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Simulated Performance of Alternative Hybrid-Electric Powertrains in Vehicles on Various Driving Cycles

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Abstract

In this paper, various alternative hybrid vehicle powertrains that are being considered by auto companies are evaluated based on simulation studies performed at the Institute of Transportation Studies, University of California-Davis. The following hybrid powertrain arrangements have been considered:

a. Single-shift, parallel (Honda)
b. Single-planetary, dual-mode (Toyota/Prius)
c. Multiple-planetary, dual-mode (GM)
d. Multiple-shaft, dual-clutch transmission (VW and Borg-Warner)
e. Series – range extended EV (GM Volt)

The primary strategy in all the options considered was to operate the engine only in the high efficiency part of its map and to lose as little as possible of the gain by losses in the energy storage unit and the electric machines. The simulations indicated that there are in general not large differences in the fuel economies predicted using the various powertrains for the same vehicle and battery. The fuel economy improvements were large in all case – 80-100% for the FUDS cycle, 40-60% for the Highway cycle, and 30-50% for the US06 cycle – using lithium-ion batteries and a 25-35 kW electric driveline.

Limited simulations were also performed for a series hybrid that could be operated as a plug-in hybrid with a range of about 30 miles. In the charge depleting mode, the vehicles operate as full-function EVs. The simulations indicated that the series hybrids will have large fuel economy improvements compared to ICE vehicles of the same size and performance in the charge sustaining mode. Hence a key issue is the economics of the series vs. the parallel plug-in hybrids and not vehicle performance and fuel economy.

Keywords: hybrid-electric powertrains, control strategy, fuel economy, lithium batteries

1 Introduction

In designing the powertrain for a hybrid/electric vehicle, designers have many choices to consider. These alternatives include the physical arrangement of the powertrain components, selection of the energy storage technology and devices, and the control strategy for the operation of the powertrain. Evaluation of these alternatives is dependent on the type/class of vehicle being designed and marketing strategies concerning performance and cost for sale of the vehicle. This paper is intended to shed some light on these evaluations based primarily on a series of hybrid vehicle powertrain simulation studies performed at the Institute of Transportation Studies, University of California-Davis. The following alternative hybrid powertrain arrangements are considered:

a. Single-shift, parallel (Honda)
b. Single-planetary, dual-mode (Toyota/Prius)
c. Multiple-planetary, dual-mode (GM)
d. Multiple-shaft, dual-clutch transmission (VW and Borg-Warner)
e. Single-planetary, single electric machine (Szumanowski/Poland)
f. Series – range extended EV (GM Volt)

The utilization of these powertrains in micro-hybrids, charge sustaining, and plug-in hybrids are analyzed for various driving cycles. Appropriate control strategies using either batteries (primarily lithium-ion) or supercapacitors are included in the analysis. The focus of the evaluations is on fuel economy/consumption and electrical energy use and the overall efficiency of the powertrains compared to conventional ICE vehicles of the same size and road load characteristics. Complexity and cost are not analyzed in detail.

2 Hybrid/Electric Powertrain Considerations

As noted in the Introduction, hybrid vehicle designers have a wide range of powertrain arrangements to consider. Each of the hybrid powertrain options has its advantages and disadvantages relative to fuel economy improvement potential, complexity, cost, vehicle performance and driveability, development cost, and applicability to a wide class of vehicles. There are presently hybrid vehicles being marketed and developed utilizing most of the powertrain arrangements listed above indicating that the auto companies are not yet sure what approach will be best in the long run. This is not surprising as the development of hybrid/electric vehicles is in its infancy in terms of both component availability and control strategy. Further the car buying public is not familiar enough with hybrid vehicle technology to readily appreciate the advantages/disadvantages of the different powertrain approaches.

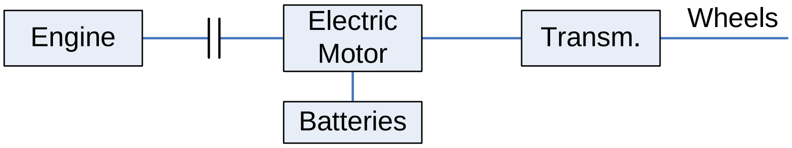
In this paper, the focus is on the fuel economy/consumption improvements that can be achieved with the various powertrain approaches under the assumption that fuel prices will increase in the future and greenhouse gas (CO2) emission reduction will become increasingly important. It is realized that the fuel economy improvements must be achieved maintaining good vehicle performance and driveability and thus the components in the powertrains are sized and the control strategy selected with these requirements in mind. The differences in system complexity and cost will be self-evident from the component requirements in the various powertrains.

3 Alternative Hybrid-Electric Powertrain Arrangements

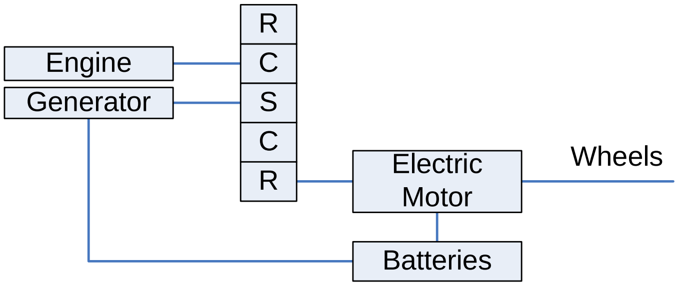
In this section, each of the powertrain arrangements will be discussed in terms of its driveline schematic and the key problems associated with its implementation. Schematics of the various hybrid powertrain arrangements are shown in Figure 1a-1f, which is included at the end of the paper. The advantages and disadvantages of each powertrain approach will be cited along with present experience with it in the market place (2008) by various auto companies.

