the surface area and bulk density. Compared with the 600-cell, 4.3-mil catalyst used in the ULEV, the newly developed catalyst has 50% more surface area which provides improved conversion performance.

In addition, the bulk density has been decreased by 35%, which results in improved catalyst light-off performance.

Fig. 6 shows two types of canning construction. The conventional method uses clamshell-type canning whereby the catalyst and holding seal mat are enclosed within an upper and lower case. This construction has a fixed inside case

diameter, so any variation in the diameter of the catalyst and holding seal mat can lead to a significant surface pressure difference being generated during the canning process. Therefore, a catalyst with an isostatic strength of 15kg/cm² or more is required for this type of canning.

The new rolling technology employs a rolled construction by which the catalyst and holding seal mat are fixed after being rolled into the case. This technology has made it

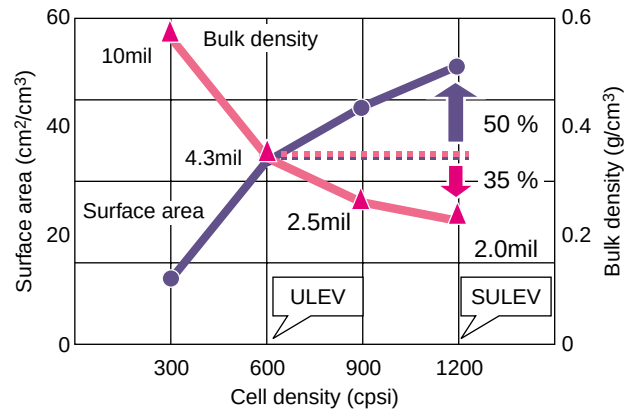


Fig.5 Cell density, bulk density and surface area

Clam shell type canning

Rolling type canning

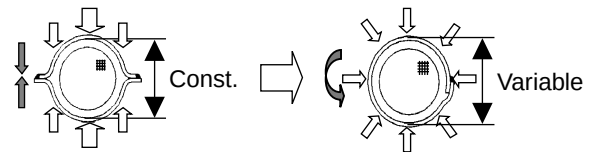


Fig.6 Canning type

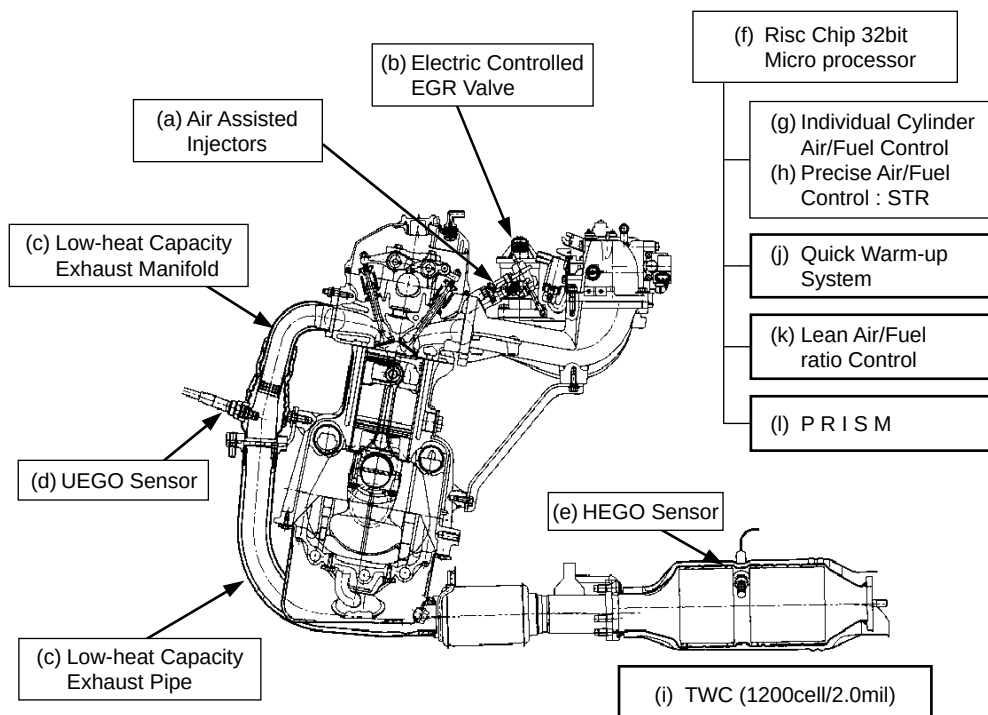


Fig.4 Overview of SULEV System

possible for the surface pressure generated during canning to be evenly distributed around the circumference of the case. It has also made it possible to vary the internal case diameter to match variations in the catalyst diameter. In addition to this rolled-type canning method, selection of the holding seal mat and improvements to the production method have made it possible to reduce the surface pressure generated during canning to less than 5kgm/cm^2 , making canning possible even with a 1200-cell, 2.0-mil catalyst that has low isostatic strength.

