CONTROL DEVELOPMENT FOR A HYBRID-ELECTRIC SPORT-UTILITY VEHICLE: STRATEGY, IMPLEMENTATION AND FIELD TEST RESULTS

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Abstract : The control strategy presented and evaluated in this paper was developed for a parallel hybrid vehicle designed for the futuretruck 2000 competition [1]. In the context of a charge-sustaining operation, the control strategy implemented focuses on fuel efficiency optimization. It is based on converting the use of the electric machine into an equivalent fuel flow leading to a simple minimization problem of univariate form. Actual road test results are presented. The same formalism is then extended to enforce emission reduction. the various static maps of the engine are taken into account to include (in a suitably non-dimensional form) the emissions into the control strategy optimization cost with appropriate weighting coefficients. It is possible to reduce nox emissions by more than 10% without significantly degrading fuel economy.

1. Introduction

Control strategies or energy managements for hybrid electric vehicles are usually aimed at several simultaneous objectives. The primary one is usually the minimization of the vehicle fuel consumption, while also attempting to minimize engine emissions and maintaining or enhancing driveability. Hybrid electric vehicles encompass two (or more) energy storage sources and associated energy converters. Regardless of the topology of the vehicle, the essence of the HEV control problem is the instantaneous management of the power flows from both (or more) devices to achieve the overall control objectives. Moreover, the control strategy must be transparent to the user regardless of the vehicle usage. One important characteristic of this generic problem is that the control objectives are mostly integral in nature (fuel consumption and emission per mile of travel), or semi-local in time like driveability, while the control actions are local in time. Furthermore, the control objectives are often subject to integral constraints, such as nominally maintaining the battery state-of-charge (SOC) in charge-sustaining hybrids. The global nature of both the objectives and the constraints does not lend itself to traditional global optimization technique, as the future is unknown in actual driving circumstances. Much can be learned from global optimization exercises over a priori known driving cycles [2,3]. However, these solutions do not directly lend itself to practical implementations.

In this paper, we present a HEV control strategy which instantaneously optimizes the power split, while accounting for the global constraints. It was developed for a parallel, double shaft hybrid configuration where the electric motor is geared to the drive shaft at the output of the transmission (Fig. 1). This vehicle was designed for the FutureTruck 2000 competition. The aim of this competition is to convert a 2000 Chevrolet Suburban into a fuel-efficient, clean vehicle without compromising the vehicle dynamic performance and other desirable user characteristics (towing capacity, off-road capability, etc.). This is a vehicle with a frontal area of 3.2 m², a drag coefficient C_d of 0.45 and it weights 3100 Kg.

![Fig. 1. Simplified configuration of the Ohio State FutureTruck2000 Powertrain](image)

The engine chosen for the Ohio State 2000 FutureTruck is a 100-kW, 2.4 liter, direct injection Diesel engine made by Fiat. An Ecostar 55-kW electric machine was chosen as the electric machine. Hawker Genesis advanced lead acid batteries were
selected to power the electric machine. The stock transmission (4-speed automatic with torque converter) and transfer case on the 2000 Suburban were kept for ease of implementation in the existing vehicle. This transmission is electronically controlled, allowing transmission control to be integrated into our supervisory controller.

2. The FutureTruck Supervisory Control Strategy

The mechanical arrangement of the FutureTruck is classified as a torque addition-type parallel hybrid. That means the true free control variables to tune the power split between the Internal Combustion engine (ICE) and the Electric Motor (EM) are the torque produced by both machines, while their speeds are imposed by the instantaneous wheel speed, although with a different mechanical ratio. The wheel torque, as a function of the engine and motor torques and gear ratio, is described by:

$$ T_w = (\lambda_g(n_g) \cdot T_{ice} + \lambda_b \cdot T_{em}) \cdot \lambda_f $$  
Eq. (1)

where $T_w$ is the total torque required at wheel, $T_{ice}$ is the torque provided by the IC engine (positive only), $T_{em}$ is the torque provided by the electric machine (positive or negative), $\lambda_g(n_g)$ is the gear ratio of the transmission and a function of the gear selected $n_g$, $\lambda_b$ is the gear ratio of the coupling between the electric motor and the drive shaft and $\lambda_f$ is the gear ratio of the final differential. Note that the various efficiencies have been neglected for clarity, but are included in the formulation of this strategy actually implemented (and in the results shown later).