3.1 Single-shift, parallel

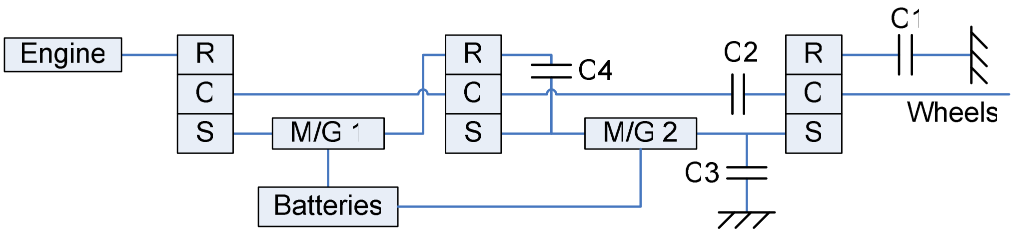
This powertrain arrangement is shown in Figure 1a. In this arrangement the engine, electric motor and transmission are on the same shaft and the motor and engine operate at the same RPM. This arrangement is the simplest of those being considered and the most straightforward to control. It is currently used by Honda in the original Insight and Civic and will be used in the new Insight to be marketed in 2009. The transmission can either be a manual (5-speed) or a continuously variable steel-belt transmission (CVT). All the Honda hybrids presently use the CVT. The single-shaft, parallel system can be built with or without a clutch to decouple the engine from the shaft when the engine is not fueled. The Honda designs do not use a clutch, but Nissan in a new hybrid vehicle to be marketed in 2010 will incorporate a clutch.



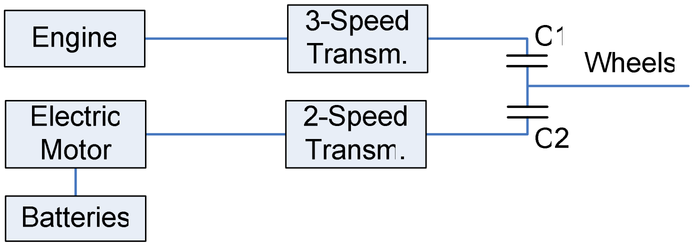
(a) Single – shaft, parallel



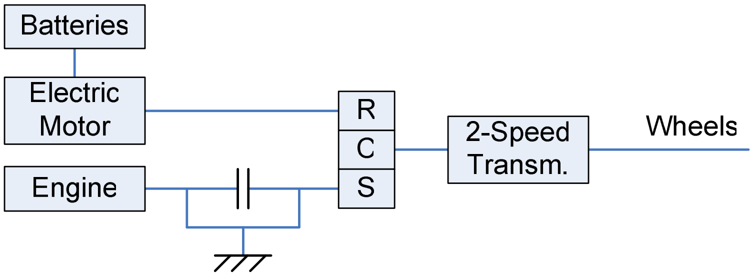
(b) Single-planetary, dual mode



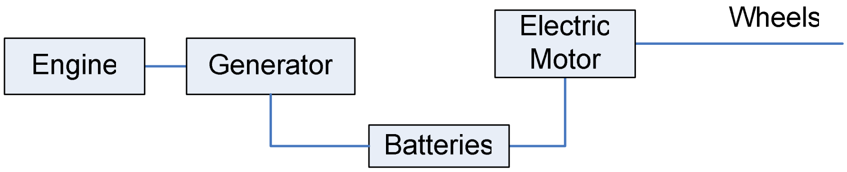
(c) Multiple planetary, dual mode (GM)



(d) Multiple – shaft, dual clutch transmission (DCT)



(e) Simple planetary, single EM (Szumanowski / Poland)



(f) Series, hybrid (GM Volt)

Figure 1 Schematics of various hybrid-electric powertrains

This arrangement is a parallel hybrid with both the electric motor and engine driving directly to the wheels. The power ratings of the motor and engine and the sizing of the energy storage unit can be selected arbitrarily to meet vehicle performance specifications and fuel economy improvement targets. Most of the simulations performed in this study utilized the CVT and the engine and electric motor components developed for hybrids by Honda [1,2]. The simulations had the capability of on-off engine operation at any speed with or without a clutch in the system. In cases in which the engine could not be decoupled from the shaft (no clutch), the effect of engine friction was included in the calculations using the Honda engine [2]. The control strategies simulated required the engine be operated along a specified maximum efficiency line (Torque vs. RPM). The control strategies in the UC Davis hybrid vehicle simulation studies are discussed in detail in [3].

3.2 Single planetary, dual mode

This powertrain arrangement is shown in Figure 1b. It is the arrangement used in the Toyota Prius and other Toyota hybrids and under license by Ford in the Escape and Nissan in the Altima. This arrangement is termed dual mode because it can operate both in parallel and series modes. It consists of an engine and two electric machines – one operating primarily as a traction motor and the other as a generator. The combination functions as a continuously variable electromechanical transmission with the effective gear ratio dependent on the torque outputs of the three prime-movers. The system utilizes no clutches. When the engine is operating, its power output is split between that to the wheels and that to the generator. This power-split feature of the powertrain arrangement permits the engine to be operated near maximum efficiency for nearly all vehicle speeds and power demands. Control of the system is not simple as discussed in detail in [4,5]. The engine characteristics used in the simulations were taken from those published by Argonne National Laboratory [6]. **Advisor** models of the first generation (2001) and second generation (2004) Prius vehicles have been developed and the fuel economy predictions validated using EPA test results. Detailed simulation results obtained using the UC Davis Prius models are given in [7].

3.3 Multiple-planetary,dual-mode (GM)

This hybrid powertrain was developed as cooperative project by GM, Chrysler, and BMW. GM Alison previously developed a two-mode hybrid system for busses that achieves two all-electric (EVT) modes with two motors, two planetary gear sets, and two clutches. The GM, Chrysler, and BMW project built upon the GM Alison system and extended its capabilities to include four fixed gear modes as well as the two EVT modes. This modified two-mode hybrid system includes two electric motors, three planetary gear sets, and four clutches in a traditional transmission like package that connects the engine to the final drive (see Figure 1c). The clutches are wet plate with hydraulic activation as in many manual transmissions and require a hydraulic pump which can be either engine or electrically driven. As indicated in Figure 2, the two-mode unit is complex with multiple gear sets connecting the two electric machines.

Figure 2: Inside view of the GHC two-mode hybrid transmission.

The engine is connected to the shaft on the left and the final drive to the shaft on the right. Control of the four clutches results in six operating modes including low-speed and high speed all-electric modes. There are four fixed gear ratio modes so the unit can operate like a four-speed transmission. The two-mode system is very flexible as it can be operated in all-electric and series and parallel hybrid modes. The two planetary gears permit power split from the engine at each of the four fixed gear ratios. This is a more flexible system than the single planetary Prius system and is especially applicable to heavy vehicles – SUVs and trucks – which also require towing capability. Detailed analyses of the two-mode powertrain are given in [8-10]. The UC Davis model [11] was based on information given in those references.