While there was some concern about a lower engine output due to greater exhaust pressure loss caused by the increased number of cells, we were able to minimize the decrease in engine output by making the catalyst walls thinner.

Fig. 7 shows the engine output characteristics for the Accord ULEV and the Accord SULEV. The power and torque produced by the SULEV at below 4000rpm are both equal to those produced by the ULEV, indicating no adverse effects from the 1200-cell catalyst, while at maximum output, the decrease in power is only 2kW and the decrease in torque is only 5Nm.

Fig. 8 shows the measured emissions in the LA-4 mode when a 600-cell, 4.3-mil catalyst (aged 100,000 miles) and a 1200-cell, 2.0-mil catalyst (aged 120,000 miles) were installed in the same vehicle. The higher cell density and thinner walls produced a 31% decrease in NMOG emissions and a 48% decrease in NOx emissions. Although a palladium catalyst (Pd, 330g/ft³) is used in the mass-produced version of the ULEV, a tri-metal catalyst (Pt/Pd/Rh = 1:15:1, 330g/ft³) was adopted for the SULEV in order to address the stricter NOx standards.

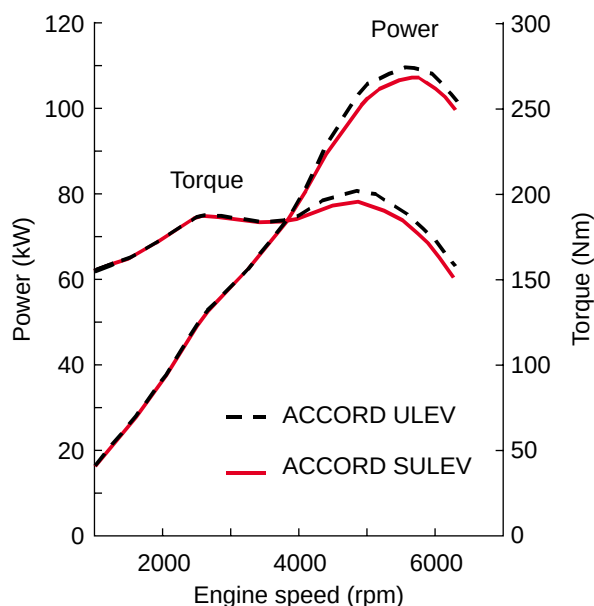


Fig.7 Characteristics of power and torque

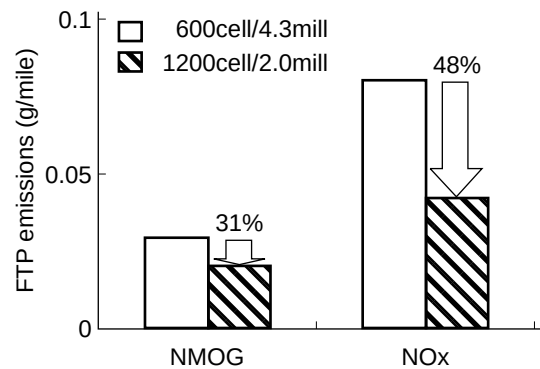


Fig.8 Comparison of emissions between 600 cell and 1200 cell catalysts (FTP cycle)

4. Technologies for Reducing Emissions at Startup and Immediately After Startup

Although a catalyst with a higher cell density and thinner walls made possible a major reduction in emissions, it was not enough by itself to satisfy the SULEV regulations. Therefore, we further reduced the emissions through engine control by achieving earlier catalyst light-off at startup and improving the lean-burn characteristics after startup.

