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Heuristic Design of Advanced Drives: Analysis of Trade-offs in Powertrain Electrification

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Abstract

Consumer demand for fuel efficient, low-emission vehicles is growing. This trend is motivated on one hand by the increasing fuel cost and on the other by government incentives and increased awareness. By hybridizing and electrifying powertrains, fuel use may be halved without a drastic reduction in drive quality or functionality. Manufacturers are introducing powertrain concepts that avoid asking drivers to compromise, other than with perhaps a slight increase in purchase price. Heuristic design methods are useful for quantifying trade-offs between key stakeholder criteria, particularly with new technologies.

Keywords: EV (electric vehicle), HEV (hybrid electric vehicle), fuel cell, powertrain, simulation

1 Introduction

Several factors are responsible for the trend towards lower emission vehicles. Besides increasing consumer environmental sensibility, fuel and vehicle purchase price play significant roles in personal mobility decisions. Figure 1 illustrates how the increasing price of diesel in France and Belgium reduces sales in countries where diesel vehicles are very popular.

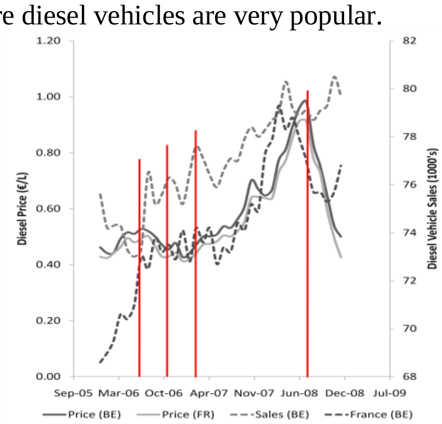

Figure 1: Diesel vehicle sales track fuel price

The ‘knee-jerk’ reaction to pump price manifests itself as a delay in buying new fossil-fuelled cars. Once price falls, however, sales return to normal levels. An interesting trend is observed in the United States, where restrictive emissions standards have limited diesel penetration: hybrid vehicle sales increase proportionally with fuel price. Figure 2 shows how more stringent emissions standards which will soon be introduced in Europe.

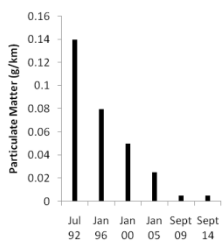

Figure 2: Tightening particulate exhaust standards

These regulations, as well as other legislative measures, will likely result in a similar push towards hybrid vehicles in Europe. The trade-offs associated with moving from internal combustion towards electrified powertrains will be examined in this paper.

1.1 Trade-offs

The trade-off which is most often weighed by consumers is that of purchase cost versus maintenance and fuel costs. Extensive maintenance data is not available for all-electric or fuel cell vehicles, however initial reports suggest that hybrid vehicles are marginally more expensive to maintain than non-hybrid variants of the same model [7]. After cost considerations, consumer preference diverges, with drivers weighing performance, utility, aesthetics, or features as most important. The challenge for manufacturers and policy makers is ensuring that environmental and social considerations are internalized when consumers choose between available options.

1.2 Heuristic Design Methods

Vehicle manufacturers prefer to adhere to incremental design approaches which keep research and development costs low while maximizing the re-use of reliable components in successive design generations, as shown in Figure 3. While the traditional 'tried and true' method is efficient when developing conventional powertrain designs, advanced hybrid and electric powertrains often may not be approached by following an evolutionary design path. In order to perform an unbiased analysis of effects of introducing various vehicle technologies, heuristic design methods are used to compose sets of vehicle designs according to 'rules of thumb'. These heuristic design rules are based in part on historical architecture design methodologies [3], as well as first principles and physical laws. These methods are particularly useful when examining technology implementation in broad markets as opposed to attempting to extrapolate based on narrow case studies.

