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A 2-Stage Approach to Diesel Emission Management in Diesel Hybrid Electric Vehicles

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Abstract: A two-stage approach to Diesel emission management in Diesel Hybrid Electric Vehicles is presented. The first aspect of this work focuses on a supervisory control strategy for charge-sustaining, parallel HEV drivetrains, which provides the a real-time control policy for the use of a CIDI engine and an electric motor, while simultaneously minimizing fuel consumption and reducing NOx emissions. Results show that only limited, although not negligible, gains in NOx emission levels can be achieved through the optimal control of the HEV drivetrain, necessitating an aggressive aftertreatment strategy. In the second facet of the work, an aftertreatment system is presented consisting of a set of parallel Lean NOx traps and a novel set of actuators for providing heat and/or hydrocarbons independent of the engine control strategy. The proper control of this system is obtained by a relatively simple dynamic model of the NOx absorbers, coupled with a real-time estimator of the NOx engine-out emissions based on the engine operating points (set by the control strategy) and their transient behavior. The system shows the potential to decrease NOx emissions by 90%. *Copyright © 2002 IFAC*

Keywords: Diesel emissions, Diesel after-treatment, Lean NOx traps, Hybrid Electric Vehicles, Supervisory control strategy

1. INTRODUCTION

It has long been known that C.I. engines, with their intrinsically higher efficiency, are one of the viable solutions for addressing global concerns about the CO_2 emissions from automobiles. However, despite very significant recent advances in C.I. engine technology with the advent of common rail, direct injection engines, NOx emissions represent one of the toughest technological challenges to overcome for this engine technology to comply with upcoming emissions standards, while offering significant improvement in CO2 emissions. At the same time, hybrid electric vehicles (HEV) have emerged as a strong medium-term technology choice to address both fuel economy and emissions. In the North American market, SUV's and light trucks have gained a very significant market share in the last 5 years, with the inherent drawback this implies in terms of overall levels of fuel consumption and emissions. In this context, one of the viable solutions to meet consumer demand for SUV's and light trucks while making significant progress towards fuel economy and emissions, is to implement hybrid electric powertrains in such a class of vehicles. Furthermore, it is highly desirable from an efficiency standpoint to take advantage of modern CIDI technology in such a powertrain. While very impressive fuel economy gains have achieved by such an approach (Brahma *et al.*, 2001, Paganelli *et al.*, 2001), NOx emissions become the largest technical hurdle to address. The hybridization of the drivetrain significantly exacerbates the intrinsic CIDI emission problem, as much of the significant gain in fuel economy in HEV's stems from the downsizing of the engine afforded by the hybridization, hence resulting in a significantly increased average load on the combustion engine. This increased load is then directly responsible for the increased NOx emissions from such powertrain. In this paper, we present a 2-tier approach to mitigating NOx emissions from such a powertrain. The first aspect of this work focuses on a supervisory control strategy for a parallel HEV drivetrain which attempts to optimize both the fuel economy and the NOx emissions by managing the instantaneous power split between the CIDI engine and the electric motor. The second aspect is to provide an aggressive approach to NOx aftertreatment to further reduce the tail pipe NOx emissions.

2. SUPERVISORY CONTROL STRATEGY FOR FUEL ECONOMY AND EMISSIONS

In the past, we have developed and successfully implemented an HEV supervisory control strategy to optimise fuel economy, so-called equivalent consumption minimization strategy (ECMS) ((Brahma *et al.*, 2001, Paganelli *et al.*, 2001).

2.1. Overview of Equivalent Consumption Minimization Strategy

This equivalent consumption minimization strategy (ECMS) is a quasi-static supervisory level HEV powertrain control strategy that optimizes the instantaneous torque split between the ICE and EM to minimize the instantaneous "equivalent" fuel consumption, while instantaneously meeting the driver demand:

$$T_{ICE,DS,OPT} = \min_{T_{ICE,DS}} \left\{ \dot{m}_{f,equiv} \right\}$$

This instantaneous "equivalent" fuel consumption is defined as a sum of actual fuel consumption by the ICE and the equivalent fuel consumption by the EM:

$$\dot{m}_{f,equiv} = \dot{m}_{f,ICE} + \dot{m}_{f,EM}$$

where the equivalent fuel consumption by the EM, $\dot{m}_{f,EM}$, is estimated from the electrical power of the EM (positive and negative) multiplied by an average fuel cost associated with the electric use in the long term by the vehicle. In charge-sustaining hybrids, all the net energy used by the vehicle is supplied in the form of fuel, so that instantaneous electrical usage either diminishes or increases past or future fuel usage by the ICE. This equivalency factor needs to be "tuned" over significant lengths of vehicle usage/driving cycles with a given powertrain configuration to be representative (*i.e.,* a period of time much longer than the shallow charge/discharge cycles encountered by the battery). In that sense, the equivalency factor between electrical usage and fuel usage represent an average round-trip efficiency for the electricity over all possible energy paths/operating conditions encountered by the powertrain. Such a quasi-static, instantaneous strategy does not lead to optimum trajectories which are charge sustaining. To instantaneously enforce the global charge-sustaining constraint, the above formulation is modified by shifting the unconstrained optimum torque split toward or away form the use of the EM, according to a non-linear penalty function which depends on the instantaneous battery state-of-charge with respect to its targeted range (Paganelli *et al.*, 2001. This penalty approach to enforce the global constraint has been proven to lead to nominally (within the allowed bounds) charge-sustaining powertrain trajectories regardless of the driver demand. In this study, the ECMS framework was extended to include the NOx emissions to the fuel cost.

2.2 Extension to Include Emissions

In this section, the methodology of including the emissions characteristics to the ECMS is described. The emissions characteristics were included by modifying the cost function (equivalent fuel consumption) to optimize as follows:

$$\dot{m}_{f,equiv,modified} = (1-\lambda)\dot{m}_{f,equiv} + \lambda \left(\sum_{\substack{i=CO,HC,\\ NOx,PM}} \alpha_i \; \dot{m}_{i,equiv} \right)$$

In the above equation, $\dot{m}_{f,equiv}$ and $\dot{m}_{i,equiv}$ are the "equivalent" fuel consumption and the "equivalent" emissions of *i*-th pollutant (due to ICE and EM operations), respectively. Following the same methodology described above used for the equivalent fuel consumption, the emissions include the actual emission of the ICE and the equivalent emissions (positive or negative) associated with the use of the electric motor. In the equation above, the α_i's are the weighting factors that defines the relative importance of penalizing the emissions of *i*-th component and λ is the overall weighting parameter that defines the importance of penalizing the emissions relative to fuel consumption. In the remainder of this paper, we will focus solely on mitigation of the NOx, as it is by far the most offending pollutant for the powertrain under consideration. This leads (after appropriate normalization) to:

$$PTOC_{FC,NOx} = (1-\lambda_{NOx})\frac{\dot{m}_{f,equiv}}{\dot{m}_{f,\max}} + \lambda_{NOx}\left(\frac{\dot{m}_{NOx,equiv}}{\dot{m}_{NOx,\max}}\right)$$

In the above equation, the equivalent fuel consumption and NOx emissions were normalized by their respective maximum values within the maximum torque envelope of the engine; with such normalization, the reasonable range of λ_{NOx} could be set between 0 and 1. Setting λ_{NOx} equal to zero emulates the conventional ECMS framework, and setting it equal to 1 result in a full consideration of NOx reduction where neglecting the drawback in fuel consumption.

Based on this formulation, the enhanced ECMS supervisory control strategy was implemented in our vehicle simulator (OSU *VP-SIM*) and the effect of different weighting parameters was systematically studied to optimize the trade-off between NOx reduction and fuel economy.

2.3 Computer Simulation

Extensive simulations were performed using our vehicle simulator to validate the formulation of the approach, and also study the potential trade-off between fuel economy and emissions (λ_{NOx}). The simulations were carried out using the OSU FutureTruck 2000 powertrain configuration (parallel HEV, with a modern CIDI 2.4 liter engine and post-transmission coupled AC induction electric machine) (Paganelli *et al.*, 2001). The simulations were carried out over the FUDS cycle.

The simulation results showed that the NOx emissions were rapidly reduced as NOx penalty weight, λ_{NOx}, was increased; however, the reduction of NOx also slightly penalized the fuel economy. The results indicated that with the optimal value of λ_{NOx}=0.60, approximately 11% engine-out NOx reduction was achieved with a 5% drop in fuel economy. Further increase in the emission penalty factor did not yield further improvements in NOx emissions, while lowering the fuel economy.