4.1. Quick Warm-up System

The temperature of the exhaust gas begins to rise immediately after the engine is started; a three-way catalyst absorbs energy from the exhaust and thus also heats up becoming more active. It is well-known that retarding the ignition timing is an effective means for increasing the temperature of the catalyst. We created a system (the "Quick Warm-up System"⁽³⁾) that, immediately after a cold start (when the three-way catalyst is not active), uses an RACV (Rotary Air Control Valve) to control the air intake, while simultaneously controlling the ignition timing.

Fig. 9 shows the characteristics of this control system. The horizontal axes represent time, and the vertical axes

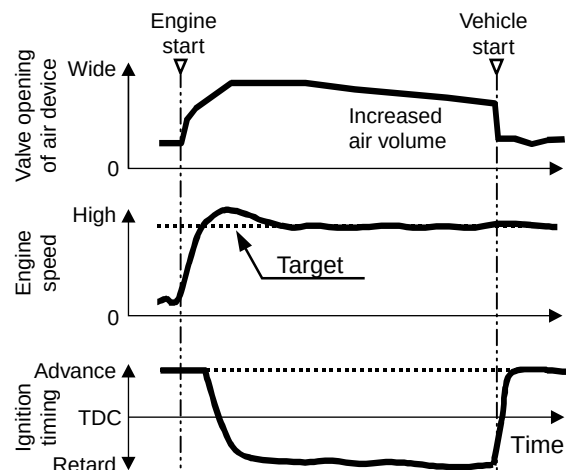


Fig.9 Ignition feedback control for Quick Warm-up System

represent the RACV opening, engine speed, and ignition timing, respectively, from the top. While the engine is idling after startup, the Quick Warm-up System uses the RACV (by means of feed-forward control) to supply a large quantity of intake air. When the engine speed exceeds a preset level, PI (proportional + integral) feedback control of the ignition timing begins. Here, the ignition timing is controlled to maintain the target engine speed. As indicated in the diagram, as the intake air is increased, the ignition timing is retarded in order to maintain the target engine speed. Fig. 10 shows a comparison of the ignition timing and exhaust gas temperature with the Quick Warm-up System used in the SULEV and those with the ULEV system. Twenty seconds after startup, the exhaust gas temperature is 240°C higher with the SULEV system than with the ULEV system. This makes rapid light-off of the catalyst possible.

4.2. Improved Lean-burn Control after Startup

Fig. 11 shows the flow of intake air into this engine with the VTEC-E system. A swirl is generated by opening only one inlet valve, making possible lean control of the air/

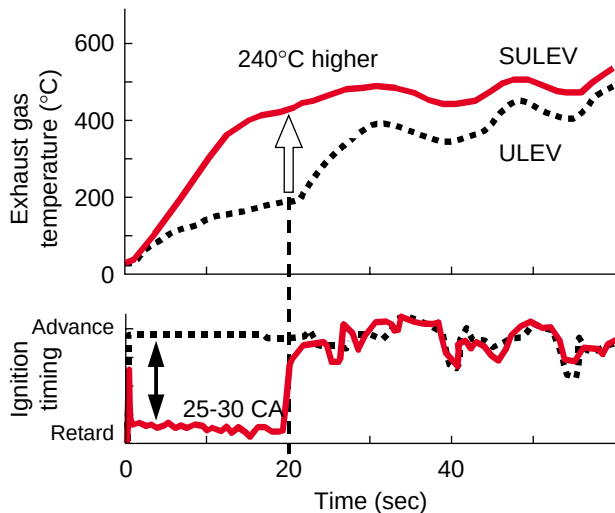


Fig.10 Effect of Quick Warm-up System at start-up period of FTP cycle

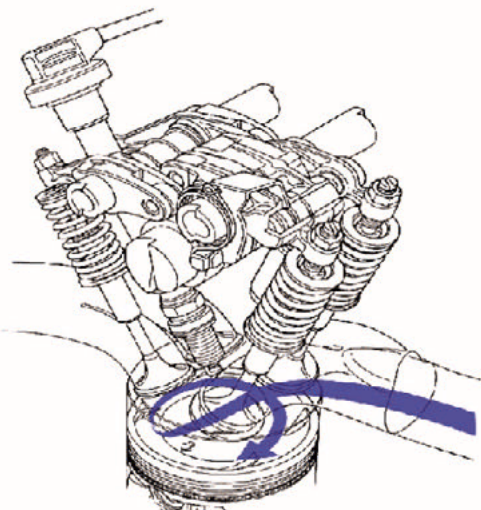


Fig.11 VTEC-E system

fuel ratio after startup. The result of making the fuel spray extremely fine and using the Quick Warm-up System is that it is possible to achieve stable lean-burn control very soon after startup.