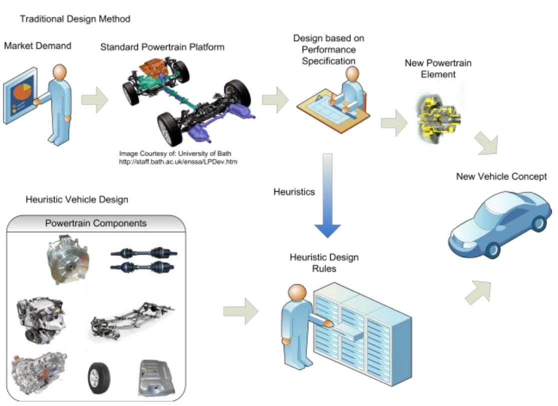

Figure 3: Heuristic and incremental design

2 Design Set

The options and heuristics used in composing the vehicle designs in this set were tailored to ensure that an investigation into the trade-offs inherent in powertrain electrification could be effectively and fairly examined.

2.1 Design Options

A comprehensive table of design options which were used can be found in Appendix A. The options were chosen to reflect the state of the art of advanced powertrain technology in 2010. It is also possible to include options that are not currently available to perform 'what-if' analysis, with the advantage of having a technology boundary within which interpolations instead of extrapolations can be performed. The allowed hybrid architectures are shown in Figure 4. It is important for the following discussion to note that the Group A architectures may be simulated using the simplification that mechanical and electrical power splitting may be performed interchangeably (i.e. no motor speed or electrical transients are considered). This allows state of charge to be the only control variable for which a control optimization must be performed.

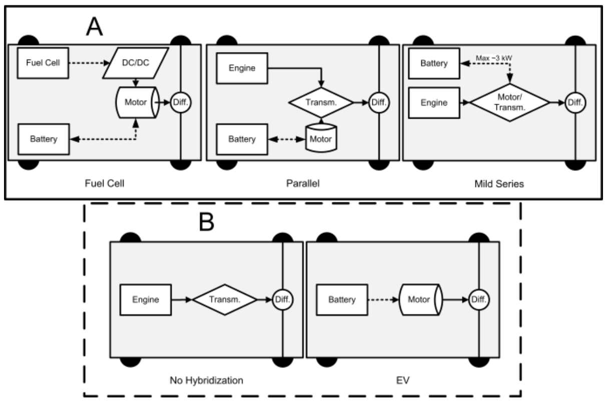

Figure 4: Permitted hybridization options

2.2 Heuristic Rules

The rules used in developing the design set can be found in Appendix B. They reduced the set of 104976 possible technology combinations to a manageable 1402 vehicle designs. Assumptions about advanced technology cost were based on Kromer's work [1], and basic cost data from the Touring Club Suisse [8] and GM[6]. Life cycle data comes from the GREET model, developed by Argonne National Laboratories [4], and was adapted to the vehicle designs in this study based primarily on weight and materials. Wherever applicable, conservative assumptions have been made in favour of optimistic ones.

3 Analysis of Results

The distribution of the design set by hybridization ratio (motor power over total power at the wheel) is shown in Figure 5, and tends to light hybridization as specified by the heuristics.

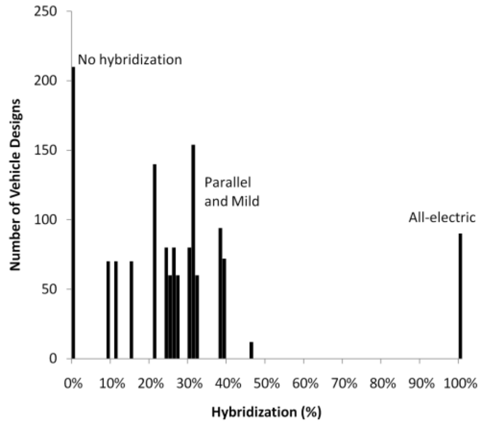

Figure 5: Design set electrification distribution

To objectively and accurately analyze the impact of changing electric powertrain technology, it is important to ensure that an optimal control policy is applied over a specific driving cycle. To achieve this end, the Bellman dynamic programming technique is applied, with the state of charge of the energy storage system as the target while minimizing energy use in the objective function. This technique has been extensively applied by Sundström for parallel and series hybrid vehicles [5]. The colour map in Figure 6 shows the optimal power split for a gasoline/electric hybrid over the EUDC driving cycle. The battery current, state of charge, and vehicle speed are also shown for reference.