This behavior probably stems from the highly constrained nature of the problem (*i.e.*, instantaneously meeting the driver's demand and the global state-of-charge constraint).

In order to illustrate the impact of NOx emission penalty on the ECMS performance, the engine operating points over a complete FUDS cycle with λ_{NOx}=0.0 and λ_{NOx}=0.6 are depicted in Fig. 1 below.

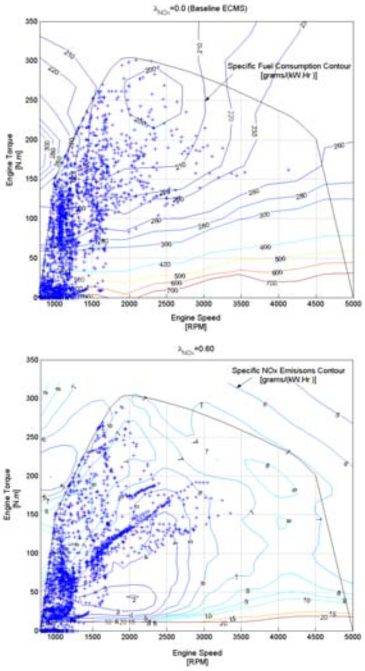

Fig. 1. Engine operating points during FUDS cycle superposed with specific fuel consumption and specific NOx emission maps of the engine (top: λ_{NOx}=0.0, bottom: λ_{NOx}=0.6)

As can be seen in figure 1, the enhanced ECMS is effectively shifting the engine operating points away from the "hill" where the specific NOx emissions are high, but at the slight detriment of the fuel economy.

In addition, the CO and HC emission levels are also increased as a result of NOx reduction. However, since the absolute levels of emissions of HC and CO from the CIDI engine are so low, the mild increases seen above (3 and 2% respectively) are insignificant compared to the NOx emission reduction achieved by the control strategy.

The same methodology can be generalized to include other pollutants, either separately or jointly. Extensive simulations have been carried out to systematically investigate the impact of such alternate control strategy. Overall, the results clearly illustrate that the reduction of specific pollutants can be achieved with the above formalism without significantly affecting the fuel economy. However, results aiming at reducing CO and HC invariably led to similar increase in NOx levels. Given the high level of NOx engine-out emissions in CIDI engines, particularly when used in a parallel HEV configuration, the supervisory control strategy is best focused on mitigating engine-out NOx emissions as much as possible.

The work described above clearly demonstrates the ease of implementation of a supervisory control strategy which is inherently self-adaptive to the topology of the fuel consumption and emission maps of any engine in light of a given set of optimization targets. The specific summaries of results obtained here are only a representation of what can be achieved with a given engine, vehicle and powertrain configuration. The results above also clearly demonstrate that HEV drivetrain control alone cannot lead to the drastic reduction in NOx required to meet the upcoming emissions standards. Again, this result is linked to the very significant fuel economy gains achieved by the use of a properly controlled parallel HEV drivetrain with a downsized CIDI engine. This fact clearly points to the need for aggressive NOx after-treatment and control downstream of the powertrain.

3. NOx AFTERTREATMENT SYSTEM IMPLEMENTATION

To achieve the aggressive reductions in NOx tail-pipe emissions, there are currently two primary viable advanced technologies: lean NOx traps (LNT) and urea-based Selective Catalytic Reduction (SCR). A LNT system using Diesel fuel for regeneration was selected due to issues related to on-board storage of urea for an SCR system. LNTs are capable of adsorbing NOx during lean engine operation for later release and reduction to N_2 during a short rich transient. LNT's require an effective regeneration strategy owing to their small NOx storage capacity relative to the engine-out NOx emissions commonly found in Diesel engines. Typically, regeneration is achieved by supplying a fuel-rich exhaust stream by temporarily operating the engine in a non-optimum, fuel-rich mode, usually with post-combustion injection into the cylinder or sometimes directly into the exhaust stream.