The position of the accelerator and brake pedals is interpreted as the continuously varying driver’s wheel torque demand $T_w$, positive or negative and prorated in function of the maximum torque available at the current vehicle speed.

Eq. (1) above is a two degrees of freedom relationship, that means only two among the three free control variables $T_{ice}$, $T_{em}$ and $n_g$ have to be tuned to define the power split satisfying the driver request $T_w$ at each time.

In our case, the power split is balanced by tuning the electric motor torque $T_{em}$, which can be positive or negative and the gear $n_g$ in a limited set of solutions defined by the transmission. This optimization process is performed under the mechanical constraints imposed by the driveline design. Since the truck will be operated according to a charge sustaining strategy, an other constraint is that the battery state of charge (SOC) is maintained within a prescribed range. Ideally the power split has to be optimized to minimize the overall engine fuel consumption over a defined driving run within the constraints listed above, such as:

$$ \text{Min} \sum m_f(t) $$  
Eq. (2)

with $m_f(t) =$ Engine fuel flow rate.

The main problem with this global minimization criterion is that the whole driving schedule has to be known a priori, thus real-time control cannot be readily implemented. To avoid this drawback the ECMS (Equivalent Consumption Minimization Strategy) power split control strategy, described in details in [3,5], proposes to replace the global criterion by a local one, reducing the problem to a minimization of an equivalent fuel consumption at each time. The criterion becomes at all times:

$$ \sum \text{Min} \sum \min f_{eq}(t) \forall t $$  
Eq. (3)

where the equivalent fuel flow rate cost function $f_{eq}(t)$ is simply defined as the sum of the actual fuel consumption rate of the engine $m_f(t)$ and the equivalent fuel use rate due to the electric motor $m_{em}(t)$ (both positive and negative):

$$ m_{eq}(t) = m_f(t) + m_{em}(t) $$  
Eq. (4)

A heuristic formulation is used to convert the electrical power flow into equivalent fuel cost based on the average “cost” of electricity through the various power paths. On that basis, the determination of the optimal power split between the two machines at each instant of time (i.e., at a given speed) can be determined by a simple minimization of a univariate form.

The global minimization problem and the local one are not strictly equivalent. However, the local one above can be easily used for real-time control as the global one is non causal and hence non realizable.

As it appears in the equation (1), in a double shaft, parallel hybrid configuration, the gear ratio of the transmission $\lambda_g(n_g)$ affects only the torque contribution of the IC engine to the wheel torque. On a practical implementation point of view this permits the separation of the overall control strategy in two sub-strategies:

- A gear shifting strategy, which selects the gear $n_g$ from a discrete set of solutions (four in this case) to optimize the operation of the engine;
- A power-split strategy, which defines the best power split between the two machines based on the ECMS approach.

The gear shifting strategy is based on selecting the highest possible gear capable of delivering the
required power from the IC engine, given the vehicle speed. Practically, this generic principle is suitably modified with hysteresis and delays to eliminate transmission "hunting" and provide better driveability.

New efficiency map and torque limitation curve are then defined for the system engine with its associated optimally controlled transmission. This entire optimized sub-system is then considered along with the electric machine for the ECMS power split strategy.

Based on the efficiency maps of the ICE and EM, the optimal power distribution was then pre-computed for every possible powertrain speed and power demand at the wheel and stored as a 3-D map for real time control. Alternatively, this could be done on line as it only requires a simple univariate minimization.

