Multi-Objective Optimisation of Vehicle Drivetrains

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Abstract

Vehicle drivetrains are complex integrated systems, which need to be designed for numerous thermodynamic, economic and environmental factors. As part of a project of the Alliance for Global Sustainability between the MIT, the SFITs and the University of Tokyo, a new evolutionary multi-objective optimisation algorithm has been developed and applied to various problems including vehicle drivetrain configurations. The simulation of a potential vehicle is complex and calculation intensive. The new algorithm, the Clustering Pareto Evolustionary Algorithm (CPEA) is attractive in this kind of problems because it allows an efficient use of each vehicle simulation - gathering more information about the solution domain for the same effort as a single point optimisation. In addition it allows optimisation of disparate objectives, for example, costs and emissions to be considered separately.

Conventional, series electric hybrid and parallel electric hybrid have been evaluated over the ECE-EUDC and US06HWY drive cycles considering performance in terms of CO2, NOx, fuel economy, estimated investment, operating and pollution costs. Although some own technology models have been developed and used, the major part of the optimisation results are based on models from Advisor which are available on the web.

The parallel hybrids were shown to be preferable to series hybrids in all cases studied, but were frequently beaten by conventional vehicles. In this first study, pollution costs considerations were limited to NOx (13.8 Frs/kg) and CO2,(0.03Frs/kg) and diesel engine vehicles proved difficult to beat in terms of operating cost, and even overall investment and operating cost. Indeed it was found that a five fold increase in pollution costs traditionaly considered in the literature, would be needed before any difference would be observed. Of course the situation looks different if investment and operating costs, without any pollution costs, are evaluated only in comparison with the NOx emission levels or if a pollution cost of particulates is added.

Among marketed hybrids the "Insight" was found to be highly attractive (keeping however in mind its limited seating capacity),although its exceptional performance is undoubtedly linked to the ultra light weight structure, which, in spite of the braking energy recovery of hybrids, is still shown to have a major effect.

It is interesting to note that the pollution costs were found to be of low significance compared to the operating and investment costs of an average vehicle, mainly due to the significant level of tax already applied to fuel in the road transport domain. Politically it would seem that applying a uniform CO2 cost accross the board of all energy domains will have a much more limited effect on the road vehicle technologies, than on other technologies such as those used for building heating and air conditioning.

Keywords

multi criteria - multi objective - optimisation - vehicle - drivetrain - multi-modal - pareto - pollution - hybrid - emission - 3^{rd} Swiss Transport Research Conference - STRC 03 - Monte Verita

1 Introduction

Transport presents a major problem for sustainability, and energy use for transport is rising faster than in any other sector. In Switzerland transport is responsible for around a third[20] of the man-made CO_2 produced, as well as many other directly harmful pollutants including NO_x, SO_x, hydrocarbons (HCs) and ozone. In high concentrations ozone can damage lung tissue, reduce lung function and sensitize the lung to other irritants, as well as damaging crops[16]. NO_x and particulate emissions have been linked[4,5] to severe health problems and even premature death.

To address this, new, energy-efficient and less polluting transport technologies must be evaluated against traditional solutions (and advances in traditional solutions) in a wide variety of situations to aid decisions on new policies.

The simulation of vehicle drivetrains is a difficult task - useful simulations tend to be complex and hence computationally expensive, even with many simplifying assumptions in the modeling. In addition there is a great deal of uncertainty and variability in the component data, and in the evaluation of potential objective critera.

To be acceptable to a large public a vehicle must have a competitive performance[1] as well as a good fuel economy, and as seen in earlier work[12] there is a tradeoff between fuel economy, performance and emissions. When investment, operation and potential pollutant costs are introduced the overall problem becomes even more complex. The new algorithm, the Clustering Pareto Optimisation Algorithm (CPEA) is attractive in this kind of problem because it allows more information to be gathered about the solution domain for the same effort as a single point optimisation, allowing costs and emissions to be considered separately.

The work presented here aims to demonstrate the feasibility of perfoming multi-modal and multi-objective optimisation (MOO) in this highly demanding area, and to produce some initial results as to the potential for some of the newer vehicle technologies.

1.1 Hybrid Vehicles

In a conventional vehicle, the vehicle's final drive (differential and wheels) is driven directly by the internal combustion engine (ICE) through a clutch and gearbox. The gearbox means that the ICE can be run near its optimal speed over a wide range of vehicle speeds. However, engine efficiency and emissions are strongly dependent on load, as well as speed, as illustrated in 1 and 2.

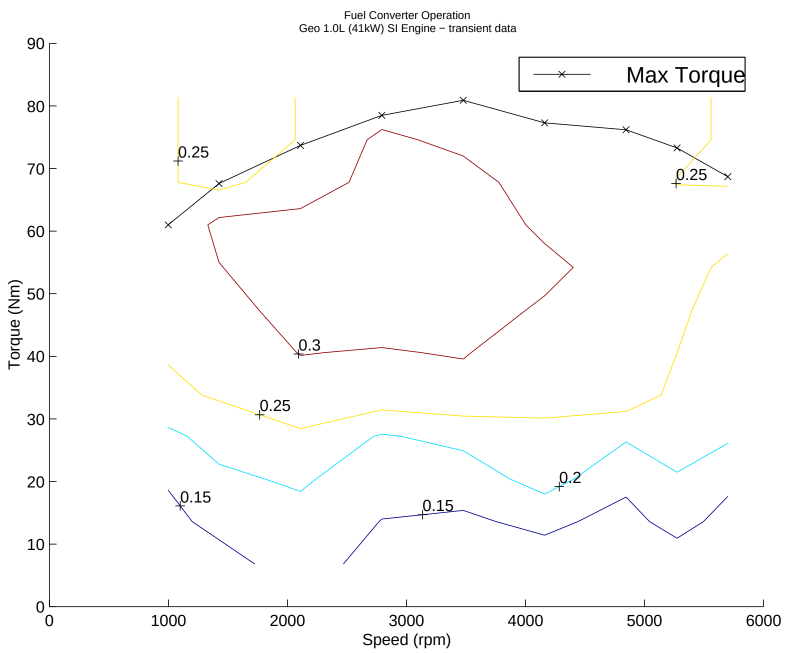


Figure 1: ICE Efficiency countours for a 41kW gasoline SI engine, shown against speed and torque, together with the maximum torque envelope.

