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The Internal Combustion Vehicle with the Lowest Emissions

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We extend a special word of thanks to Mr. Shigeaki Kakizaki at Nissan Motor Co., Ltd., Advanced Engine Engineering Department, for providing information and illustrations.

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By Thomas Pöhlmann, dSPACE GmbH

Abstract:
Since January 2000, the new Nissan Sentra CA is being sold on California's automobile market. With this vehicle, Nissan has accomplished a significant breakthrough: They produce the first gasoline-powered car that fulfills California's strict P-ZEV Standard (Partial Zero Emission Vehicle). A decisive factor for Nissan's success is that they successfully turned their ideas into reality at a fast pace and with great flexibility. Using TargetLink by dSPACE, their development team implemented the essential engine control components with automatically generated C code, directly from the development environment MATLAB/Simulink. TargetLink helped bring the vehicle to production stage quality within an extremely short time.

Nissan has blazed a trail that other manufacturers are sure to follow sooner or later. The Nissan Sentra CA, introduced at the Detroit Motor Show in January 2000, is the first vehicle with a conventional internal combustion engine to fulfill the Partial Zero Emission Vehicle Standard and already meet the upcoming Californian requirements.

A critical step when developing such innovative concepts is always the programming of the electronic control units (ECUs): When programmers carry out this step via handcoding, too much time is required to transform control algorithms into ECU code. Nissan's plan, however, was to launch the Sentra CA on the American market as quickly as possible. To do so, Nissan conducted development and tested automatic production code generators at the same time.

The Decision on TargetLink

After evaluating various production code generators, Nissan placed their trust in TargetLink by dSPACE, mainly due to the advantages that this program offers:

- efficient, extremely reliable ANSI C code
- code generation directly from MATLAB/Simulink/Stateflow
- easy, practical operation
- highly readable code with high-quality documentation
- adaptability to Nissan's development environment

TargetLink also offers intelligent test mechanisms to compare the generated code to the specifications. For example, users can test the generated code, study the differences between fixed-point and floating-point simulation, and trace any potential implementation errors. With evaluation hardware connected to TargetLink, the generated code can also be executed directly on a target processor. This even makes compiler errors and target hardware errors visible. Consequently, unpleasant surprises when programming the actual ECU are a thing of the past.

By using TargetLink, the development team at Nissan was able to quickly transform many of their initial ideas into ECU code. For example, they recognized a large optimization potential for increasing the catalytic converter's efficiency in the air-fuel ratio control. As a result of their efforts, a unique, optimized lambda control was developed for the Sentra CA. The developers mainly let TargetLink handle the C coding, which enabled them to dedicate more time to their own control tasks. This method paid off: TargetLink's automatic code generation reduced the development time for this complex control to 60%.

The Goal: Optimized Catalytic Converter Efficiency

The air-fuel ratio must be tuned continuously so that the catalytic converter can operate at an optimal performance rate. The challenge is to have the engine combustion steadily maintain the stoichiometric air-fuel ratio where the ideal theoretic combustion occurs. The goal of Nissan's development team was to maintain the air-fuel ratio at the optimized working point even more precisely. The new control could therefore allow only an extremely narrow tolerance range. This is a particularly demanding control task because the dead times in the control loop complicate the development of rapid controls, thereby making it more difficult to improve the catalytic converter's efficiency.

To meet these demands, the control implemented in the Sentra CA has a total of three lambda sensors. A special observer continuously determines the current oxygen proportion in the catalytic converter. The values are then used by a feed-forward control to regulate the air-fuel ratio. MATLAB/Simulink by The MathWorks was applied to develop this control.

Conversion with TargetLink

TargetLink performs automatic code generation directly from MATLAB/Simulink – with a single press of a button. This proved to be a great advantage for Nissan's developers: They were able to generate the ECU code from the model without leaving the modeling environment at all.

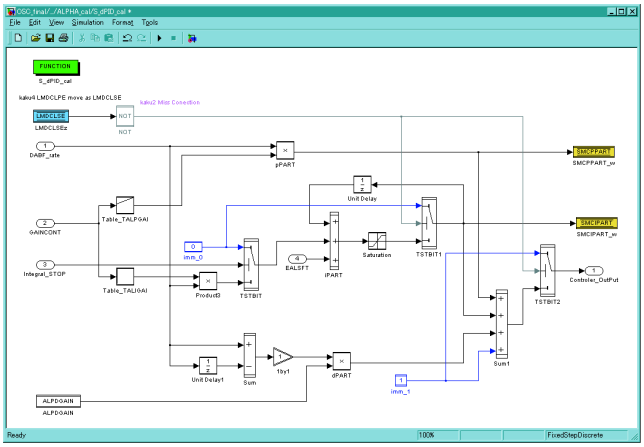

Figure 1: Graphical programming of the air-fuel ratio control and automatic production code generation with TargetLink.