To practically enforce the global state-of-charge constraint, a SOC correction factor is used in order to shift the optimal power split up or down according to the error between the actual state-of-charge and the target state-of-charge. A non-linear "penalty function" is defined to heuristically embody the desired characteristics. The shape of the penalty function used to define this SOC correction factor is depicted in Fig. 2. In this figure, the abscissa is normalized, with –1 representing the low SOC limit and +1 represent the high SOC limit. This function is relatively flat around the SOC set point, allowing the optimal distribution to be (nearly) maintained when the battery state-of-charge is close to the target value. This is required to achieve maximum benefits from the hybridization by letting the powertrain (and hence the state-of-charge of the battery) best utilize the energy sources on board as long as they are (nominally) available. On the other hand, this function becomes significantly larger when the state-of-charge approaches the preset low and high limits. This is required to make avoid under- or over-charge of the battery regardless of the vehicle and driver demand. The shape and width of this penalty function can be adjusted to reflect the battery charge and discharge characteristics and the desirable range of use of the battery pack selected.

so that the performance of the vehicle is never affected regardless of the SOC. The further the actual state of charge is from the SOC target value, the more the optimal distribution is shifted. However, according to the torque limitation of both the ICE and EM, the shift is limited so that the operating point translation does not exceed the performance characteristics of the two machines. Note that in case of very aggressive driving, the prime necessity to satisfy the driver request may not leave enough degree of freedom in the choice of the electric machine operating point to prevent temporary hard deviation of the state of charge from the target range.

The practical implementation of this control strategy is predicated on the availability of a robust, on-line SOC estimation. This is usually recognized as a difficult problem, as most methods proposed tend to provide "time-deviating" SOC estimation. To that effect, a robust, on-line SOC estimation technique has been developed for this project. It yields good field results based on open circuit voltage estimation through real time current, voltage and temperature measurements for the battery pack with appropriate signal processing.

Further details about the real time implementation of the control strategy and the SOC estimator were recently presented [1]. Very promising preliminary simulation results were also given at the recent AVEC’2000 conference [4] demonstrating the robustness of this control strategy under a wide range of driving conditions. In the following sections, we present experimental results obtained during actual road tests.

3. Experimental Results

The supervisory control scheme described before was implemented in real time using an ETAS ES-1000 controller [1]. In this implementation, the control software had an update time of 0.01 sec. This ETAS system was also used to perform a data acquisition function during the actual runs.
Fig. 3a shows the driving profile for a 22.36 miles test over 45 minutes conducted in fully automated HEV mode. The only inputs to the control computer were the positions of both the accelerator and brake pedals. No other interaction between the driver and the powertrain was necessary. The IC engine was cold at the start of the test and the battery pack was fully charged. All the data presented here was acquired with a 0.1 sec. sample time.

The vertical line in Fig. 3 around t = 950 sec. represents the boundary between what we considered the highway portion and the urban portion of the drive. This boundary was post-selected to closely match the speed statistics of the standard urban and highway US driving schedules in both portions. Actually, our highway section was driven at an average speed slightly higher than the standard US highway cycle.

It should be noted except for the initial battery transient, the SOC remains within the 60% to 80% target range specified in our charge-sustaining operational strategy (fig. 3b). At the very beginning, the battery SOC is outside this desired band (fully charged) and the control strategy automatically favors a heavy use of the electric machine until the SOC is within target. On other drives (not shown here for brevity) where the initial state-of-charge was below the targeted range, we observed the opposite, with the ICE striving to recharge the battery pack in addition to meeting the vehicle demand. We have had ample evidence that our strategy for charge-sustaining operation is effective regardless of demand.

Based on this trip, the fuel economy of the vehicle was determined. The numbers were corrected to account for the small depletion of the battery over the trip. The fuel efficiency on the highway section is 26.96 MPG, while it is 19.69 MPG on the city section. On the entire trip the fuel efficiency achieves 23.44 MPG. When accounting for the density and heating value difference between Diesel fuel and gasoline, the average fuel efficiency in miles per gallon (MPG) of equivalent gasoline is 21.69 MPG. This is approximately 1.5 times the fuel efficiency of the original Suburban with its 5.3-liter gasoline engine.

Fig. 5 shows the distribution of operating points of the electric machine during the same driving section. The surrounding envelopes indicate both the maximum positive and negative torque capability of the motor used. As expected, the electric machine is more heavily used (bi-directionally) during the urban portion of the driving cycle. In fact, during highway driving (not presented here for brevity) the engine operates at a very good efficiency while providing most of the motive power. The control strategy does not require torque from (or does not provide torque to) the electric machine, except during speed transients (accelerations or decelerations).

The table 1 shows the energy balances results for this drive. The high ICE shaft-to-wheel overall efficiency (90%) is due to the hybridization of the powertrain, as a significant part of the kinetic energy is re-captured by the electric motor in regenerative braking mode.