One of first applications of this hybrid powertrain was to the GM Tahoe. The UC Davis model of the two-mode hybrid system was validated by comparing the fuel economy predicted for the GM Tahoe to the fuel economy for the vehicle published by EPA [24]. The two-mode model has also been applied with success to the new Saturn Vue hybrid (Table 1).

3.4 Multiple-shaft, dual-clutch transmission (VW and Borg-Warner)

This powertrain arrangement is shown in Figure 1d. It is the application of the dual clutch transmission (DCT) developed by Borg-Warner [12-14] and recently marketed in conventional ICE vehicles by VW. In that application, the engine is connected to a single input shaft of the DCT and the final drive is connected to the two output shafts of the transmission. The advantage of the DCT for the conventional vehicles is that it permits the vehicle to have the powertrain efficiency of a manual transmission and the driveability of an automatic transmission. This occurs because the shifting between the two branches of the transmission can be done smoothly without a noticeable interruption in the output torque. In the case of the hybrid application, the input-output of the DCT is reversed with the input of the transmission having two shafts and the output to the final drive having a single shaft. As shown in Figure 1d, the engine and electric motor are connected to the input shafts which drive the separate branches of the DCT. Each of the prime-movers drives through a multi-speed transmission with shifting between branches and through the gears in each branch controlled by actuating one of the two clutches in the DCT unit. The primary advantage of the DCT approach is that the engine can be coupled and decoupled from the driveline smoothly with minimum delay and when the engine is not being fueled, there is no issue with engine friction as is the case for the single-shaft arrangement (Figure 1a).

There are several issues concerning the efficiency and operation of the DCT hybrid powertrain that are important to its successful implementation. First, how is the engine restarted after it has been decoupled from the transmission? In the UC Davis model [15] of the DCT the engine is restarted using a dedicated, small starter motor (1.5 kW). The energy required for this restart is included in the calculation of system efficiency. The second issue is concerned with clutch activation and application. The energy required for the activation and the losses associated with clutch application are included in the system efficiency calculations. These issues are treated in detail for conventional ICE vehicle applications in [13,14]. The same general control strategy for the operation of the engine and electric motor was used for the DCT hybrid powertrain as was used for the other hybrid powertrains. The engine when it was on and being fueled, it was required to operate along a high efficiency line on the engine map. This was done by switching back and forth between the two branches of the DCT as the vehicle switched from being powered by the electric motor and the engine. While operating in a particular branch, the DCT is shifted much the same as with a multi-speed manual transmission.

3.5 Single-planetary, single electric machine (Szumanowski/Poland)

This powertrain arrangement, which is shown in Figure 1e, utilizes a single planetary gear system as does the single-planetary, dual mode arrangement of Toyota except that it uses only one electric machine. This arrangement, termed the compact hybrid planetary transmission drive (CHPTD) by Prof. Szumanowski in [16] utilizes clutches and shaft brake mechanisms to couple and decouple the engine and electric motor from the driveline. For vehicles requiring high speeds, as is the case for passenger cars, a 2 or 3 speed transmission is needed as shown in Figure 1e. This hybrid system operates as a parallel hybrid and is not dual mode as is the case for the Toyota planetary hybrid. However, the CHPTD does offer the engine powersplit and variable gear ratio features of the Toyota planetary hybrid. The CHPTD powertrain has not been modeled as yet at UC Davis, but its operation is described and modeling is discussed in detail in [16]. The simulation results presented in the reference indicate that engine operation can be maintained in the high efficiency part of the map resulting in large fuel economy improvements. Since this approach requires only one electric machine and offers the pure parallel mode for high speed highway operation, it appears to be a lower cost option than the Toyota powertrain and a more efficient option than the Honda single-shaft approach. It also appears to be easily adapted to plug-in hybrid vehicles. Modeling of the CHPTD powertrain at UC Davis is planned for the near future.

3.6 Series – range extended EV (GM Volt)

The hybrid powertrain arrangements shown in Figures 1a-e are related to those in conventional ICE vehicles. The series hybrid powertrain (Figure 1f) is related to that of a battery-powered electric vehicle and can be referred to as a range-extended electric vehicle. This hybrid vehicle is essentially an electric vehicle with on-board electricity generation via an engine-powered generator or a fuel cell. In the case of the GM Volt, it is intended to be utilized as a plug-in hybrid with much of the electricity used provided by a relatively large battery. It could, however, be used as a charge sustaining hybrid using a smaller battery.

Battery-powered and series hybrid vehicles are modeled/simulated at UC Davis using SIMPLEV, which is a vehicle simulation program developed at the Idaho National Engineering Laboratory [17]. Component efficiency maps are available in SIMPLEV for a wide variety of engines, electric, and lithium-ion batteries. The available control strategies permit the simulation of series hybrids as plug-in and charge sustaining hybrids.

4 Energy storage and control strategies

In this section, the characteristics of batteries and ultracapacitors for energy storage in hybrid vehicles are reviewed and how their characteristics influence the choice of control strategy is discussed.

4.1 Batteries

Energy storage is central to the successful operation of all the hybrid vehicles discussed in the previous sections. In order to increase the fuel economy of the vehicles, the engine must operate more efficiently than it does in a conventional ICE vehicle. This is done by utilizing the electric motor to provide the drive torque rather than the engine when the engine would operate inefficiently. In addition, the electric driveline is used to recover energy during braking events. In order to provide