3.1 The Nature of the NOx Trap Implementation Problem

The LNT at first may first seem like a relatively simple solution to the problem of lean burn engine NOx emissions. However, many facets of the implementation of the system present problems. The current lack of an effective NOx sensor for in-vehicle feedback is a major problem. This feedback would be used to monitor the state of the trap to control when regeneration was necessary. Providing the rich exhaust gases for the reduction step also poses a significant problem for diesel engines. Diesel engines can be operated rich for brief periods using combinations of intake air throttling, post injection, and EGR settings. Control of this event such that it is transparent to the driver is difficult, especially when it is required every few minutes. A third complication for the implementation of a LNT system is sulfur poisoning. The sulfur found in fuels and lubrication oils slowly accumulates on the active catalysts sites reducing the catalyst effectiveness.

The sulfur can be removed by exposing the catalyst to a rich exhaust at a temperature greater than 600°C. Low sulfur fuels prolong the duration between sulfur regenerations; however, even with 15ppm sulfur fuel, catalyst efficiency is reduced by 40% after only 150 hours of aging (Diesel Emission Control, 2000)

3.2 High Efficiency LNT System

In this work, we are investigating a LNT system that can provide very high NOx conversion efficiency with low impact on fuel economy. This device was developed specifically to provide additional means of controlling the thermo-chemical environment of the after-treatment system. The system utilizes a novel, proprietary atomization technique to provide ultra-fine (< 1μm MSD) atomization of Diesel fuel (non-wetting, "fog-like"), suitable for either combustion in a heater or as a finely atomized HC source independent of engine operation.

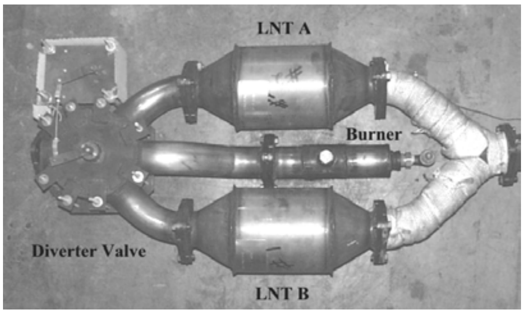

Fig. 2. Bifurcated aftertreatment system layout

As shown in figure 2, the system is a two-trap, or bifurcated, design. This allows one catalyst to actively trap NOx while the other is independently being regenerated. Fuel injection for regeneration is accomplished using the atomizing technique mentioned above, which requires only a 12 VDC power and low-pressure fuel supply and delivers sub-micron atomized diesel fuel.

The bifurcated design minimizes the free oxygen contained in the regeneration gasses. With engine-based regeneration methods, combustion in the engine is not complete resulting in a significant amount of free oxygen in the exhaust. The free oxygen is undesired because it consumes reductant once it reaches the catalyst, which both wastes reductant as well as increases the catalyst temperature. If unchecked, a large exotherm can result in damage to the catalyst substrate.

The central chamber also serves as a rapid light off burner that is activated on cold starts. The system brings the catalyst temperature up rapidly to eliminate NOx slip due to a cold, inactive catalyst. When targeting NOx conversion efficiencies greater than 80%, the warm-up time of the catalyst becomes critical. In addition to the rapid light off capability, the burner also provides sulphur regeneration capability. In this mode, the burner provides a hot and rich stream of reductant to purge the trap of sulfur.

The system under investigation provides a number of attractive potential benefits. These benefits are at the cost of increased complexity in the exhaust system. Among issues that need to be addressed are packaging the system effectively, ensuring that the exhaust valves will not fail over the lifetime of the vehicle, as well as the cost of the such a system for use in a production vehicle. To realize the potential benefits of such an aftertreatment system, appropriate control of the aftertreatment system must be developed to actively manage the thermo-chemical state of the traps. Unlike more traditional after-treatment approaches, the system presented here has additional degrees of freedom, which can be controlled to operate the traps more optimally. Due to the current lack of direct NOx feedback sensors, the system must rely on a model-based control of the traps for determining when regeneration is appropriate. Two facets of this problem are presented in the following sections: First, a simplified NOx trap model suitable for real-time control, along with some preliminary comparison between experimental results and simulation, and second, the development of a robust engine-out NOx estimator suitable for real-time estimation of the NOx levels fed into the after-treatment system (and its model) under both steady and unsteady conditions.