Fig. 12 shows the Sauter mean diameter (measured by LDSA) of the fuel sprayed by the air-assisted injectors. The spray is measured at a point 100mm directly above the injector.

Compared with the injectors used in the ULEV system, improvements to assist air pathways have reduced the pressure loss, resulting in a fuel spray that is 35% finer than before.

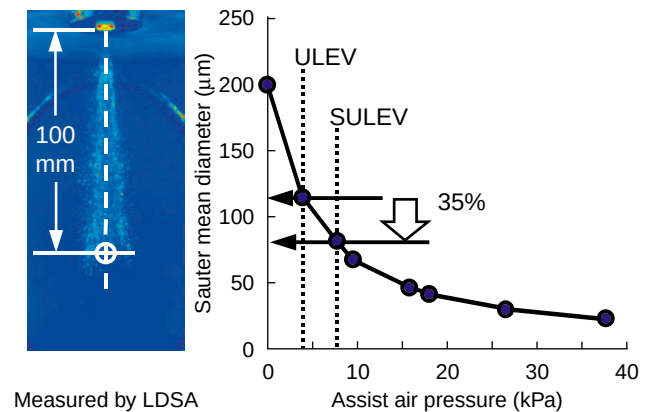


Fig.12 Air assisted injection spray characteristics

The Quick Warm-up System also offers benefits other than earlier catalyst light-off. Fig. 13 depicts the intake manifold pressure and the lean air/fuel control at the start of the FTP cycle for both the ULEV system and the Quick Warm-up System. Since this system delivers more air at startup, the engine can run in a higher load range than before, and combustion is more stable. As a result, the lean-burn range after startup is expanded and combustion is improved, as shown by the lower graph in Fig. 13.

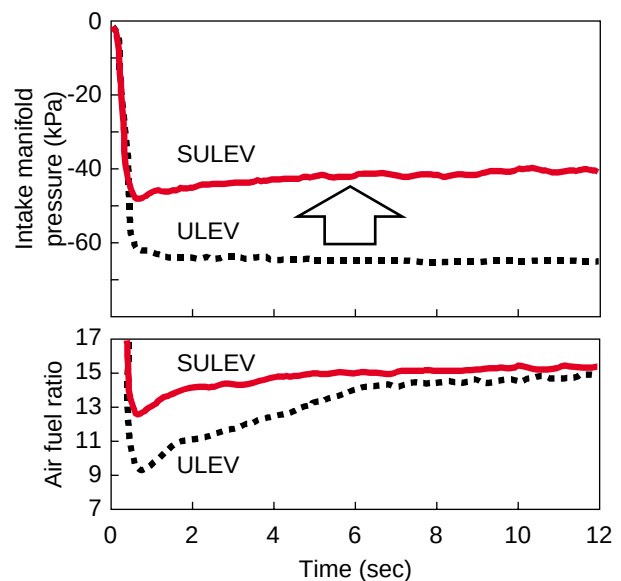


Fig.13 Lean air fuel control at start-up in the FTP cycle

Fig. 14 shows a comparison of the emissions produced by the SULEV system and the ULEV system in the sixty-second period after startup in the FTP cycle. The upper graph shows the total hydrocarbons and the center graph shows the NOx emissions. Each emission component shows the dramatic decrease achieved by using the Quick Warm-up System and expanding the lean-burn range. This improvement is the result of reducing cold-start emissions and the early light-off of the catalyst. Furthermore, the peak emissions come sooner with the SULEV system than with the ULEV system due to the large volume of air that is fed into the engine after startup by the Quick Warm-up System.