Table 2: Power (W/kg) and Energy Ratios for various batteries

Battery	Ah/ wgt.kg	R mOhm	Wh/kg	W/kg 90%	W/kg 75%	P/E 90%	P/E 75%
Chemistry							
Iron phosphate							
EIG	15/.424	2.5	115	897	1865	7.8	16.2
A123	2.1/.07	12	88	1132	2354	12.9	26.8
K2	2.5/.082	17	86	682	1418	7.9	16.5
Lithium titanate							
Altairnano	12/.34	2.2	70	693	1441	9.9	20.6
EIG	11/.44	1.9	43	620	1290	14.4	28.0
Li(NiCo)O_2							
EIG	18/.45	3.0	140	913	1898	6.5	13.6
GAIA	42/1.53	.48	94	1677	3488	17.8	37.1
Quallion	1.7/.047	70	170	374	778	2.2	4.6
Quallion	1.3/.043	59	144	486	1010	3.4	7.0
NiMt hydride							
Panasonic. HEV	6.5/1.04	11.4	46	393	818	8.5	17.8
EV	65		68	87	181	1.3	2.7
Lead-acid							
Panasonic HEV	25		26	146	303	5.6	11.6
EV	60		34	89	185	2.6	5.4
Zn-Air							
Revolt Technology			450		.5-1.0		

P_{max} = Eff. (1- Eff.) $(V_{oc})^2$ /R
P/E = (W/kg) / Wh/kg

these functions, the energy storage capacity (kWh) and power capability (kW) of the energy storage unit must be larger than specified minimum values that are dependent on the vehicle design and expected use pattern and driving cycle for the vehicle. At the present time, all hybrid vehicles being marketed use nickel metal hydride batteries, but it is expected that in the future most of the hybrid vehicles will use lithium-ion batteries. In nearly all cases, the batteries are sized by the power requirement and they store much more energy than the minimum required. The high power requirement of their design has resulted in a sacrifice of energy density. The characteristics [18,19] of a number of batteries designed for use in hybrid vehicles are given in Table 2. The key characteristic for charge sustaining hybrid vehicle applications is the pulse power density for 90% efficiency. If the battery in a vehicle experiences frequently higher power density than $(W/kg)_{90\%}$, the losses associated with the transfer energy in and out of the battery will be large and the improvement in fuel economy for the vehicle will be less than desired. One of the major advantages of the lithium-ion batteries is their high power capability. In the design of plug-in hybrid vehicles, both high energy density and high power density are required. Lithium-ion batteries are also favored for this application.

Table 3: Characteristics of ultracapacitors

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell*	2.7	2885	.375	1.08	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
ApowerCap**	2.7	55	4	.22	5.5	5695	50625	.009	---
Apowercap**	2.7	450	1.3	.58	5.89	2766	24595	.057	.045
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.3	.95	4.4	1310	11640	.522	.379
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	.151
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	.245
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	.48
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18225	.50	.572
Power Sys. (activated carbon, propylene carbonate) **	2.7	1350	1.5	2.0	4.9	650	5785	.21	.151
Power Sys. (graphitic carbon, propylene carbonate) **	3.3 3.3	1800 1500	3.0 1.7	5.4 2.5	8.0 6.0	486 776	4320 6903	.21 .23	.15 .15
JSR Micro (AC/graphitic carbon)	3.8	1000 2000	4 1.9	4 3.8	11.2 12.1	900 1038	7987 9223	.113 .206	.073 .132

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated
(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge
* Except where noted, all the devices use acetonitrile as the electrolyte
** all device except those with ** are packaged in metal containers

Table 4: Comparisons of the P/E ratio for various energy storage technologies

Device technology	Nominal cell voltage	Wh/kg	P/E 90%	P/E 75%
Carbon/carbon supercapacitors	2.7	5	500-1000	1200-2400
Hybrid carbon supercapacitors	3.8	12	140	340
Lithium-ion batteries				
Iron phosphate	3.25	90-115	8-13	16-27
Lithium titanate	2.4	40-70	10-14	20-30
$NiCoMnO_2$	3.7	95	19	40
	3.7	140	6.4	17
	3.7	170	2	4
Ni Mt hydride HEV	1.2	46	8.5	18
Lead-acid HEV	2.0	26	5.6	11.6
Zn-air		450	.5-1.0	

4.2 Ultracapacitors/supercapacitors

The analysis presented in this paper and in previous papers [20-22] has indicated that ultracapacitors alone can used for energy storage in charge sustaining hybrid vehicles. Recent studies have shown that an energy storage of 50-150 Wh is sufficient for the hybrid vehicle applications if a large fraction of the energy in the energy storage device is useable. This is not the case for batteries, but it is the case for ultracapacitors. The characteristics of a number of ultracapacitors being developed for vehicle applications are given in Table 3. A comparison of the power characteristics of batteries and ultracapacitors is given in Table 4.

For most vehicle designs using ultracapacitors, the key device characteristic is its useable energy density, because the pulse power density of ultracapacitors is very high. This is especially true of devices using activated carbon in both electrodes (carbon/carbon devices). As discussed in [23], R&D is underway world-wide to increase the energy density of ultracapacitors so that applications requiring smaller energy storage units and/or larger amounts of energy storage than can be satisfied with the current carbon/carbon technology will be possible.

4.3 Control strategies

The fuel economy improvement achieved/expected with a hybrid powertrain is closely tied to the strategy utilized to control the power commanded from the engine and the electric machines as the vehicle operates over various driving cycles. The general objectives of any control strategy are to operate the engine only in the high efficiency regions of its map and to utilize zero fuel when the engine is not providing power. This must be done in such a way that the electric machines operate at high efficiency (>90%) and the losses associated with the energy storage are small (round-trip efficiency >90%). Otherwise a significant fraction of the gain in hybrid engine efficiency compared to the conventional ICE vehicle will be lost and the improvement in fuel economy will be disappointedly small.

One approach to achieving large improvements in fuel economy is to operate the engine in the hybrid vehicle along an operating line (Torque vs RPM) that results in high engine efficiency [3]. Further when possible to constrain the engine to operate at torques greater than a minimum value. In general, this strategy requires the vehicle to operate in the electric mode when possible and to utilize the engine to recharge the energy storage when it is powering the vehicle. The consequences of this strategy are the energy storage is recharged at relatively high power and the losses associated with the recharging the energy storage can be relatively high unless its resistance is very low. Vehicle simulation results have shown that using nickel metal hydride batteries, this strategy can result in roundtrip efficiencies for the energy storage unit of only 75-80%. For lithium-ion batteries, the roundtrip efficiencies are in the range of 90-95% and for carbon/carbon ultracapacitors, the range is 95-98%. The roundtrip efficiencies would be higher for control strategies requiring less demanding energy storage recharge rates, but this would result in lower engine operating efficiencies.