4. LNT SIMPLIFIED MODEL

A simple model of LNT operation has been created for the purposes of control development. To determine the appropriate time to regenerate and amount of fuel necessary for regeneration, a simplified efficiency based model is effective. The layout of the aftertreatment system considered here allows for many model simplifications to be made, especially considering that the regeneration takes place under strictly controlled conditions. A model based on experimental measurements of trap efficiency during regeneration and trapping can effectively be created. For control, such models have been created in the past as in reference (Larson *et al.*, 1999).

Through empirical tests on the NOx traps, the efficiency of the trapping cycle is defined as the amount of the NOx entering the trap that can be stored by the trap as a function of temperature and cumulative quantity of NOx contained in the trap. The equation below shows the trapping phase:

$$Q_{NOx}^{stored} = \eta(T,\Theta)Q_{NOx}^{in}$$

where Θ is the ratio of the quantity of NOx stored to the trap capacity, Q_{NOx}^{in} is the flow rate of NOx into the trap, η is the trapping efficiency and Q_{NOx}^{stored} is the flow rate of NOx into storage in the trap.

To simulate trap function, an emissions map of an engine and a map estimating the exhaust temperature conditions at the entrance of the trap are used to determine NOx flow rate and exhaust temperature at the entrance of the trap. The LNT efficiency map then determines the rate of trapping possible from the exhaust conditions provided and the quantity of NOx that has accumulated in the trap during the cycle. The efficiency relationship for the LNT trapping over normal engine operating ranges for a hybrid vehicle is shown in the figure below.

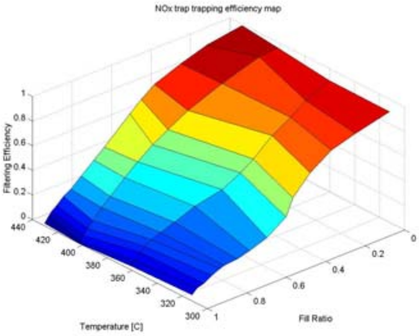

Fig. 3. LNT trapping efficiency

A similar relationship can be established for the regeneration cycle. In this case, the efficiency is defined as the amount of NOx that can be reduced from the trap for a certain amount of hydrocarbon reductants injected into the trap. This efficiency is dependent on trap bed temperature, the stored quantity of NOx and the concentration of hydrocarbons in the trap. Due to the fact that in the specialized regeneration case considered here where the mixture in the trap stagnates during regeneration, the effect of the concentration of hydrocarbons and the temperature of the bed of the trap are assumed to be functions of the flow rate of reductant and is assumed to be constant and negligible in the calculation of regeneration efficiency. This means that the regeneration efficiency can be simplified for the purposes of evaluating LNT control to a monotonic relationship with the quantity of stored NOx.

The simplified model is highly effective in modeling a LNT for the purposes of control. Notice in figure 4 below, that the model accurately shows the amount on NOx that accumulates in the trap. The figure compares the simulated data generated from the model to tests performed in a dynamometer test cell. Notice that the quantity of NOx stored in the trap with time is shown. The data from the model during trapping is effective in selecting the fill ratio of the trap where regeneration is appropriate.

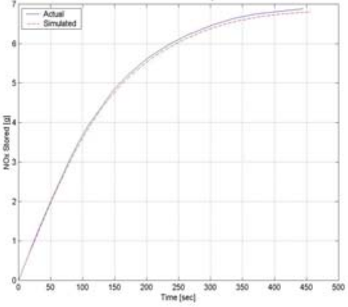

Fig. 4. Comparison between experimental and model results of NOx trapped

Similar results are realized for the regeneration cycle. In this case, the simulated data provides insight into how long regeneration should take place and the amount of hydrocarbons that should be injected. The model has the capability to maintain a certain upper and lower limits on the fill ratio in the trap. Once the trap has filled to a certain upper limit, it is regenerated until it is emptied to the point set in the simulation. In the figure below, a regeneration cycle is shown. It compares the possible flow rate of NOx before regeneration when the trap is completely full, the duration of regeneration and the fill of the trap after regeneration. Notice that the duration of regeneration is similar for both simulated and dynamometer cases.