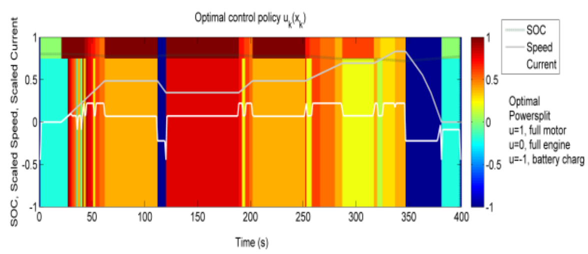

Figure 6: Optimal hybrid control for EUDC

Each of the Group A architectures was simulated over the full 11km NEDC driving cycle to determine its optimal control policy and hence minimum fuel consumption and emissions. This ensures fair comparison of the various technologies by ensuring that all influence parameters are considered, such as battery size impacting overall vehicle weight, for example.

The results are sensitive to controls optimization, to the extent that fuel consumption can vary up to 40% between un-optimized and optimized cycle runs.

The sensitivity of fuel consumption to vehicle weight is reduced through hybridization, as is shown by the relative slopes of the lines in Figure 7. This is a direct result of the energy recaptured during regenerative braking reducing inertial losses.

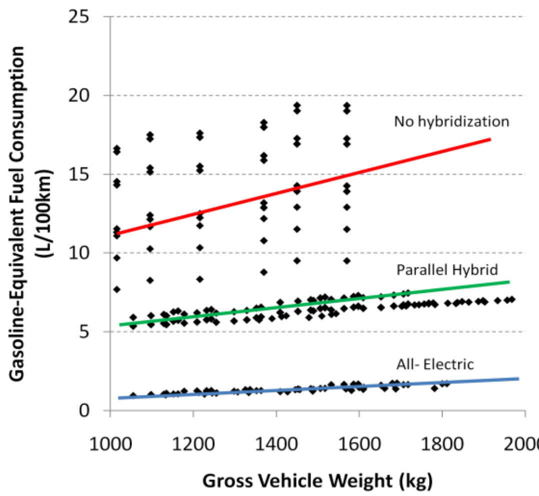

Figure 7: Hybrid sensitivity to weight reduction

It is also clear from Figure 7 that as the degree of hybridization increases, the sensitivity of the vehicles fuel consumption to weight decreases. Figure 8 illustrates the fuel consumption to performance trade-off, which is dominated by compact, parallel hybrids. The figure also shows that electric vehicles are severely underpowered for their weight in this design set.

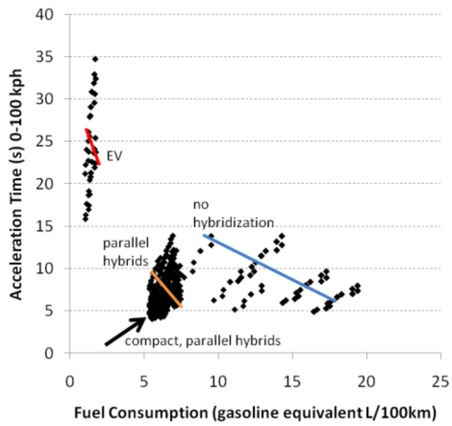

Figure 8: Consumption/performance trade-off

Top speed is directly proportional to vehicle power, and inversely proportional to aerodynamic drag. The trend line in Figure 9 shows how increased top speed performance results in a tendency to higher greenhouse gas emissions.