To prepare the Simulink/Stateflow model for code generation with TargetLink only a few modifications had to be made. For this step, TargetLink offers a practical user interface where all the necessary settings can be determined.

TargetLink then automatically transforms the model into ANSI C code. This makes modifications during a later stage much easier: Alterations are completed directly in MATLAB/Simulink and converted in a new C code via TargetLink. The code is extremely readable and well documented, which further simplifies its integration into the existing project.

During the code generation, TargetLink performs optimizations to ensure, for example, that unnecessary intermediate variables are not transformed into code. This guarantees that the generated fixed-point code always has a very high efficiency and reliability. Nissan's development team was therefore able to implement the code directly in the ECU.

Extremely Successful Project Completion

The complex air-fuel ratio control was developed in just three months. This includes the time required for the entire controller development and for the final transfer into ECU code. Within this incredibly short development time the vehicle was ready for the Detroit Auto Show in January 2000.

Even when the time required for training in TargetLink is included in the time schedule, Nissan still reduced their development time significantly. As a consequence, they are now planning to use this innovative development method, based on automatic code generation, in future projects as well. For example, Nissan's Advanced Engine Engineering Department intends to completely integrate TargetLink into its own development environment.

The Success of the Sentra CA – The First Gasoline-Powered SULEV Vehicle

The Sentra CA is the first gasoline-powered car that already meets the SULEV Standard and will also fulfill future Californian standards as a Partial Zero Emission Vehicle (Partial-ZEV). In comparison to the former cleanest production vehicle in California, the Sentra CA generates only one fourth of the hydrocarbon and one tenth of the nitrogen oxide.

The Sentra CA also meets the requirements of the California Air Resources Board (CARB) regarding "Zero Evaporative Emissions." This means that with the Sentra CA – unlike with any typical vehicle – no fuel vapors are emitted from the fuel system. This is not the first time that Nissan has launched an astonishing new innovation. Already in 1999 Nissan was the only automobile manufacturer to receive the Climate Protection Prize of the U.S. Environmental Protection Agency (EPA).

For the Sentra CA, Nissan relies on a conventional combustion drive, since this still carries advantages over other drive concepts for combustion engines:

- Intact infrastructure (filling stations)
- Range, driving performance and safety levels meet those of previous vehicles
- Favorable retail price
- Highly reliable technology
- Drive concept is applicable worldwide

The only disadvantage is that California is currently the only region where fuel with a very low sulfur percent is available. As a result, for the time being, California is the only state where the Sentra CA can utilize its full potential.

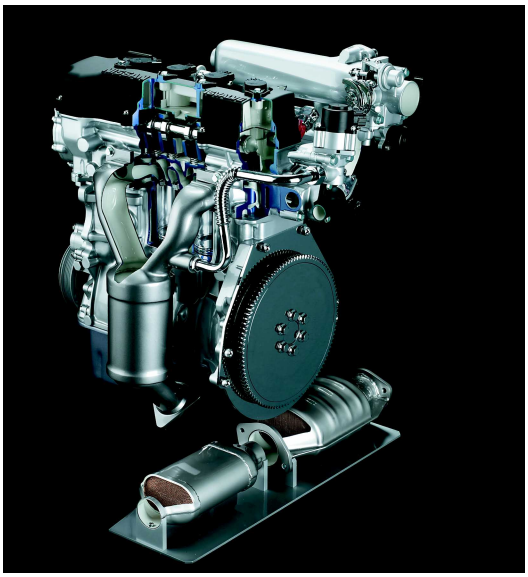

Figure 2: The first conventional engine that meets SULEV - the engine of the Sentra CA.

Current and Future Exhaust Regulations

Even though emission levels of today's modern motor vehicles are becoming increasingly better, the air quality in many metropolises still proves to be unsatisfactory. Solar radiation converts the emitted nitrogen oxide, particles and unburned hydrocarbon into notorious smog. In addition, the ozone levels are being exceeded more often due to the high amount of unburned hydrocarbon, which is responsible for the formation of ozone.