5 Hybrid vehicle design options

In addition to the choice of alternative hybrid powertrain to utilize, the designer has several vehicle options from which to choose. As noted in the Introduction, the basis of this choice is often the assumption relative to the price differential for the hybrid vehicle that would be acceptable in the market. Broadly speaking, the general categories of hybrid vehicles being considered are the following: (1) micro-hybrids, (2) charge sustaining hybrids, and (3) plug-in hybrids. Within each of these categories, the designer can vary the power rating of the electric driveline from a mild to full hybrid and the size (kWh) of the energy storage unit. For the micro-hybrid and charge sustaining hybrids, the designer has the option of using batteries or ultracapacitors. The electric driveline options for the various categories of hybrids are shown in Table 5. Simulation results for these various hybrid vehicle designs are given in the next section of the paper.

Table 5: Electric driveline options for various types of hybrid-electric vehicles

Type of hybrid driveline	System voltage V	Useable energy storage	Maximum pulse power at 90-95% efficiency kW	Cycle life (number of cycles)	Useable depth-of-discharge
Plug-in	300-400	6-12 kWh battery 100-150 Wh ultracapacitors	50-70	2500-3500	deep 60-80%
Charge sustaining	150-200	100-150 Wh ultracapacitors	25-35	300K-500K	Shallow 5-10%
Micro-hybrid	45	30-50 Wh ultracapacitors	5-10	300K-500K	Shallow 5-10%

Table 6: Advisor simulation results using the DCT hybrid powertrain

Vehicle	Battery	Powertrain	mpg-FUDS *	mpg-highwa *	mpg-US06 *
Civic	-----	Honda eng. i-VTEC	33	45	30
	NiMtHydride	CVT-single shaft	56.5	62.5	39.2
	Li A123	CVT-single shaft	58.5	63.5	40.9
	NiMtHydride	DCT	54.0	52.9	35.3
	Li A123	DCT	62.4	59.6	39.2
Prius	------	Prius eng. Atkinson	35.5	43	33.2
	Li A123	CVT-single shaft	65	70	43
	NiMtHydride	Prius single-planetary	68.0	67.5	41.9
	Li A123	Prius single-planetary	73.3	68.2	42.6
	NiMtHydride	DCT	62.1	63.1	45.2
	Li A123	DCT	71.7	68.8	50.3

* L/100 km = 238/mpg for gasoline fueled vehicles

6 Simulation results for the various alternative powertrains

Simulations of the operation of hybrid vehicles using the various alternative powertrains and energy storage technologies (nickel metal hydride and lithium-ion batteries and ultracapacitors) have been run using the UCDavis version of **Advisor** that includes the special component and powertrain models discussed in the previous sections. The results of the simulations for selected cases are presented in this paper, but more complete results are given in [7, 24].

6.1 Passenger Cars using the Single-shaft, single-planetary, and DCT powertrains

Simulations were run for the Civic and Prius hybrid vehicles using the single-shaft, single-planetary, and dual clutch transmission hybrid powertrains. For all the Civic simulations, the Honda I-VTEC engine was used and for the Prius simulations, the Prius Atkinson cycle engine was used. For each vehicle, their respective weights and road load parameters were used in the simulations. The fuel economy results for the Civic and Prius using nickel metal hydride and the A123 lithium-ion batteries are given in Table 6 for various driving cycles.

It is clear from the table that the implementation of the hybrid powertrains results in large improvements in fuel economy for all the driving cycles. The improvements are largest using lithium batteries primarily because of their higher efficiency. The differences are in the range of 10-15%. For all the batteries, the improvements in fuel economy are largest for the FUDS cycle. These improvements can be as high as nearly 100% with the Lithium batteries. Using the engine operating line control strategy to optimize the engine efficiency can result in relatively large improvements even for the highway driving cycle of up to 40-50%. The improvements on the USO6 cycle are the lowest being in the range of 30-40% for most cases.

The simulations indicate that the fuel economy improvements are largest using the Prius single-planetary powertrain. This powertrain utilizes both a large electric motor (50 kW) and generator (27 kW) in the Prius. The single-shaft and DCT powertrain utilize only a single electric machine that is used alternately in the motor and generator modes. The battery cell weight was about 25 kg for all cases. The fuel economy improvements with those powertrains are in general slightly less than with the Prius single-planetary arrangement. The electric machine rating in the DCT powertrain was 25 kW and in the single-shaft only 15 kW. The sum of the engine and electric machine ratings in these powertrains is about 100 kW. The results in Table 6 indicate that large improvements in fuel economy can be obtained using relatively small electric machines. It seems clear that the vehicle designers have a wide range of choices for the powertrain arrangement and component ratings.

6.2 SUVs using the two-mode, two-planetary powertrains

Simulations were run for the GM Tahoe and the Saturn Vue SUVs utilizing the two-mode hybrid transmission. These vehicles were selected because they are presently being marketed and there is EPA fuel economy test data available for them (Reference 28). The simulation results for the vehicles are given in Table 7 for both nickel metal hydride and lithium-ion batteries. The power rating of the electric machines in the drivelines for each vehicle were selected to be equal to that advertised by GM and Saturn, respectively, for the Tahoe and Vue. The battery weight was about 40 kg in all cases. Simulations were also run for the Prius replacing the Prius single-planetary with the two-mode arrangement with all the other components the same. The results indicated that the fuel economy of the Prius was essentially the same using the two hybrid powertrains for all the driving cycles.

The use of the two-mode hybrid powertrain yielded large improvements in fuel economy for the FUDS cycle for both the Tahoe and Vue with the increase being greater in the Vue. The fuel economy improvements were much smaller for the Highway and US06 cycles. This was especially the case for the Tahoe. For both the Tahoe and Vue, the simulation fuel economy results agreed well with the fuel economy measured by EPA. When considering only improvements in fuel economy, the simulation results presented in Table 6 and 7 indicate that in general the two-mode, two planetary powertrain does not offer clear advantage over either the single-shaft or Prius single-planetary arrangements. The prime applications of the two-mode powertrain [8] are stated to be in large vehicles like the Tahoe and Vue and not in light-duty vehicles like the Civic and Prius.