<table>
<thead>
<tr>
<th>fuel</th>
<th>ICE shaft</th>
<th>EM shaft</th>
<th>Wheels</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.04 kWh (0.9 gallon)</td>
<td>12.71 kWh</td>
<td>-0.25 kWh</td>
<td>11.52 kWh</td>
</tr>
</tbody>
</table>

The remarkable 37% average engine efficiency was can be attributed to the supervisory control strategy, which operates the IC engine in the vicinity of its peak efficiency (42% for this engine).
In summary, the overall vehicle efficiency from fuel to the wheels is near 33%. This is more than 50% higher than the efficiency of the original vehicle. Those practical results are evidence of the efficiency, robustness and suitability for real time application of the control strategy presented. The following section proposes an extension of the current approach to emission reduction.

4. Enhancement of the control strategy for emission reduction

4.1. Description of the extended strategy

The control strategy described above was strictly focused on optimizing the power split to minimize fuel consumption while meeting the driver demand and nominally maintaining the battery state of charge. This control strategy has been extended to include emission characteristics by modifying the cost function to be instantaneously minimized. The cost function, which is essentially the sum of actual fuel consumption due to ICE and equivalent fuel consumption by the EM, has been modified in the following fashion:

$$m_{eq, modified} = m_{eq} \times \left(1 + \lambda \sum_{i=CO,NOx,PM} \alpha_i \frac{m_i}{m_{target,i}}\right)$$

Eq. (5)

where $m_{eq}$ is the equivalent fuel consumption (identical to the existing control strategy), $m_i$ is the instantaneous mass flow rate of major pollutant components ($i = HC, CO, NO_x, Smoke$), $m_{target,i}$ and $\alpha_i$ are the normalization factor and the individual weighting factor for each emission component respectively, and finally, $\lambda$ is the overall emission weighting factor.

The weighting parameters, $\lambda$ and $\alpha_i$, in this penalty function approach need be properly selected to meet the control objectives of the hybrid-powertrain. These parameters need to be optimized to achieve the best trade-off balance between fuel economy and emissions.

Since the HC and CO emissions are often negligible in a CIDI engine because of lean combustion, we are first focusing on reducing NOx emissions at this time. In that context, the above equation reduces to the following (in normalized form):

$$m_{eq, modified, normalized} = (1 - \lambda_{NOx} \frac{m_{eq}}{m_{f,max}}) + \lambda_{NOx} \frac{m_{NOx,equiv}}{m_{NOx,max}}$$

Eq. (6)

where $m_{NOx,equiv}$ is the equivalent NOx emissions, calculated in a fashion similar to the equivalent fuel consumption (i.e., the sum of the actual NOx emissions by the ICE and the virtual emissions due to the usage of electric machine). In the above equation, $\lambda_{NOx}$ represents the importance of penalizing NOx emission (ranging from 0 to 1). A value of 0 emulates the conventional control strategy, which considers the fuel economy as the only objective of optimization. The normalization factor for both the fuel consumption term and the NOx emission term have been taken as their largest value over the entire engine map ($m_{f,max} = 6.8$ g/s and $m_{NOx,max} = 0.196$ g/s, respectively for our engine).

The equivalent NOx emissions due to the use of the EM operation has been computed by assuming an average value of NOx emissions which accounts for the past/future operation of the ICE for sustaining the battery SOC. This value of the equivalent NOx emissions for the EM was optimized on the FUDS cycle and set to 5.0 g/kW.hr.

Based on this formulation, the supervisory control strategy was implemented in our vehicle simulator (VP-SIM) and the effect of the different weighting parameters was systematically studied to optimize the trade-off between emissions and fuel economy. Some sample results are shown in the next paragraph.