The situation is especially dramatic in Los Angeles, the city with the worst air quality in the USA. This megalopolis carries a heavy burden due to its enormously high number of combustion vehicles, and the formation of smog in this region is promoted by the city's geographic location and high solar radiation.

Consequently, the USA (especially California) has long been the forerunner as its government pushes for stricter exhaust norms that are implemented step-by-step. For conventional vehicles, stricter regulations have led to a considerable improvement in exhaust emissions. Recent examples are the dramatic reduction in the emission of unburned hydrocarbons over the past decades and the introduction of three-way catalytic converters.

ULEV, SULEV and Zero Emission Vehicles

Just like in Europe, new registered vehicles in California must not exceed specific emissions limits. But to promote environmentally friendly vehicles even more, the car manufacturers' entire vehicle ranges are also evaluated.

Each car manufacturer is required to sell at least a certain percent of low emission vehicles. The currently valid exhaust standard for these low emission vehicles is ULEV (Ultra Low Emission Vehicle), which allows an emission of 0.04 g/mile NMOG (non-methane organic gases, meaning hydrocarbons with the exception of methane). The government-required minimal percent of vehicles that conform to ULEV will increase greatly over the next years.

In addition to ULEV, new, even stricter emission regulations will be introduced in the future. These new laws must also be met by at least a certain percent of vehicles. A large gap is predicted for the model year 2003: As of 2003, 10% of all new registered vehicles by a manufacturer must fall into the Zero Emission Vehicles (ZEV) category, which designates vehicles that produce no local exhaust at all. At the moment, only electrical vehicles make this possible; and realistic predictions indicate that this vehicle type will not reach a high acceptance in such a short time span.

For this reason, the regulations have left a different option open for automobile manufacturers. Only 4% of the new registered vehicles must actually qualify as ZEV vehicles. To reach 10%, manufacturers can provide the missing 6% via other vehicle types, if these vehicles fulfill the new SULEV Standard (Super Ultra Low Emission Vehicle).

In comparison to ULEV, SULEV only allows one fourth of the emissions, resulting in 0.01 g/mile NMOG. A vehicle cannot help fulfill the 10% ZEV proportion until it can maintain these values over 150,000 miles. For example, a natural gas vehicle conforming to the SULEV requirements receives up to 0.4 ZEV credits, which means that 15% of the automobile manufacturer's sales must be attributed to this vehicle type in order to acquire the necessary 6% ZEV. In contrast, a gasoline-powered vehicle can only reach a maximum of 0.2 ZEV credits.

The SULEV Standard was introduced to compare different drive concepts and their environmental compatibility. Up to now, only 'alternative' drive concepts were capable of meeting the SULEV Standard: electric vehicles, electric hybrid vehicles, natural gas vehicles, and fuel cell vehicles are traditionally placed in the SULEV category. The ground-breaking Sentra CA is the first conventional gasoline-powered vehicle that can also fulfill this standard.

New Technologies for the Sentra CA

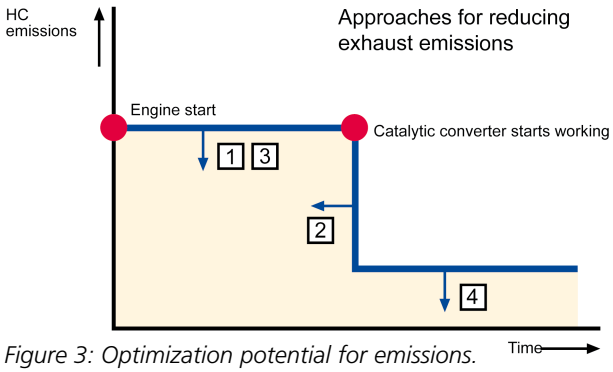

Figure 3: Optimization potential for emissions.

The new technologies utilized by the Sentra CA also required a wide range of clever innovations. The air-fuel ratio control described above is just a starting point for improving the emission of harmful substances, even if it is the most effective method. The case of unburned hydrocarbon is a prime example for showing where the potential for further improvements in modern combustion engines lies. When one considers the time curve of the emissions over a period of time, the following points are evident (Figure 3):

1. Reduced engine emissions
2. Shortened response time of the catalytic converter
3. Fewer hydrocarbons before starting the catalytic converter
4. Improved catalytic converter efficiency (engine control, as described above)

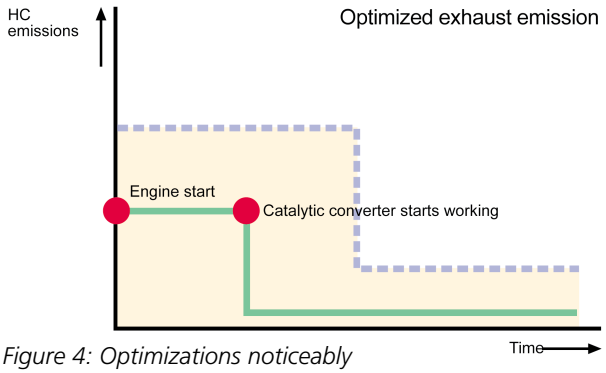

Figure 4: Optimizations noticeably reduce emissions.