[1]The trend in the demand in the US is still towards faster 0-60mph acceleration times[16]

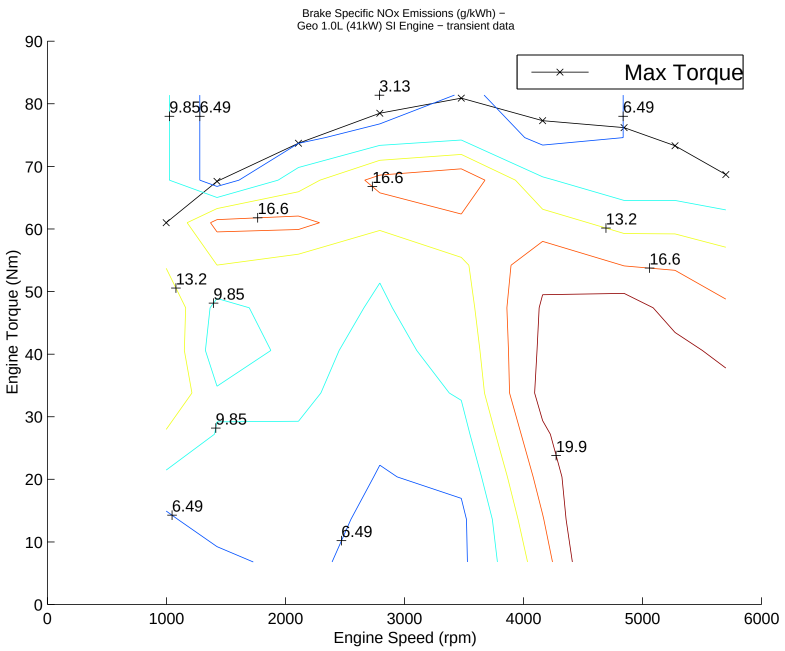


Figure 2: ICE NO_x production in g/kWh for a 41kW gasoline SI engine, shown as contours against speed and torque, together with the maximum torque envelope.

Consequently, while an ICE's peak efficiency can be over 30%, overall vehicle efficiencies can be lower than 15%[9]. Most of these losses are due either to the engine running away from its most efficient point, or to the engine running while the vehicle is stopped (more than half of the time in most homologation cycles). Conventional gearboxes and differentials, for example, are extremely efficient, and drivetrain losses are generally only on the order of 5%. Hybrid vehicles are an attempt to reduce these losses by flattening the demands on the ICE. In addition, they can improve efficiency by recovering some of the energy dissipated in braking, which otherwise only serves to heat and wear out the braking system.

A hybrid vehicle, in the broadest sense, is a vehicle that contains several power sources, and attempts to use those power sources in order to maximise overall efficiency. In this and earlier work[12] the emphasis has so far been on thermal-electric hybrids with an internal combustion engine and an electric motor[2]. These may be configured in a series or parallel configuration. A hybrid vehicle superconfiguration, showing a series hybrid with bold arrows, is shown in Figure 3.

In a series hybrid, an internal combustion engine is connected to a generator, which either charges a battery or powers an electric motor. The motor powered either by the battery or the generator, then powers the wheels. This means that the ICE can, if the control system wishes, always be run at its best operating point [3], while the electric motor, with better characteristics over a wider load/speed range, copes with demand variations. Series hybrids are relatively simple compared to parallel hybrids (described below). However, in situations where the vehicle operating point would allow the ICE to run well, such as at constant speed on a motorway, there is nothing to gain from the hybrid series configuration, but one still has to pay the losses of the complex mechanical-electrical-mechanical energy chain. There are also additional problems[16] such as the limited capacity of the batteries to absorb the energy produced by the engine operating at an optimal point, and the potential for increased emissions when repeatedly stop starting the engine.

Parallel hybrids solve this problem by allowing the ICE to either drive the generator or power the vehicle final drive directly. This involves the use of a torque coupling device (for example, the Toyota Prius has an epicyclic gearbox controlled by the generator[22]) between the ICE, electric motor, generator and final drive.

However parallel hybrids suffer from increased complexity and potentially higher maintenance costs than conventional solutions[4].

[2] This is the most likely next step to improve emissions and fuel economy and to meet demand for short term acceleration. Fuel cells for small cars are still very much in the prototype stage, and information on performance is currently limited.

[3] Clearly the "best" is not clear - best for pollution or best for economy?

[4] In a survey published by the TCS[21] the cost of maintenance of conventional vehicles is shown to vary dramatically - from as little as 400 sfr for 100,000km up to 4200 sfr.