4.2 Simulation Results

Two extreme cases were first studied to verify that the control strategy is properly modifying the IC operating points according to the relative importance given to the emissions. These 2 cases correspond to $\lambda_{NOx} = 0.0$ (no penalty on emission, equivalent to previously described control strategy) and $\lambda_{NOx} = 1.0$ (high weighting on the emissions). Results depicting the ICE operating points during a FUDS cycle are shown for these two extreme cases in Figure 6 and 7, respectively. In figure 6, the iso-contours of specific fuel consumption are shown, while the iso-contours of NOx emissions are shown in Figure 7. However, these iso-contours are characteristics of the engine and are not related to the control strategy. They are shown in separate plots only for clarity, but they apply to both cases equally. However, the selection of the ICE operating points with respect to these characteristics is the end result of the control strategy.

![Fig. 6. ICE Operating Points with $\lambda_{NOx} = 0.0$](image-url)
It can be clearly observed in the above figures that penalizing NOx emission has a significant impact on the ICE operating points. In particular, it is capable of exploiting the “dip” in the NOx contours, which occur between 1500 and 2000 RPM at relatively high load. For fuel economy only (\(\lambda_{\text{NOx}} = 0.0\)), this region of the map is often visited, as it corresponds to a good fuel economy for the engine at significant power levels. However, this same region contributes to higher NOx specific emissions. The control strategy effectively avoids this feature of the NOx map to reduce emissions. However, it also shifts the engine away from fuel-efficient operating points. In other words, the NOx emissions and the fuel economy requirements are conflicting. Therefore, it is important to select an appropriate value of \(\lambda_{\text{NOx}}\) to achieve the best trade-off balance between them.

Figures 8 and 9 show the effect of \(\lambda_{\text{NOx}}\) on the fuel economy and NOx emission integrated over the entire FUDS cycle. The figures show that the mileage monotonically decreases with increasing \(\lambda_{\text{NOx}}\) (Figure 8) while the NOx emissions also decrease initially but reach a plateau near \(\lambda_{\text{NOx}} = 0.6\).

Based on these results, it appears that a value of \(\lambda_{\text{NOx}} = 0.6\) yields a good compromise between fuel economy and NOx emissions. With this value, the NOx emissions can be reduced by 11.6% while sacrificing the fuel economy by only 3.4%. While these results may not be very impressive, it should be noted that the fuel consumption and NOx emissions iso-contour lines are nearly parallel to each other, so that the control strategy can only exploit the relatively small differences between these two sets of lines. For a given driving cycle and vehicle, the power requirements at the wheel are given at each instant, and furthermore, in a charge-sustaining HEV, the control strategy cannot produce a net decrease of the ICE power requirements over the cycle, but only trade off the instantaneous usage of the ICE against past or future usage to minimize overall fuel consumption and emissions. The fact that the control strategy is capable of achieving a net lowering of the NOx emissions at the “price” of only a minor fuel economy decrease is very encouraging. Work currently in progress is applying a similar methodology to other emissions such as HC, CO and smoke. As these other pollutants have maps which are far more irregular than the NOx map, we expect the control strategy described here to be very successful in mitigating additional pollutants without strongly affecting the results shown here. This control strategy for fuel economy and emissions is being implemented on the Ohio State FutureTruck 2001 to validate these simulation results. Furthermore, the methodology will also be extended to account for the effectiveness of the after-treatment system (particularly NOx traps), where the weight given to the instantaneous NOx emissions \(\left(\lambda_{\text{NOx}}\right)\) will be dynamically tuned to account for the state of the NOx storage capability of the traps.

5. Conclusions

This paper describes a practical formulation for the supervisory powertrain control problem in charge-sustaining hybrid electric vehicles. This formulation is based on adjusting the instantaneous power split between the IC engine and the electric machine and selecting the appropriate gear ratio in the transmission to minimize the instantaneous equivalent fuel consumption of the combined powertrain. To implement the global constraint of charge-sustaining operation, the optimum power split is biased using a non-linear penalty function of the battery state-of-charge deviation from its target value. This strategy was implemented in an actual double shaft, parallel hybrid vehicle (FutureTruck 2000, based on a full-scale SUV platform) and implemented in real time as a powertrain supervisory controller. Extensive road tests have confirmed the validity of this approach, yielding outstanding fuel economy improvements over the stock vehicle and
while maintaining the battery state-of-charge within its target range. Finally, the same formalism has been extended to include emissions reduction showing that an HEV configuration with an appropriate control strategy can mitigate the engine-out emissions while maintaining delivering significant fuel economy benefits.

References