The corresponding curve for the Sentra CA is considerably better because Nissan made decisive improvements at all four points (Figure 4).
Point 4, improved catalytic converter efficiency, has already been described above.

Reduction of the Engine Emissions

With the Sentra CA, Nissan dramatically reduced engine emissions. This was made possible in part by using innovative technologies such as high-speed fuel intake and high swirl combustion. The high swirl combustion in particular ensures a good air utilization where the particle emissions can be reduced.

Shortening the Response Time of the Catalytic Converter

A conventional combustion engine never burns all of the hydrocarbons in the fuel. A residue of unburned hydrocarbons is always present in the exhaust. These are burned later in the catalytic converter as soon as it reaches its operating temperature. A modern catalytic converter requires a high operating temperature: For example, a catalytic converter does not perform any significant emission conversion until it passes approx. 250° C. This warm-up time can be reduced when electrically heated catalytic converters are employed. The disadvantage, however, is that such electrically heated converters are rather expensive and require a high voltage.

Nissan therefore applied a new type of catalytic converter for the Sentra CA. The coating material of the catalytic converter is extremely thin and thus heats up much quicker. In addition, due to the thin coating, the structure of the catalytic converter's cells can be constructed in a much finer manner. The result is that many more cells can be placed within the same space, which guarantees an improved post-combustion of the unburned hydrocarbons and also increases the efficiency of the catalytic converter.

Reduction of the Hydrocarbons Before Starting the Catalytic Converter

Starting the catalytic converter can require a long time, depending on the outer temperature and engine load. To stop these hydrocarbons from being emitted, the Sentra CA includes two additional catalytic converters that bind the hydrocarbons with a storage material. As soon as the catalytic converters reach their operating temperature these hydrocarbons are burned. This method considerably reduces the emission levels during engine start-up.

An Additional Measure: Reducing the Ozone While Driving

A further innovation that the Sentra CA has to offer is the treatment of ozone. The fins of the radiator are coated with a unique catalyst (PremAir®). According to the manufacturer (Engelhard Corp.) this catalyst can convert up to 80% of the ozone molecules (0_3) that pass through into oxygen molecules (0_2).

No Evaporations at All

Conventional cars constantly evaporate fuel from the fuel circulation system and the fuel tank. The amount of this evaporated fuel depends on numerous factors. When the engine is running the amount of evaporation is high. It is also rather high after the vehicle was just in operation and is still warm. A vehicle evaporates fuel even when it is parked for a long time: When the solar radiation is quite strong the fuel system can reach a high temperature, which promotes evaporation. In modern vehicles these evaporations are captured, for the most part. Charcoal canisters store the unburned hydrocarbons and feed them back into the fuel system during the next drive.

Nissan took this principle one step further by planning to suppress these evaporations completely. The Sentra CA includes a charcoal canister with an increased capacity. In addition, the vehicle relies on new technologies and materials for the fuel tank, fuel line and connectors. Nissan's success speaks for itself: The Sentra CA fulfills the requirements of the California Air Resources Board (CARB) regarding "Zero Evaporative Emissions." This means that the Sentra CA – in comparison to other vehicles – does not evaporate any exhaust from the fuel system.

Future Outlook

The increasing complexity of vehicle technology is placing great demands on the automobile industry. The growing number of ECUs and stricter regulations demand a great deal of development efforts, which is becoming more and more difficult to meet by conventional means. This especially affects the programming of the ECU code, which programmers will soon not be able to handle alone.

Successful developments, such as the fuel-mixture control of the Nissan Sentra CA, clearly show that goal-oriented development with state-of-the-art development tools is becoming increasingly important. In the future, automatic production code generators that can generate production code directly from a development model within the shortest time possible will play a key role in ECU development. The reason is that only this kind of code generator can transform the complex controls into production code within a reasonable time.

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