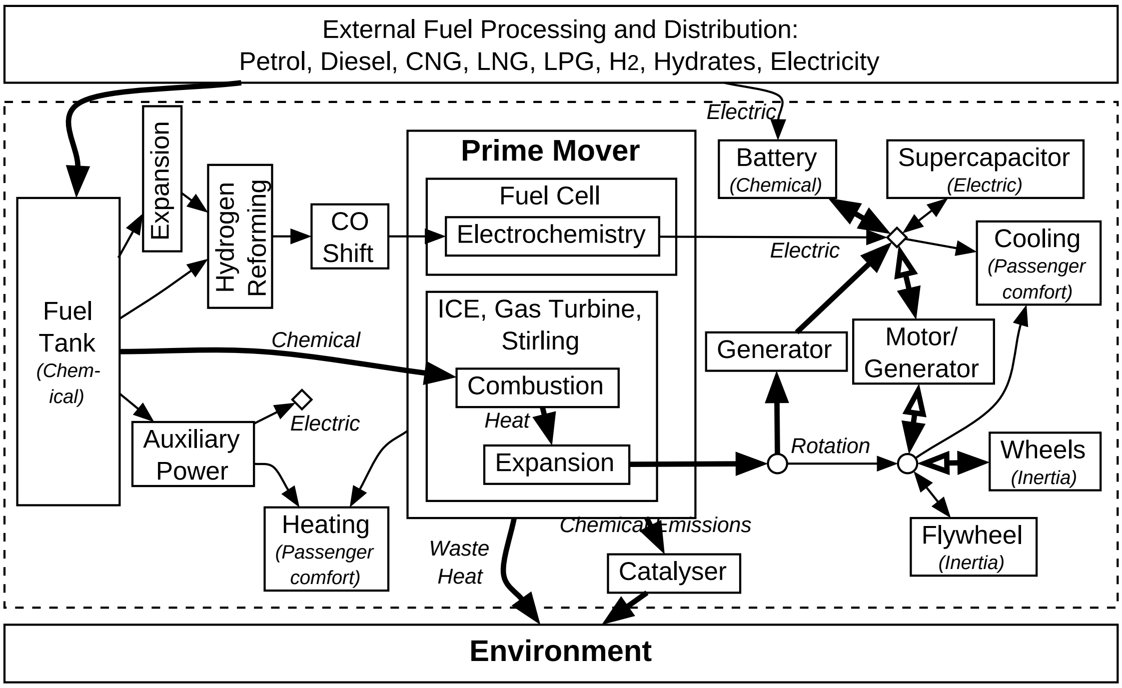


Figure 3: Hybrid Vehicle Superconfiguration in its broadest sense. The links showing a series hybrid are shown in bold.

Generally, battery capacity in a hybrid is low (the Prius has 50 kg of batteries while the General Motors EV1 *electric* car has 520 kg[8]) and the ICE needs to be run frequently to top up the battery charge, as well as whenever the vehicle has high power demands. In order to reduce charge cycle losses and improve battery life, batteries are usually kept within a narrow range of charge situated around half full. Consequently the batteries are usually larger and heavier than strictly necessary. If, however, the battery capacity is high, the ICE can be turned off completely for short periods, which may be interesting, for example, for crossing a town centre where only non-emitting vehicles are allowed.

The best choice of battery capacity, as with most vehicle design choices, is not evident - the Toyota Prius[22] has twice as many battery modules as the Honda Insight[27].

One reason for the slow growth of the hybrid car market is the cost of the electric components (since these are not in mass production in the same way that IC engines are) and the doubt over the operational benefits. In order to address this it is necessary to compare the cost of different options as well as emissions and performance, in particular to identify the sensitivity of the best choice to the relative cost of the electrical components.

2 The Vehicle Simulation Model

2.1 Problems in Simulating a Vehicle

Modelling a vehicle poses several particular difficulties:

- To evaluate a vehicle design it must be "driven" around a test cycle, equivalent for example to a car following a test cycle on a rolling road. If unable to follow the cycle what should be done?
- A vehicle is a highly dynamic system. Considering even quasi-static behaviour means evaluating the performance at many hundreds if not thousands of points around the test cycle. To model detailed dynamic behaviour (for example what happens in the combustion chamber as the throttle is opened) is not feasible as part of a system-level simulation.
- Many of the sub-components that make up a vehicle are themselves complicated, may be non-linear and may themselves require optimisation to run efficiently. During a drive cycle many components will be running "off-

design[5]", so simulation models must be detailed enough to predict off-design losses, or follow an optimal control map.

Because of the time required to run such a simulation, it is important to get as much information from each evaluation as possible, hence multi-objective techniques detailed previously are more attractive than single objective techniques.

A search of the literature identified a MATLAB Simulink vehicle simulation model called ADVISOR[26], with a modular, extensible structure.

2.2 ADVISOR Vehicle Simulation

ADVISOR was developed by the Vehicle Systems Analysis Team (VSAT) of the National Renewable Energy Lab (NREL)'s Center for Transportation Technologies and Systems (CTTS)[26], and currently has ten engineers involved directly in the development of component models and testing of components and vehicles, as well as the support of many industrial collaborators and universities (with more than 600 users in May 1999[3])

It is freely available for research purposes and has an open, extensible, modular structure. Use of ADVISOR has greatly increased the number of component models available and allowed the work to concentrate on optimisation[6].

The ADVISOR simulation toolbox allows a vehicle to be built up from a series of components, each of which publishes a set of controlling parameters that may be modified from an initial default value. Once specified, a given configuration (a car) can be *driven* through a drive cycle using a specific strategy and fuel economy, emissions and many other quantities monitored throughout.

However, the ADVISOR Simulink model is computationally expensive - requiring several tens of seconds to run on a modern PC. To optimise all but the most trivial of examples requires thousands of simulations. In order to cope with this a parallel version of the CPEA was implemented as described earlier in[15] which allowed multiple computers to run the simulation concurrently[14] on either a loose collection of Windows 2000 machines, or more recently on a dedicated Linux cluster[23] of 22 machines. The Linux cluster has allowed the previously published work[12] to be greatly enhanced and developed.

The models are a combination of tabularised test data (for example engine emissions maps) and thermodynamic calculations. A vehicle "structure" is chosen (for example parallel hybrid) that defines specific components and default values for parameters. Model parameters may be changed, and the component models will reflect these changes where appropriate - for example scaling the maximum power of an IC engine will scale the emissions test data and fuel consumption and also the engine mass. This in turn will be reflected in the overall vehicle mass.

2.3 ADVISOR Vehicle Models

The work presented here made use of 6 standard vehicle models, and 2 specific vehicle types for comparison.

- Conventional SI - A conventional vehicle with a spark ignition 41kW gasoline engine (based on a Geo Metro 1.0L gasoline engine) and 5 speed manual gearbox. This engine was also used in the SI hybrids.
- Conventional CI - A conventional vehicle with a compression ignition 60kW diesel engine (based on a Mercedes 1.7L Diesel engine) and 5 speed manual gearbox. This engine was also used in the CI hybrids.
- Series SI - A series hybrid with a 41kW gasoline engine, a Unique Mobility 32kW permanent magnet motor, and a second 32kW permanent magnet motor as the generator. Nominally 50 Ovonic NiMh 28Ah 6V battery modules.
- Series CI - A series hybrid with a 60kW diesel engine, a Unique Mobility 32kW permanent magnet motor, and a second 32kW permanent magnet motor operating as the generator. Nominally 50 Ovonic NiMh 28Ah 6V battery modules.
- Parallel SI - A parallel hybrid with 41kW gasoline engine and Unique Mobility 32kW permanent magnet motor. The electric motor was also used as the generator. Nominally 50 Ovonic NiMh 28Ah 6V battery modules.
- Parallel CI - A parallel hybrid with 61kW diesel engine and Unique Mobility 32kW permanent magnet motor. The electric motor was also used as the generator. Nominally 50 Ovonic NiMh 28Ah 6V battery modules.