6.3 Hybrid vehicles using ultracapacitors

Simulations of a mid-size passenger car using the ultracapacitors in micro-hybrid, charge sustaining, and plug-in hybrid powertrain designs were performed using the **Advisor** vehicle simulation program. All the powertrains were in the same vehicle having the following characteristics: test weight 1660 kg, C_d =.3, A_F =2.25 m^2 , f_r =.009. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The rated engine power was 120 kW for the conventional ICE vehicle and the micro-hybrid and 110 kW for the charge sustaining and plug-in hybrids. All the hybrids use the single-shaft approach similar to the Honda Civic hybrid. The simulation results are summarized in Table 8 for a conventional ICE vehicle [25] and each of the hybrid designs. Results are given for fuel usage in terms of both L/100 km and mpg for various driving cycles. It is clear from Table 8 that large improvements in fuel usage are predicted for all the hybrid powertrains using ultracapacitors for energy storage. The results for the micro-hybrids are particularly interesting and surprising, because of the large fuel economy improvements predicted. These improvements were about 40% on the FUDS and ECE-EUD cycles and 20% on the Federal Highway and US06 cycles using the carbon/carbon ultracapacitor units. The improvements were significantly less using the hybrid carbon units because of their lower round-trip efficiencies. In the micro-hybrid designs, the rated engine power used was the same as that in the conventional ICE vehicle in order that the performance of the hybrid vehicle when the energy stored in the ultracapacitors was depleted would be the same as the conventional vehicle. The ultracapacitors were used to improve fuel economy with only a minimal change in vehicle acceleration performance. As was the case for the mild and full hybrids, the control strategy used was to operate on the electric drive when possible and to recharge the ultracapacitors when the engine was operating. As shown in Figure 2, this resulted in a large improvement in average engine efficiency from 19% in the ICE vehicle to 30% in the micro-hybrid even though the electric motor had a peak power of only 6 kW.

Table 7: Simulation results for various vehicles and driving cycles using the two-mode hybrid powertrain

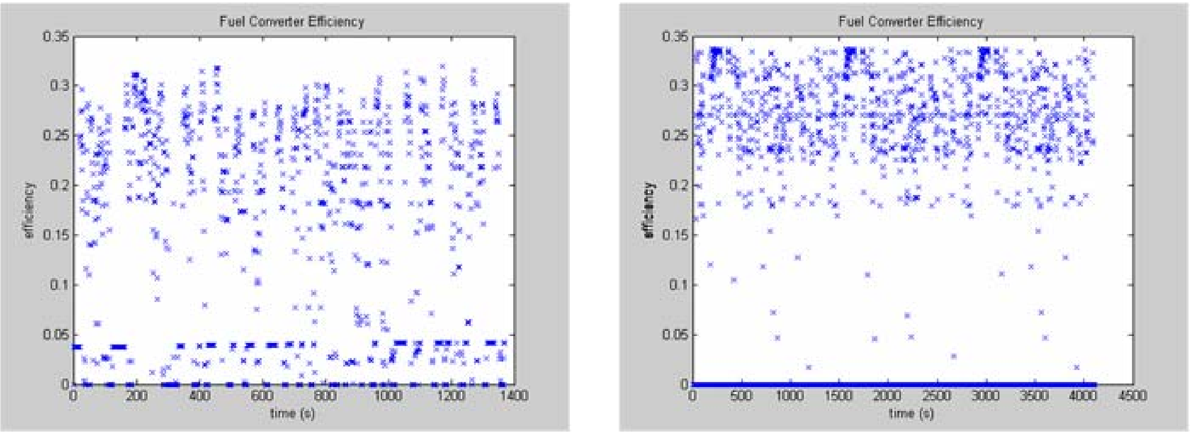
Vehicle	Powertrain configuration	Battery type	Mpg Fuds	Mpg HW	Mpg US06
Prius	Single planetary	NiMtHd	68	66	43
Prius	Two-mode	NiMtHd	67.8	62.9	44.9
Tahoe	Two-mode	NiMtHd	20.2	23.6	17.6
Tahoe	Two-mode	Li A123	21.3	23.7	17.9
Tahoe (EPA)	Two-mode	NiMtHd	21	22	
Tahoe	Conventional ICE- V8 220kW		13.4	22.0	16.3
Tahoe (EPA) *	Conventional ICE- V8 220kW		13.3	21.8	
Saturn Vue	Two-mode	NiMtHd	33.2	35.6	26.2
Saturn Vue	Two-mode	Li A123	35.5	35.9	27.1
Saturn Vue (EPA-estim.)	Two-mode	NiMtHd	31	35.9	-----
Saturn Vue	Conventional ICE 190kW		18.5	28.9	22.5
Saturn Vue (EPA) *	Conventional ICE 190kW		17.8	28.2	-----

* EPA test values uncorrected

Table 8: Summary of the vehicle fuel economy simulation results using ultracapacitors for various driving cycles

L/100 km/ mpg

Driveline type	Energy storage type	Voltage and weight cells (kg)	EM Peak kW	FUDS	HWFET	US06	ECE-EUDC
ICE baseline				10/ 23.8	6.9/ 34.4	9.6 24.7	9.7/ 24.6
Micro-HEV	Lead-acid/ ultracaps	48					
	Carbon/carbon	6 kg	6	5.7/ 41.7	5.3/ 44.7	7.8/ 30.6	5.9/ 40.2
	Hybrid carbon	3 kg	6	7.3/ 32.8	6.3/ 38.0	8.9/ 26.7	7.1 33.4
Charge sustaining hybrid	Ultracaps	200					
	Carbon/carbon	30 kg	35	5.4/ 43.8	5.0/ 47.9	7.1/ 33.6	5.5/ 43.2
	Hybrid carbon	13 kg	35	5.8/ 40.9	5.2/ 45.8	8.0/ 29.9	5.8/ 41.3
Plug-in hybrid .	12 kWh Li battery and ultracaps	300	70 kW with 45 kW from ultracaps				
	Carbon/carbon	40 kg	45	5.5/ 43.2	5.0/ 47.7	7.0/ 33.9	5.5/ 42.9
	Hybrid carbon	18 kg	45	5.8 41.2	5.2/ 46.2	7.9/ 30.2	5.8/ 41.2