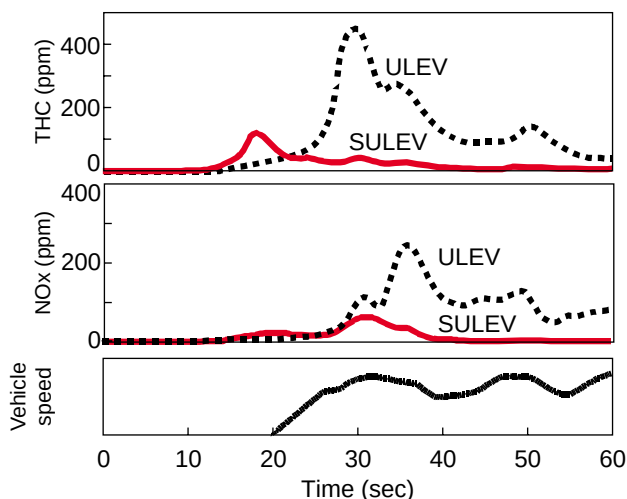


Fig.14 Emissions reduction effects of the SULEV system at startup in the FTP cycle

4.3. Vehicle Test Results

Fig. 15 quantifies the emissions in the CT phase of the FTP cycle. Most of the emissions in the CT phase occur during the first twenty seconds after startup.

As can be seen by the significant reduction in emissions shown in Fig. 14, the SULEV system reduces NMOG emissions by 70% when compared with the ULEV system, and reduces NOx emissions by 35%. This demonstrates that the SULEV control system utilizes the VTEC-E system and three-way catalyst to their maximum potential.

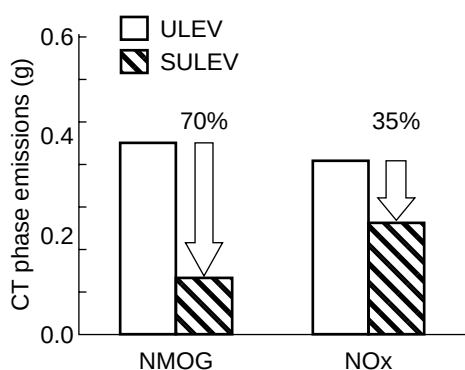


Fig.15 Emissions reduction effects of the SULEV system

5. Technologies for Reducing Emissions after Light-off of the Three-way Catalyst

Although we were able to attain high conversion efficiency by using a high cell density, thin-walled (1200-cell, 2.0-mil) catalyst, a further reduction in emissions was needed after catalyst light-off in order to satisfy the SULEV regulations. A control system based on pre- and post-catalyst air/fuel ratio sensors was previously used to obtain maximum conversion performance from a three-way catalyst. The Accord ULEV similarly used feedback control based on an UEGO sensor (Universal Exhaust Gas Oxygen Sensor), with corrections made to the air/fuel ratio in response to the output from the post-catalyst HEGO sensor (Heated Exhaust Gas Oxygen Sensor). This type of system is typically known as a "Secondary Oxygen Feedback Control System," and its purpose is also to enhance the conversion performance of a three-way catalyst.

We developed for the SULEV system a control technology that would improve the conversion performance of the catalyst beyond that of the Accord ULEV system. Although the purpose of high-precision control is to precisely control the air/fuel ratio for optimal catalyst conversion efficiency, there is an extremely long dead time until the amount of fuel sprayed by the injector to achieve the desired air/fuel ratio is detected by the post-catalyst HEGO sensor. It was essential that we take this dead time into account. Furthermore, we needed to always keep in mind the changing characteristics of the catalyst that occur as a car logs mileage.

Fig. 16 shows an overview of the new feedback control system. A subsystem that calculates the target value for the air/fuel ratio has been added to the STR (Self-Tuning Regulator)⁽⁴⁾⁻⁽⁶⁾ that was adopted in the Accord ULEV. This new subsystem consists of three modules: the Identifier, the Predictor, and the Sliding Mode Controller. The subsystem is called "PRISM" (Prediction and Identification-type Sliding Mode Control).⁽⁷⁾⁽⁸⁾

Identifier: This contains an internal catalyst model (a numerical model comprising the dead time and a low-pass filter), and identifies the dynamic characteristics of the catalyst model in real time based on the pre- and post-catalyst sensor output. As a result, the system can adapt in real time to changes in the catalyst characteristics while the engine is running.

Predictor: This predicts future values of the output from the post-catalyst HEGO sensor on the basis of catalyst model parameters q (a_1 , a_2 , b_1) calculated by the Identifier, and on the basis of pre- and post-catalyst sensor outputs. This module compensates for the long dead time between the actuator and the post-catalyst sensors, resulting in improved performance of the control system.

Sliding Mode Controller: This robust controller uses adaptive sliding mode control⁽⁹⁾.