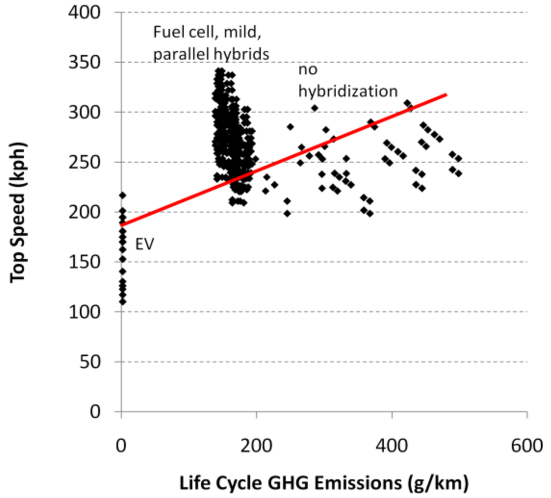

Figure 9: Higher top speed with higher emissions

It is clear from Figures 8 and 9 that there is a large degree of data clustering present in the design set. The hybrid vehicle designs are grouped very closely, with EV's and non-hybrid's representing outlier sets. This illustrates clearly the intuitive trend that exists in the hybrid cluster, namely, that the higher the degree of electrification, the lower the fuel consumption and the lower the performance.

Although elaborate emission control technologies installed on modern high-end vehicles moderate the trend shown in Figure 10 [2], the driving factors behind NOx emissions are fuel consumption and vehicle weight. Electric powertrains offer reduced GHG and NOx emissions at a relatively low cost.

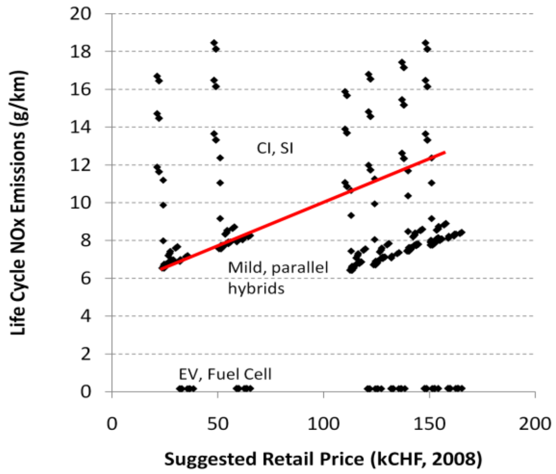

Figure 10: Heavy and high powered vehicles result in higher life-cycle NOx emissions

Table 1 provides criteria averages to put the various results into perspective.

Table 1: Design set criteria averages

Acceleration time (s) 0-100 kph		9.64
Maximum Velocity (kph)		260.40
Maximum Grade (degree)		8.60
Suggested Retail Price (CHF, 2008)	CHF	110'921.58
Fuel Consumption (Gas. Equiv. L/100km)		7.34
Greenhouse Gas Emissions (g/km)		18751.83
Nitrous Oxide Emissions (g/km)		8.13

4 Conclusions

To objectively analyze the impact that electric powertrain technologies have, a design set has been composed according to heuristic rules. The performance of previously-untried combinations of powertrain and control technologies has been studied, as opposed to examining and incrementally optimizing existing systems. The design set was then rigorously simulated, and the results were used to evaluate performance using key criteria such as environmental impact, drivability, and cost among others. The conclusions that were reached are that:

- the sensitivity of hybrid vehicles to weight reduction is lower than that of conventional vehicles,
- control optimization is important for objective comparisons,
- powertrain electrification leads to a reduced trade-off between fuel consumption and performance, with marginal cost increases,
- EV's and fuel cell vehicles offer similar life-cycle environmental trade-offs with respect to performance,
- Fuel cell vehicles incur greater cost, but qualitative utility of electric vehicles is lower due to long recharge.

Acknowledgments

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Authors

Erik Wilhelm is working towards his PhD from the ETH Zurich in the Technology Assessment group (GaBE) at the Paul Scherrer Institut. His focus is on advanced powertrain simulation and heuristic vehicle design. The results of this research will be applied for policy analysis using multi-criteria analysis. He has an Honours Bachelor and Masters of Chemical Engineering from the University of Waterloo.