Engine operating efficiency for the ICE vehicle- average engine efficiency .19

Engine operating efficiency for the micro-hybrid - average engine efficiency .30

Figure 2: A comparison of engine efficiencies for a conventional ICE vehicle and a micro-hybrid on the FUDS cycle using carbon/carbon ultracapacitors

6.4 Series hybrid vehicles

Simulations were performed using the SIMPLEV program for series hybrid vehicles for comparison with battery-powered vehicle (BEV) and parallel hybrid results [24]. The electric drivelines of the series hybrid vehicles were the same as that of the battery-powered vehicles except that the batteries stored only 40% of the energy in the BEVs. The engine/generator power was selected such that the

Table 9: Summary of the vehicle characteristics and simulation results

Vehicle	Test weight kg	Engine/ generator kW	Battery kWh	FUDS mpg	Highway Mpg
Mid-size car					
Series HEV (1)	1830	40 (2)	10	40	47
CS HEV	1640			36	44
Conventional ICE	1640			20	32
Mid-size SUV					
Series HEV (1)	2150	55 (3)	13.3	29	31
CS HEV	1910			28	32
Conventional ICE (4)	1910			16	25

(1) All-electric range of 30 miles, lithium-ion batteries – 120 Wh/kg
(2) Electric motor power 105 kW
(3) Electric motor power 145 kW
(4) All the vehicles have the same acceleration performance (0-60 mph in 9 sec)

Table 10: Comparisons of fuel economy using various hybrid powertrains in the Prius

Driveline (1)	FUDS	Highway	US06
Single-shaft (2)	65	70	43
Single-planetary	73	68	43
DCT	72	69	50
2-planetary,dual mode	68	63	45
ICE conventional	36	44	33

(1) All the cases use the Prius road load and 23 kg of A123 lithium-ion batteries
(2) I-VTEC Honda engine, all other cases used the Prius Atkinson cycle engine

vehicles had acceptable steady gradeability on generator electricity alone. The simulation results are summarized in Table 9 for a mid-size passenger car and SUV.

As plug-in hybrids, the series hybrids have an all-electric range of about 30 miles if the batteries are discharged to 80% of their rated capacity. The simulation results indicate that the fuel economy of the series hybrids is slightly higher than that of the parallel charge sustaining hybrids when both are operated in the charge sustaining mode. The engine/generator was sized such that the series hybrids were full-function vehicles. Thus all the hybrid vehicles including the series hybrids in the all-electric mode have performance equivalent to the conventional ICE vehicle.

6.5 Powertrain selection considerations

The previous sections have been concerned with the analysis of the fuel economy of vehicles utilizing various hybrid powertrain options and control strategies. A summary of fuel economy results for the Prius are shown in Table 10. The table indicates that there are in general not large differences in the fuel economies predicted using the various powertrains for the same vehicle and battery.

The primary objectives in all the options considered were to operate the engine only in the high efficiency part of its map and to lose as little as possible of the gain by losses in the energy storage unit and the electric machines. The control strategies considered all required the engine to operate in an on/off mode at all speeds and with no fuel when the engine was off. In those cases in which the engine was connected to the output shaft when it was not being fueled, it is necessary to minimize engine losses via friction and potential air flow through the valves. It was found that losses in the batteries from the high power charging needed to operate the engines near maximum efficiency were significant with the efficiencies of the nickel metal hydride batteries often being only 75-80%. For this reason, the advantages of using lithium-ion batteries or ultracapacitors became clear as those energy storage technologies resulted in round-trip efficiencies near 95% and higher. The simulation results also indicated that losses in the mechanical transmissions were significant in some cases. For example, the losses in the CVT were particularly troublesome especially when the vehicle operated in an all-electric mode and the electric motor efficiency was not a strong function of RPM. In the analysis of the DCT, it was found that the efficiency map used for the multi-speed manual transmissions had a significant effect on fuel economy of the vehicle on the urban driving cycles. Hence one of the key uncertainties in the input data for the simulations was found to be the efficiency maps (losses vs. torque and speed) for the CVT and the multi-speed manual transmissions.

Most of the simulations were done for light-duty vehicles with a test weight of less than 1800 kg and moderate acceleration capability (0-60 mph in about 9 sec). For these vehicles, there did not seem to be a clear advantage of the GM dual-mode hybrid powertrain compared to the single-planetary Prius arrangement. The simulations indicated that the dual-mode (two planetary) powertrain did function efficiently for the large Tahoe vehicle. For all the various hybrid powertrain arrangements, the selection of the control strategy and an low loss energy storage unit were more important than the powertrain arrangement.

Limited simulations were done for a series hybrid that could be operated as a plug-in hybrid. Detailed analyzes of parallel plug-in hybrids have previously been discussed in [7]. The series hybrids considered in this paper are modifications of battery powered vehicles. Hence in the charge depleting mode, these vehicles operate as full-function EVs. Since the engine in a series hybrid can be operated at high efficiency, large fuel economy improvements compared to ICE vehicles of the same size can be expected when the series hybrid is operated for long distances. The key issue is then the economics of the series vs. the parallel plug-in hybrids and not vehicle performance and fuel economy.

7 Summary and conclusions

In this paper, various alternative hybrid vehicle powertrains that are being considered by auto companies are evaluated based on simulation studies performed at the Institute of Transportation Studies, University of California-Davis. The following hybrid powertrain arrangements have been considered:

a. Single-shift, parallel (Honda)
b. Single-planetary, dual-mode (Toyota/Prius)
c. Multiple-planetary, dual-mode (GM)
d. Multiple-shaft, dual-clutch transmission (VW and Borg-Warner)
e. Series – range extended EV (GM Volt)

The utilization of these powertrains in micro-hybrids, charge sustaining, and plug-in hybrids are analyzed for various driving cycles. Appropriate control strategies using either batteries (primarily lithium-ion) or supercapacitors are included in the analysis. The focus of the evaluations is on fuel economy/consumption and electrical energy use and the overall efficiency of the powertrains compared to conventional ICE vehicles of the same size and road load characteristics.