[5]A component will usually have one optimal operating state. When used away from this state the component is being used "off-design".

[6]Future work may integrate the previously developed compressed natural gas engine and other models from the AGS project.

Each of the standard vehicles made use of a typical small car body with a glider mass (without engine, gearbox, exhaust system, drivetrain, motor etc.) of 592kg, frontal area of 2m^2 and the coefficient of drag (Cd) of 0.33. With a conventional 41kW SI engine and powertrain, together with 5 speed gearbox this resulted in a total vehicle mass of 1192kg. A stoichiometric close coupled catalyser was fitted to all vehicles.

In addition certain of the optimisations were run with ADVISOR models of the Toyota Prius (Japanese version)and the Honda Insight. The Honda Insight and the Toyota Prius both have a lightweight chassis, low Cd and low rolling resistance wheels. The Insight is a "thin" parallel electric assist (similar to Figure **??**) with a 10kW electric motor taking the place of the flywheel and with the clutch between the engine/motor assembly and the gearbox. The engine is an advanced VTEC 1.0 litre three cylinder gasoline engine with variable valve timing. Unfortunately no emissions data was available for the Insight, so it could not be included in the optimisations for pollution or NO_x.

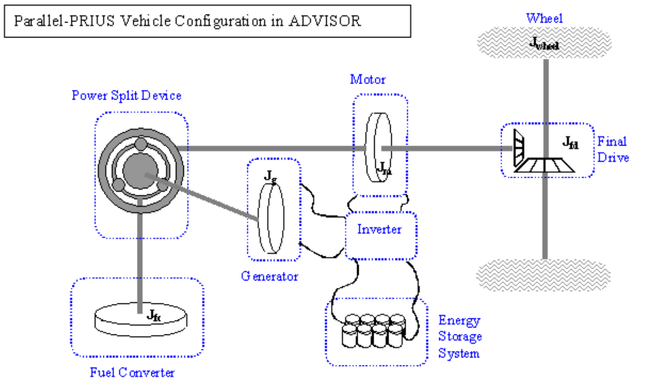


Figure 4: Toyota Prius Configuration (from Advisor documentation).

The Prius uses a planetary gear set as a power split device with the electric motor speed directly proportional to the wheel speed, and the IC engine speed controlled by the torque applied by the generator.

Both the Prius and the Insight seem to use the same spiral wound NiMh 6.5 Ah batteries, with a nominal 7.2V per module. The Insight has 20 modules and the Prius 40.

2.3.1 Hybrid Control Strategies

There are many possible strategies for controlling the IC engine and electric motor interaction, and this can have a dramatic impact both on fuel economy and on emissions.

For this work the Advisor control strategies outlined below were used for the parallel and series hybrids. These all made use of the maximum and minimum state of charge (SOC) of the battery pack as parameters to the control system.

Parallel Electric Assist The parallel electric assist control strategy uses the motor for additional power when needed by the vehicle and maintains charge in the batteries.

A relatively simple parallel assist strategy [10] was used that controlled the electric motor in a variety of ways:

- The electric motor can be used for all driving torque below a certain minimum vehicle speed.
- The electric motor is used for torque assist if the required torque is greater than the maximum that can be produced by the engine at the engine's current operating speed.
- The motor charges the batteries by regenerative braking.
- When the engine would run inefficiently at the required engine torque at a given speed, the engine will shut off and the electric motor will produce the required torque. Clearly there is an energy requirement to restart the engine.
- When the battery SOC is low, the engine will provide excess torque which will be used by the motor to charge the battery.

Series Electric Control Strategy The series strategy controls the IC Engine as follows:

- The IC engine may be turned off if the battery pack SOC gets too high.
- The IC engine may be turned on again if the power required by the generator (to meet the demand from the motor) gets high enough.
- The IC engine may be turned on again if the SOC gets too low.

When the IC engine is on, its power output tends to follow the power required by the motor, accounting for losses in the generator so that the generator power output matches the motor power requirement. However,

- The IC engine output power may be adjusted by the SOC, tending to bring the SOC back to the center of its operating range.
- The IC engine output power may be kept above some minimum value.
- The IC engine output power may be kept below some maximum value (which is enforced unless the SOC gets too low).
- The IC engine output power may be allowed to change no faster than a prescribed rate.

Prius Control Strategy The Prius has a planetary gear system to control the flow of power (torque) between the motor, the IC engine, the generator and the wheels (Figure 4).

For a given vehicle speed, and a desired output power (determined by drive cycle, or driver inputs)

- determine the desired operating point of the engine (based on max efficiency curve)
- determine the generator speed (which is controlled by generator torque) to have engine at the desired operating point
- determine motor torque (power or regeneration) to provide necessary power to the wheels (or recapture energy from wheels)
- batteries provide additional power when needed or take back extra charge provided by generator or motor in regeneration.

There are several heuristics:

- Below a SOC of 0.5 the engine is always on.
- If the SOC is $> SOC_{high}$ then the batteries are not charged.
- If the SOC is $< SOC_{low}$ then the batteries are charged if the engine can produce enough torque.
- The batteries are charged on braking via the generator.

In addition the IC engine is started if the temperature drops below a certain limit - by keeping the engine near operating temperature, emissions at restart can be minimised.

Interestingly this strategy can result in the engine running to charge the batteries even when the vehicle is stationary.

Insight Control Strategy The Honda Insight control strategy in ADVISOR is based on test data collected at NREL [11].