Fig. 17 illustrates the operating principles of sliding mode control. The Sliding Mode Controller in the PRISM module limits sensor output VO_2 to the switching line in the phase plane with the difference between the HEGO sensor output and target values as the axes, and controls the output by sliding it to the origin. In order to bring VO_2 to the target value, the Sliding Mode Controller calculates the target air/

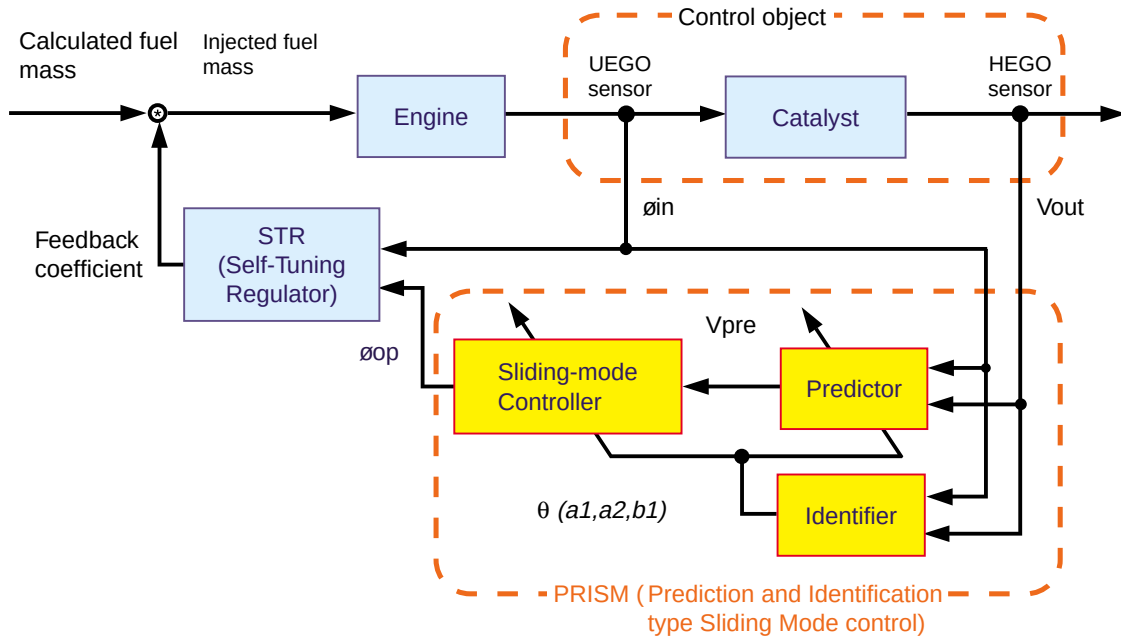


Fig.16 Overview of SULEV Feedback-System

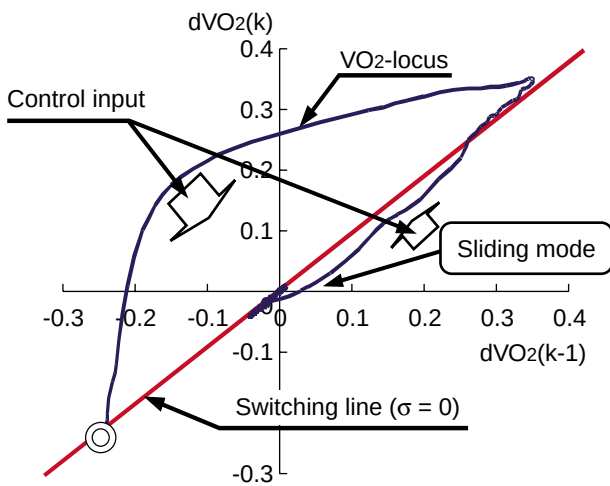
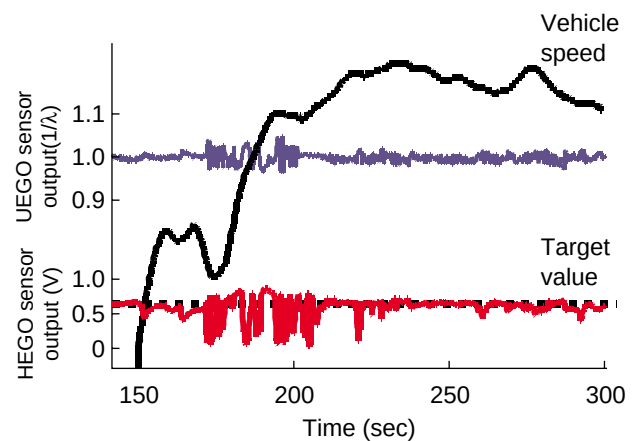