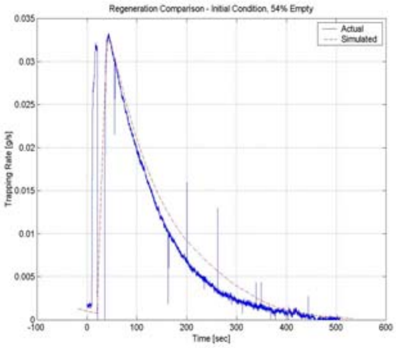

Fig. 5. Regeneration Comparison

Each NOx adsorber requires regeneration approximately every 30-120 seconds to maintain high trapping efficiency (see figure 4) and needs approximately 15-30 seconds to complete (see figure 5). The fuel economy penalty of the system is estimated to be of a few percent due to the added fuel usage during regeneration. However, it is expected to be significantly less than the additional fuel used when running the engine rich for regeneration purposes.

5. DYNAMIC ESTIMATOR OF NOx ENGINE-OUT EMISSIONS

While the simple NOx trap model shown above is sufficiently accurate and simple for real time implementation of a control policy for the traps, such model requires a reliable estimate of the NOx engine-out emission entering the after-treatment system. While steady-state NOx maps are easily available, the relatively short integration time associated with the NOx trap filling requires having an accurate estimate of the engine NOx emissions during transient engine operation. To that effect, transient emission data from a C.I. engine was used to evaluate the transients effects on engine-out NOx emissions and capture these effects through a computationally simple, heuristic transient NOx estimator.

Specifically, a dynamic estimator of engine-out NOx emissions was developed by applying a stochastic estimation technique to the FTP transient emission test data of a modern CIDI engine. The transient NOx characteristics were modeled as a polynomial function of engine speed and load and their respective derivatives:

$$(NOx)_{est,tr} = f(T, \omega, \Delta T, \Delta\omega)$$

The stochastic estimation method optimizes the polynomial coefficients to minimize the least square error between the measured data and the estimated values. Some examples of practical implementation to engine processes of this heuristic method can be found in Guezennec and Gyan, 1999 and Lee *et al.,* 2000. Initially, full polynomials up to 3rd order were investigated, which lead to an ordering of terms according to their importance. Finally, this led to a reduced polynomial form with 10 terms capable of an accurate representation of the transient emission data with the minimum number of terms as shown in the figure below:

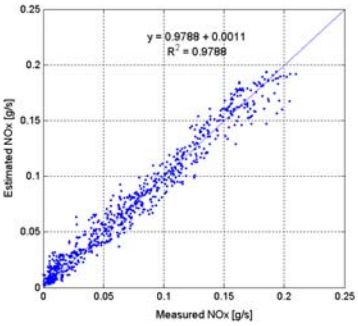

Fig. 6. Estimated *versus* measured NOx transient data during FTP cycle

This transient NOx model showed that NOx engine-out emissions are primarily dependent on engine power (speed and torque), *i.e.*, the quasi-static terms, but also showed a significant linear correlation with the engine speed transients. This correlation is essentially implying that the steady state estimation of the engine-out NOx emissions underestimates or overestimates during engine accelerations and decelerations, respectively. However, results (not shown here for brevity have shown that integrated over a full driving cycle, these effects compensate, so that the static approximation for NOx emissions is sufficient with respect to regulated emissions measured at the end of a driving cycle. However, over shorter windows of time (of relevance to the time scale of adsorption/regeneration of the aftertreatment system), these transient effects are relevant. Given the small computational burden associated with the transient estimation of the emissions, this estimator should be used to "feed" the LNT model. On the other end, at the level of the supervisory control strategy for the hybrid powertrain, the results of interest are averaged over significant length of time, and a quasi-static approach such as the one used in section 2 is valid. Furthermore, in a powertrain with a stepped transmission, the engine speed transients are a direct consequence of the vehicle speed and cannot be controlled. In the case of a powertrain with a CVT or EVT, the dynamic dependency of the emissions could be accounted for in the control strategy, owing to the additional degree of freedom.

6. CONCLUSIONS

In conclusion a 2-tier approach to mitigating NOx emissions from Diesel powered HEV vehicles was presented. It was shown that some NOx reduction can be achieved by an appropriate supervisory powertrain control strategy while maintaining good fuel economy. However, an aggressive aftertreatment system is required. A configuration for such a system was proposed, which, coupled with appropriate model-based control has the potential of lowering NOx emissions very significantly, hence potentially meeting emissions target with a Diesel-powered HEV configuration with superior fuel economy.

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