The primary strategy in all the options considered was to operate the engine only in the high efficiency part of its map and to lose as little as possible of the gain by losses in the energy storage unit and the electric machines. It was found that losses in the batteries from the high power charging needed to operate the engines near maximum efficiency were significant with the efficiencies of the nickel metal hydride batteries often being only 75-80%. For this reason, the advantages of using lithium-ion batteries or ultracapacitors became clear as those energy storage technologies resulted in round-trip efficiencies of 90% and higher. The simulations indicated that there are in general not large differences in the fuel economies predicted using the various powertrains for the same vehicle and battery. The fuel economy improvements were large in all case – 80-100% for the FUDS cycle, 40-60% for the Highway cycle, and 30-50% for the US06 cycle – using lithium-ion batteries and a 25-35 kW electric driveline.

Limited simulations were also done for a series hybrid that could be operated as a plug-in hybrid with a range of about 30 miles. The series hybrids considered in this paper are modifications of battery powered vehicles. Hence, in the charge depleting mode, the vehicles operate as full-function EVs. There seems to be little doubt that the series hybrids will have large fuel economy improvements compared to ICE vehicles of the same size and performance in the charge sustaining mode when those vehicles are operated for long distances. The key issue is then the economics of the series vs. the parallel plug-in hybrids and not vehicle performance and fuel economy.

References

[1] K. Akima, K. Sedo, W. Taga, K. Torii, S. Nakamura, *Development of New Low Fuel Consumption 1.8L i-VTEC Gasoline Engine with Delayed Intake Valve Closing,* SAE 2006-01-0192

[2] T. Iijima, *Development of Hybrid System for 2006 Compact Sedan*, SAE 2006-01-1503

[3] Burke, A.F., Miller, M., and McCaffery, Z., The World-wide Status and Application of Ultracapacitors in Vehicles: Cell and Module Performance and Cost and System Considerations, Proceedings of the 22nd Electric Vehicle Symposium, Yokahama, Japan, October 2006

[4] Wang,W., Revisions on the Model of the Toyota Prius in Advisor 3.1, SAE 2002-01-0993, March 2002

[5] Muta,K., Yamazaki, M., and Tokeida, J., Development of the New-Generation Hybrid System THS II- Drastic Improvement of Power Performance and Fuel Economy, SAE 2004-01-0993, March 2004

[6] Duoba, M., Ng, H., and Larsen, R., In-situ mapping and Analysis of the Toyota Prius HEV Engine, SAE 2000-01-3096, March 2000

[7] Burke, A.F. and Van Gelder, E., Plug-in Hybrid-Electric Vehicle Powertrain Design and Control Strategy Options and Simulation Results with Lithium-ion Batteries, paper in the proceedings of the EET-2008 European Ele-Drive conference, Geneva, Switzerland, March 11-13, 2008

[8] T. Grewe, B. Conlon, A. Holmes, *Defining the General Motors 2-Mode Hybrid Transmission*, SAE 2007-01-0273

[9] K. Ahn, et. al. (2006), *Performance Analysis and Parametric Design of the Dual-Mode Planetary Gear Hybrid Powertrain*, IMechE Vol. 220 part D, Journal of Automobile Engineering, 2006

[10] K. Ahn, Suk Won Cha (2008), *Developing Mode Shift Strategies for a Two-Mode Hybrid Powertrain with Fixed Gears*, SAE 2008-01-0307

[11] Van Gelder, The Two-Mode Hybrid System from the Global Hybrid Cooperation (BMW, Chrysler, GM) Applied to a Prius Model in ADVISOR for Comparison with a Single Mode Hybrid System, internal ITS-Davis memo, July 2008

[12] Moser,A., Schafer, M. and Gunter, F., High efficiency DualTronic- Efficiency Dynamic comfort- The ideal supplement for hybrid powertrains, prepared by Borg Warner, 2007

[13] Song,X., Lui, J., and Smedley, simulation Study of Dual Clutch Transmission for Medium Duty Truck Applications, SAE 2005-01-3590

[14] Harris, B., How Dual Clutch Transmissions Work, “How stuff works” from auto.howstuffsworks.com/dual-clutch-transmission

[15] Zhao, H. Modeling of the DCT Transmission for the Simulation of Hybrid-Electric Vehicles, internal ITS- Davis memo, February 2009

[16] Szumanowski, A., Hybrid Electric Vehicle Drives Design (edition based on Urban Buses), ISBN- 83-7204-456-2, published 2006 by Radom, Poland

[17] Cole, G.H., SIMPLEV: A Simple Electric Vehicle Simulation Program-Version 2, EG&G Report No. DOE/ID-10293-2, April 1993

[18] Burke, A.F., Emerging Lithium-ion Battery Technologies for PHEVs: Test data and performance comparisons, Presentation at the pre-conference battery workshop, Plug-in 2008, San Jose, California, July 21, 2008

[19] Burke, A.F. and Miller, M., Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Hybrid Vehicles, Proceedings of EVS-24, May 2009

[20] Burke, A.F. and Miller, M., Electrochemical Capacitors as Energy Storage in Hybrid-electric Vehicles: Present status and future prospects, Proceedings of EVS-24, May 2009

[21] Burke, A.F., Considerations for Combinations of Batteries and Ultracapacitors for Vehicle Applications, Proceedings of the 18th International Seminar on Double-layer Capacitor and Hybrid Energy Storage Devices, Deerfield Beach, Florida, December 2008

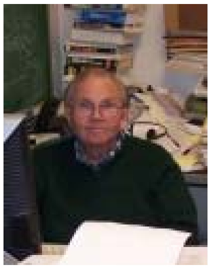
[22] Burke, A. and Miller, M., Supercapacitors for Hybrid-electric Vehicles: Recent Test Data and Future Projections, Advanced Capacitor World Summit 2008, San Diego, California, July 14-16, 2008

[23] Burke, A.F., Materials Research for High Energy Density Electrochemical Capacitors, published by the Materials Research Society in their Symposium Series-Spring 2008 Symposium JJ

[24] Burke, A.F., Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles, IEEE Journal, special issue on Electric Powertrains, April 2007

[25] EPA Fuel Economy Guide 2009,, also on www.fueleconomy.gov

Authors



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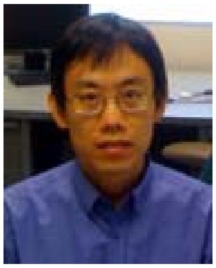

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