The demand is translated to a required torque at the clutch. Based on this value and the vehicle speed, the electric motor torque contribution is calculated. The remaining torque is demanded from the ICE. The electric motor torque is decided based on the following criteria:

- When accelerating, based on the torque and rate of acceleration, the electric motor assists the ICE, producing around 10 Nm of torque.
- During regeneration (in reality, when the brake is depressed), the electric motor regenerates a portion of the negative torque available to the driveline. Regeneration can only take place if the clutch is engaged.
- At low vehicle speeds, typically below 10 mph, the braking is primarily only the friction brakes.
- There is no electric assist in the first gear.[7]

[7] This is the model currently implemented in Advisor but represents a very early model Insight. In newer models electric assist is clearly active [25].

3 Optimisation and the Clustering Pareto Evolutionary Algorithm

3.1 Introduction to Multi-Objective and Multi-Modal Optimisation

Multi-objective minimisation of two objectives attempts to find the tradeoff curve between each objective defined such that at any point on the curve the value of one objective cannot be decreased without increasing the other (Pareto frontier [?]). This is illustrated in Figure 5 for a problem where cost and pollution are both of concern. In the real world many engineering problems are multi-objective, for example investment cost and running cost, or overall cost and pollution emitted.

In dealing with this the traditional approach is to combine the objectives to give one design criteria by weighting the objectives according to their perceived importance - a technique which immediateley introduces questions about the subjective weights, usually requiring several optimisations to identify the sensitivity of the best solution to the chosen weighting.

Multi-objective optimisation overcomes this difficulty by keeping the objectives separate - in addition providing a detailed tradeoff surface allowing for better informed decisions.

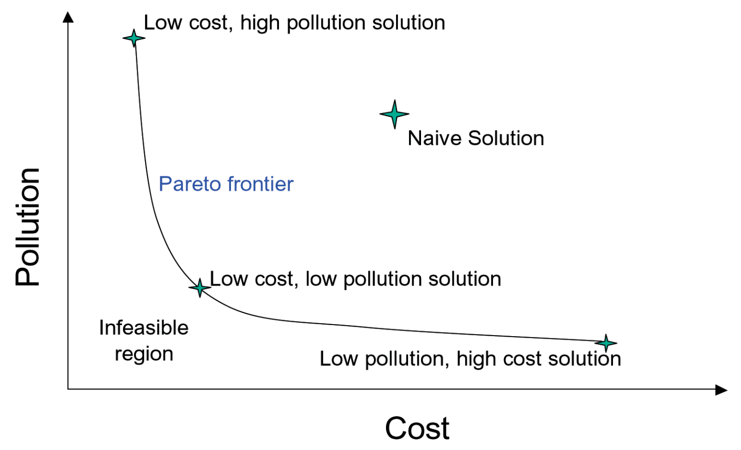


Figure 5: Multi-Objective Optimisation and the Tradeoff Surface. A typical tradeoff curve showing a naive solution such as might be found by hand, as well as the two extreme solutions.

Multi-modal optimisation addresses the situation where a problem has more than one, near optimal solution. In a practical engineering solution the second best solution may be preferable to the ideal solution for difficult to quantify reasons - for example less critical manufacturing tolerances, hence less cost. This is illustrated in Figure 6.

The motivation behind the CPEA was to develop a MOO method that required little or no tuning, and behaved well on a wide range of problems, producing a good distribution of solutions along the non-dominated frontier, while simultaneously keeping a distribution of solutions in variable space. In some problems this means finding multiple locally non-dominated fronts, while in others, different regions of the variable domain may contribute to the global Pareto front.

3.2 Description of Algorithm

In the CPEA, multi-objective optimisation is integrated with clustering and multi-dimensional scaling concepts from statistical multivariate analysis. In contrast to many algorithms clustering is in parameter space to try to preserve local optima, and a "breed and die" population control is employed which allows the population to expand over the non-dominated fronts.

Details of the CPEA are available in [15,13], and illustrated below with a simple test problem.

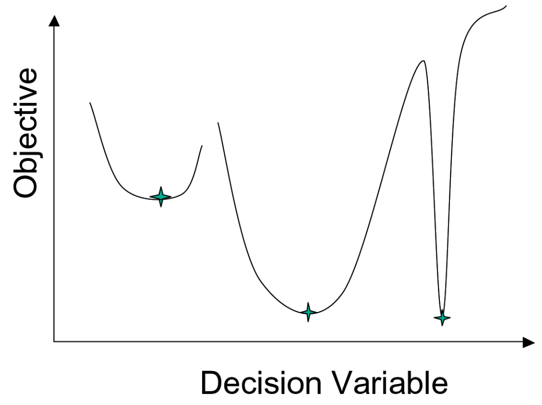


Figure 6: Multi-Modal Optimisation. An imaginary problem with multiple local minima. The best engineering solution may not correspond to the ideal global minimum for difficult to quantify reasons such as manufacturing tolerances.

3.3 Test Problem

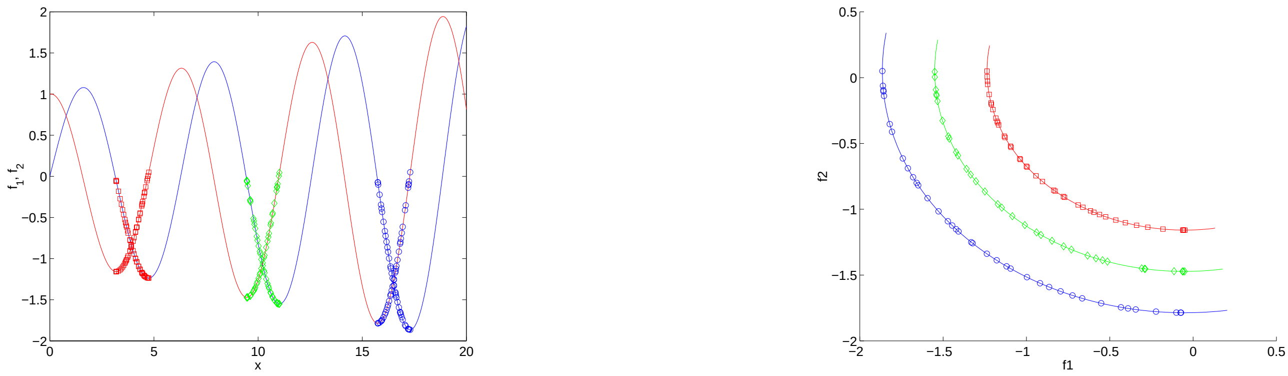
A simple test problem to demonstrate the local optima preserving features of the algorithm, the one dimensional function below was constructed.

$$\begin{aligned} \text{Minimise} f_1 &= \sin(x) * (1 * x/20) \\ \text{Minimise} f_2 &= \cos(x) * (1 * x/20) \end{aligned} \tag{1}$$

This function has three local Pareto-optimal regions in the domain $0 < x < 20$, the rightmost completely dominating the other two. The CPEA was run with the parameters: $p_{initial}$=10 , $p_{min\_cluster\_size}$=10, $p_{max\_cluster\_size}$=25 , $n_{clusters}$=3, c-means clustering.