Warren Schenler did his undergraduate studies in engineering physics at Oregon State University, and graduate studies in Technology and Policy, Operations Research, and Energy Systems Analysis at the Massachusetts Institute of Technology. He came to Switzerland to work at the ETH Zurich on energy research projects studying electric power system issues in Switzerland, Romania and China, and has continued this work at the Paul Scherrer Institut in the GaBE group. His research interests also include transportation, geothermal and hydrogen energy systems.

Appendix A: Technology Options

Category	Technology Choices				Options
CLASS	compact sedan (C)	midsize sedan (M)			2
HYBRIDIZATION	none (No)	mild series (SHV)	parallel (PHV)	all electric (EV)	4
FUEL	diesel (D)	gasoline (G)	hydrogen (H)		3
PROPULSION	compression ign (CI)	spark ign (SI)	fuel cell (FC)		3
MARKET	passenger (P)	luxury (L)	sport (S)		3
DISPLACEMENT	1.4	2.4	3.2		3
PEAK FUEL CELL POWER (kW)	65	90			2
PEAK BATTERY POWER (kW)	15	40	55		3
BATTERY CAPACITY (Ah)	8.5	32	60		3
SEATING	2	4	5		3
INDUCTIVE FORCING	none (NoF)	Turbocharger (Tur)	Supercharger (Sup)		3
				All Option Combinations:	104976

Appendix B: Heuristic Design Rules

Endogeneous Options
CI uses diesel
SI uses gasoline, hydrogen
FC uses hydrogen
Inductive forcing with SI
sport fuel cell 90kW
compact fuel cell 65 kW
2 seating only for sport
4 seating only for compact

Dependent Endogeneous Options
mild series hybrids only 0.5 kWh and 3 kW
parallel hybrids only use 20 and 60 kW
parallel hybrids only use 8.5 and 32 Ah
sport vehicles have Cd of 0.2
passenger vehicles hav Cd of 0.3
luxury vehicles have Cd of 0.25
compact have base weight of 1096 kg
midsize have base weight of 1450 kg
pickup have base weight of 2062 kg
no mild series fuel cell hybrids
luxury adds 120 kg
sport subtracts 80 kg
compact has frontal area of 2.1 m
midsize has frontal area of 2.9m
sport fuel cell has only 90 kW
no fuel cell without hybridization
mild series hybrids only add power assist in low range

Assumptions
Cost
Compact vehicles have a baseline cost of CHF 21207
Midsized vehicles have a baseline cost of CHF 48137
SUV vehicles have a baseline cost of CHF 67964
Average diesel premium paid is CHF 2884
no additional cost for gasoline
cost of hydrogen storage integrated in fuel cell cost
luxury adds a cost premium of CHF 100026
sport adds a cost premium of CHF 88892
no cost associated with increased engine displacement
battery and fuel cell costs defined by Kromer [1]
Weight
no additional weight variation for diesel or gasoline
fuel cell has 360 W/kg including hydrogen storage systems
motor adds weight proportional to 1.35 kW/kg
specific power of motor/battery is 0.76 kW/kg
specific energy of battery is 0.06 kWh/kg
battery weight is heavier of either volumetric/gravimetric
Other
displacement correlates linearly with power
acceleration is linearly related to power and weight
constant efficiencies: for electric path 80%, for fuel cell 50%, for otto 20%, for diesel 30%
idle losses are assumed for non-hybrid and fuel cell powertrains, scaled with engine/fuel cell size
life-cycle emissions scaled from GREET [4]
half of efficiency improvement from forcing dedicated to efficiency improvement, half to performance increase
maximum hill climbing speed is 20 kph
stoichiometry for hydrogen combustion is 0.92, as with CNG
state of charge may float up to 5% between start and end cycle
interior volume depends only on width and height