 Fig.17 VO_2 -locus in Phase plane


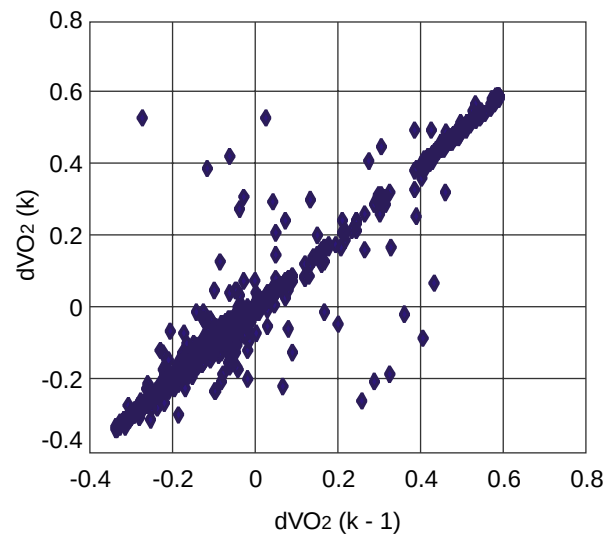
Fig.18 Improved controllability of secondary HEGO sensor output

fuel ratio for the STR (Self-Tuning Regulator), which performs pre-catalyst air/fuel ratio feedback.

Fig. 18 shows the control states of PRISM during the FTP cycle. The output from the post-catalyst HEGO sensor is controlled very well at around the target value without becoming stuck at 0V (a lean atmosphere) or 1V (a rich atmosphere). This indicates that the atmosphere in the three-way catalyst is always in the vicinity of the stoichiometric air/fuel ratio, which clearly demonstrates that PRISM precisely maintains the air/fuel ratio that is best suited for the three-way catalyst.

Fig. 19 shows the sliding mode control states. This figure clearly indicates that HEGO sensor output VO_2 is limited to a switching function in the dVO_2 phase plane.

Fig. 20 shows a comparison between the measured emissions for a ULEV system and PRISM when using the


 Fig.19 Secondary HEGO sensor output in phase plane (LA-4 2ND hill)

1200-cell, 2.0-mil catalyst. The graphs show that PRISM reduces NMOG by 20% and NO_x by 48%; PRISM is clearly effective in reducing NO_x, which is particularly sensitive to variation in the air/fuel ratio. PRISM has made it possible to further improve the conversion efficiency even after the catalyst has warmed up.

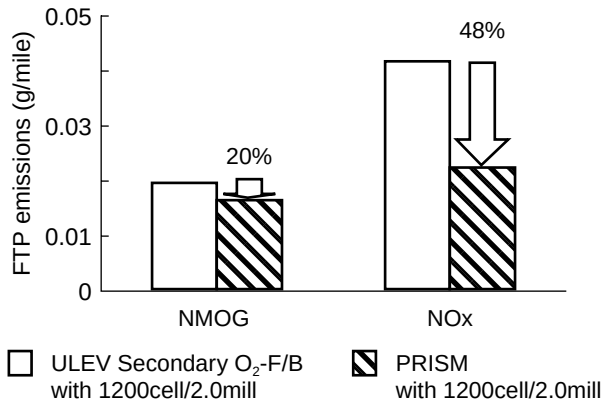


Fig.20 Comparison of ULEV's Secondary O₂ Feedback and PRISM

6. Conclusion

We were able to develop the Accord SULEV in compliance with the LEV-II SULEV regulations by combining the technologies described in this paper. Table 2 shows the emission levels that have been achieved with this system.

In keeping with our original principles, we were able to configure an extremely simple system without adding any special hardware. This system enables us to offer a car that complies with the Super Ultra Low Emission Vehicle regulations while maintaining engine performance that is to that of the Accord ULEV.

Table 2 ACCORD SULEV emissions
In-house data

	NMOG	CO	NO _x
STD Values	0.010	1.00	0.020
Achieved Values	0.0084	0.16	0.016

(g/mile)

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