The results from a typical run after 2000 evaluations are shown in Figure 7.

All three local Pareto-optimal frontiers are well defined after only 250 evaluations and remain stable even after 20000 evaluations - the dominant frontier does not overwhelm the other two.



(a) Final population in variable space (b) Final population in objective space

Figure 7: The Sin-Cos Function

If the CPEA is run without clustering, only the dominant, global Pareto front is found and maintained.

4 Drivetrain Optimisations

4.1 Optimisation Variables, Conditions and Parameters

The ADVISOR simulation gives access to an extremely large number of variables that could be optimised, including the structure of the vehicle - choice of catalyser, battery type etc.

However, with the already heavy overhead of the ADVISOR simulation it was decided to limit the number of variables optimised. In addition to a choice of basic vehicle configuration, seven variables were chosen, although not all are operative for all of the configurations.

Four drive cycles were used in the optimisations. The ECE cycle representing a urban European city [1] (Paris, Rome), the EUDC cycle representing inter urban use with a maximum speed of 120km/h, and the US06HWY cycle representing an American short highway driving cycle.

The ECE-EUDC is a combined cycle consisting of 4 ECE segments followed by an EUDC cycle. It is currently used for homologation in Switzerland and was used in the majority of the optimisation work as representative of typical mixed use.

The US06HWY, ECE, EUDC and ECE-EUDC cycles were used for the multi-cycle optimisation of fuel economy.

The drive cycles are shown in 8 and 9. During the optimisations all of the cycles were run with initial conditions set to standard ambient conditions - i.e. cold start.

Independent Variable	**Limits**
ICE Size	2-74kW for SI,12-108kW for CI)
Final Drive Ratio	0.5 to 5 (needed for Prius which has final drive ratio of 3.94)
SOC$_{high}$	0.3 to 0.85
SOC$_{low}$	0.3 to 0.85
($SOC_{high} < SOC_{low}$ was considered infeasible)	
Electric Motor	4.8 to 58 kW
Electric Generator	4.8 to 58 kW
No. of Battery Modules	1 to 60

Table 1: Independent Variables and Limits

The vehicle configuration problem posed particular difficulties not confronted in the other problems. Notably, with the complete change of vehicle configuration between conventional and hybrid drivetrains, some components are added and removed from the configuration, and the optimal dimensions of others differ greatly.

In order to deal with this the similarity comparison used to identify duplicates in the population was modified to take into account only those variables that were relevant for the configuration — for example the value of battery SOC for a conventional vehicle is clearly meaningless. The variables were implemented as scaling factors, so were equally appropriate for the vehicles with different basic components.

The unused variables do, however, contribute to the evolution of the population as a whole - when crossing two different vehicle configurations all the variables are taken into account and hence the variation in the population is preserved.

In order to avoid unfairly biasing hybrid configurations with large battery capacities, the state of charge of the vehicle batteries at the end of the cycle was required to be within 0.5% of its initial state. To achieve this the cycle had to be run iteratively, adjusting control parameters until the required final charge state could be achieved. Hybrid vehicles which failed to satisfy this requirement were also removed from consideration.

A vehicle design was also considered infeasible if it could not follow the chosen cycle within 0.01km/h. This was chosen to be small since it was found that optimum solutions will tend to take advantage of the minimum acceleration required.

The vehicle was required to accelerate from 0 to 60mph in less than 12 seconds[8].

This meant that the Prius (Japanese and European versions) could not meet the requirement as it stood.

Unless otherwise indicated in the following work the CPEA was run with the parameters: $p_{initial}$=250, $n_{clusters}$=8 corresponding to one cluster for each vehicle type and with clustering limited to the vehicle type[9]. The relatively large initial population was used to ensure a good spread of solutions over the vehicle types, since it proved more difficult to find feasible solutions randomly for certain vehicle configurations[10]

[8] The US Council for Automotive Research (USCAR) proposed the PNGV [24], which suggests this value.

[9] Where the Insight was not included the number of clusters was adjusted to 7.

[10] The initialisation code could alternatively have been changed to produce an equivalent number of each vehicle type.

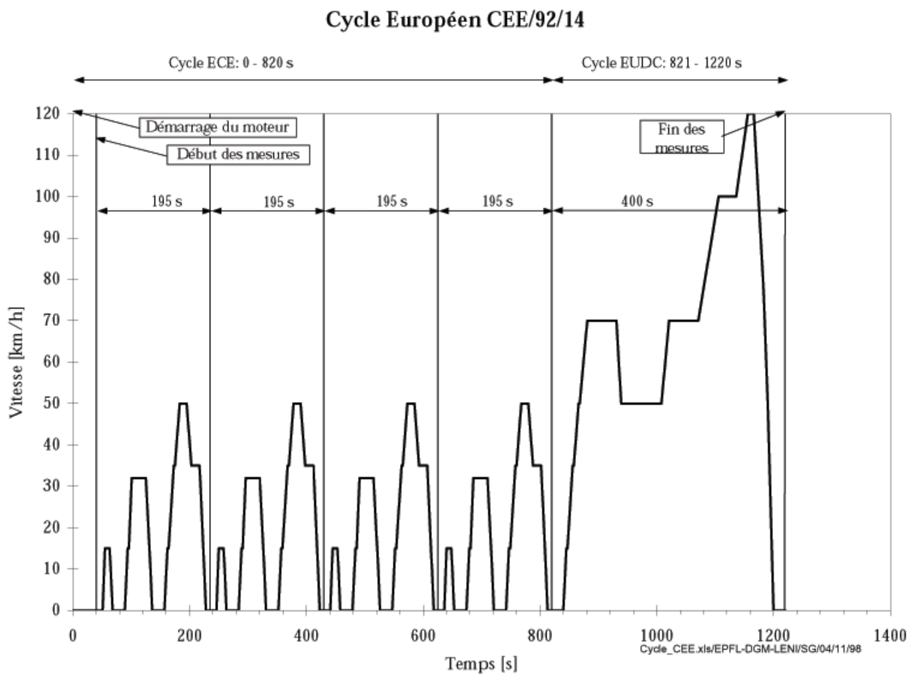


Figure 8: The ECE-EUDC and ECE drive cycles.

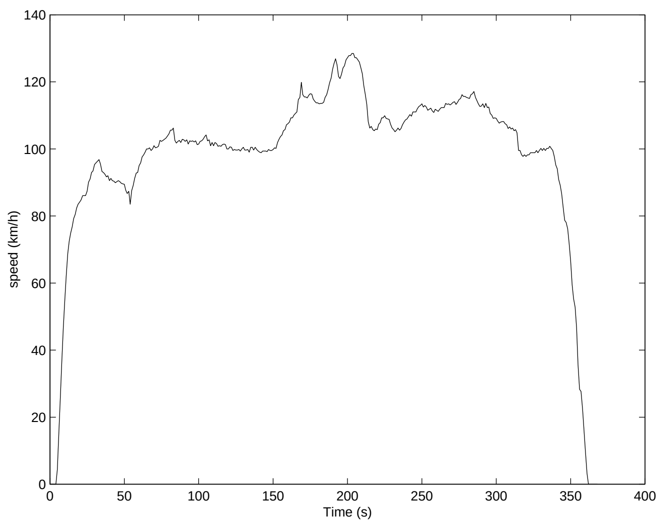


Figure 9: The US06-HWY Drive Cycle.

4.2 Fuel Economy Over Multiple Drive Cycles

The aim of this optimisation was to identify whether different vehicle configurations were, as might be expected, preferable for different driving patterns. Earlier work [12] had considered the US06HWY and ECE-EUDC cycle and had produced a slightly surprising set of results favoring parallel hybrid designs. With ADVISOR running on a Linux cluster with 22 machines the optimisation could be repeated in a fraction of the time taken in previous work. This quickly highlighted some faults in the earlier work that had been penalising conventional vehicles - indeed most were being marked as infeasible.

The objectives chosen were fuel economy over the drive cycle, where fuel economy for diesel engine vehicles was converted to the equivalent gasoline value. Two different combinations were run: the US06 HWY cycle (see Figure 9) against the ECE-EUDC mixed cycle (see Figure 8), and the US06 HWY against just the ECE urban cycle (4 cycles as shown in Figure 8).

The initial results for the Prius were surprising — much worse fuel economy on the ECE cycle than on the other cycles. Closer inspection of these results showed that the Prius ran the ICE continuously. The control system will run the ICE until it reaches operating temperature[11], which happens more quickly on the more aggresive US06HWY cycle, and which happens on the ECE-EUDC cycle because it is longer.

In order to alleviate this fact the problem was run again with hot initial starting conditions.

Figure 10 shows the NDFs from the current work using the US06HWY cycle and mixed ECE-EUDC cycle and Table 2 gives values for the labeled points.

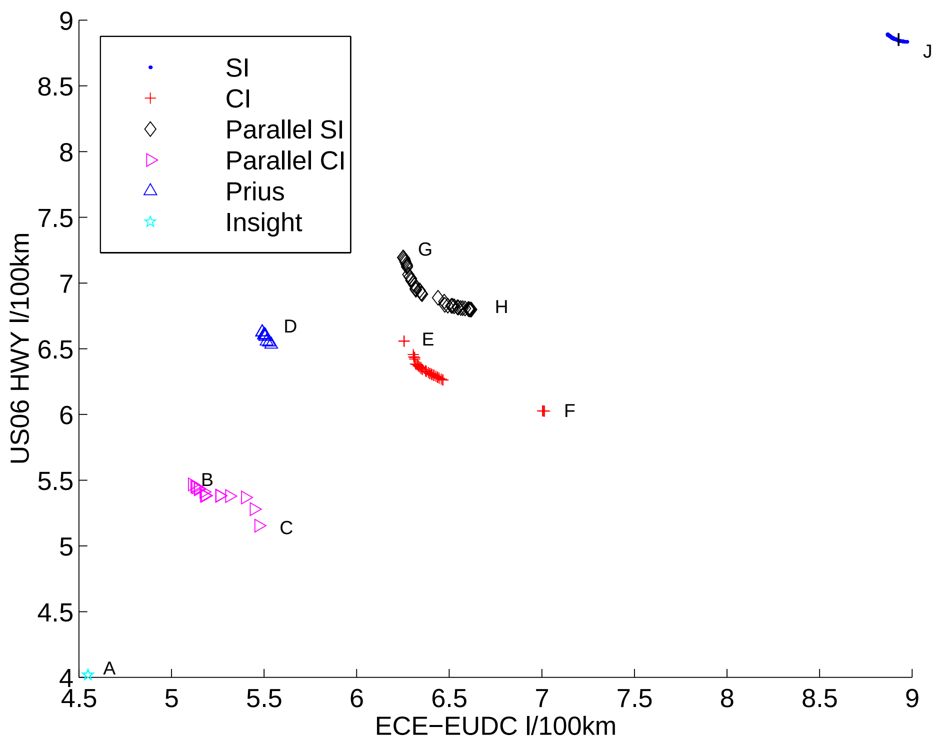


Figure 10: Two cycle fuel economy optimisation results for US06HWY and ECE-EUDC mixed cycle with hot initial starting conditions. The fuel consumption for diesel has been adjusted to an equivalent gasoline value. The vehicles must also meet the 0-60mph in 12s acceleration test.

Overall Behaviour The results are not quite as expected—notably there are no conventional drivetrains at all in the Pareto-optimal set, and these had been expected to perform well in the US-06 HWY cycle. The results show that there is a clear difference between performance on an urban cycle and a highway cycle, and that in general parallel hybrids are favoured over the other vehicle types.

The series vehicles are heavily punished since the ICE must still be dimensioned for the acceleration, so that when cruising the ICE is not running at maximum efficiency.

It was speculated earlier that conventional drivertains should perform well on highway driving, as a hybrid drivetrain, at first view, offers no advantages in this mode. However, while the US-06 HWY cycle is for the most part at a constant

[11]Practical experience with the Prius[7] confirms this behaviour.

		ICE (kW)	Final Drive	SOC_{high}	SOC_{low}	Motor (kW)	Battery Modules
A	Insight	96.9	0.7	0.8	0.3	8.8	36
B	Parallel CI	35.8	0.9	0.7	0.5	41.6	28
C	Parallel CI	51.6	0.6	0.8	0.5	43.7	28
D	Prius	60.2	4.7	0.5	0.4	36.1	60
E	CI	68.2	1.0	-	-	-	-
F	CI	95.6	0.7	-	-	-	-
G	Parallel SI	32.2	1.2	0.6	0.5	50.8	35
H	Parallel SI	45.5	1.1	0.6	0.4	52.7	39
I	SI	74.1	1.5	-	-	-	-
J	SI	77.2	1.4	-	-	-	-

Table 2: Variable values for points labeled in Figure 10 from the optimisation of fuel economy over the US06HWY and ECE-EUDC cycles.

high speed, it also contains a hard acceleration at the start of the cycle. Thus, in a conventional vehicle, the ICE must be sufficiently large to provide the acceleration and so is not dimensioned for economy.

The parallel hybrid configurations show a marked reduction in ICE size and consequently marked reduction in fuel consumption achieved by using an electric assist for the accleration phase.

As expected they still show the same basic trend.

The battery capacities in the cars that perform well on the US-06 HWY are used to provide acceleration, rather than storage — thus it is the battery's *power* density, rather than its *energy* density that is important.

All of the vehicles show the same trends with respect to ICE size. Vehicles with smaller ICEs do better on the ECE-EUDC cycles than on the US06HWY cycle. Here the ICE is being sized for the aggressive acceleration of the US06HWY cycle.

Note that the fuel economy results for the Prius do not show much in the way of a trade-off, and this is thought to be due to the control strategy that results in the ICE turning on and off much more frequently than with simple strategy in the other parallel hybrids.

The Insight had better economy on the ECE-EUDC than on the US06HWY. Since it is much lighter than the other vehicle types (see Figure 13 and Section 6.2) it has a distinct advantage for the acceleration. The small electric motor assists in order to further boost the performance on the acceleration phase of the US06HWY cycle, and the efficient ICE then supplies the required cruising ability.

5 Vehicle Costing

A very simple cost model was introduced to estimate operating costs, $C_{operating}$ and investment costs, C_{inv} as:

$$C_{inv} = c_{ice}P_{ice} + c_{elec}P_{elec} + C_{fix} \tag{2}$$

where c_{ice},c_{elec} are respectively the cost per kW of the IC engine and the electrical components, and P_{ice},P_{elec} are the maximum rated power output in kW.

In order to account for parallel hybrid designs that have no generator the P_{elec} was taken defined as :

$$P_{elec} = P_{motor} + P_{generator} \tag{3}$$

It was considered that a diesel engine, due to the higher compression ratio and high pressure common rail (or direct injection) would be 20% more expensive.

$$C_{CI} = 1.2c_{SI} \tag{4}$$

The C_{fix} is taken to include the bodywork and all the anciliary components, and is assumed to be fixed and the same for a hybrid or conventional vehicle. In reality it is clear that this is a greatly simplified costing, since as engine power varies so does the cost of many associated components such as braking systems, suspension systems and tyres.

Operating costs were calculated as:

$$C_{operating} = c_{gasoline}M_{gasoline} + c_{diesel}M_{diesel} \tag{5}$$

where $c_{gasoline}$,c_{diesel} are respectively the cost per litre of gasoline and diesel, and $M_{gasoline}$,M_{diesel} are the volume of fuel used over the assumed life of the vehicle. Values of $c_{gasoline} = 1.35sfr/l$ and $C_{diesel} = 1.36sfr/l$ were used.

The average distance driven in Switzerland (per vehicle) is given as $15,000$km by the TCS (Touring Club Suisse)[21], and maintenance and running costs are typically calculated over $100,000$km (ie a life of 7 years). However, in light of the 5 year / $100,000$km guarantee offered on the hybrid system of the Prius, this was modified to assume $20,000$km per year over 7 years as a more reasonable estimate, and to allow the expected better economy of hybrids to be more apparent.

For the purposes of this analysis the maintenance costs have been neglected - this is valid if the maintenance cost is more or less similar for the hybrid and conventional cars (see footnote on p94).

This suggests that maintenance costs are not very closely tied to technology but are much more dependent upon good design and marketing choices.

The electrical system cost was not broken up into individual components partly because detailed costs were not readily available, but also to keep the model simple. It would, however, seem reasonable to assume that the two major elements in the electrical system of a hybrid are the electric motor/controller assembly, and the batteries. The cost of the electric motor/controller can be expected to increase with rated power. The cost of batteries can be considered to be accounted for indirectly since they form a significant mass disadvantage that is included in the vehicle mass and hence apparent both in the acceleration test and the fuel use. Consequently solutions with fewer batteries will have lower operating (fuel) costs, and hence be better than solutions with an excessive number of battery modules.

To estimate initial values for c_{elec} and c_{ice} data was taken from a comparative review[2] of the performance and cost of the Prius, Peugeot 307 (gasoline) and the Ford Focus (diesel). Additional data was taken from tests performed by TCS [17,18,19]. The major characteristics of each are given in Table 3.:

This resulted in initial values for $c_{SI} = 157$, $c_{CI} = 188$, $c_{elec} = 396$ sfr/kW. The calculated value for the cost of electric components, c_{elec}, was varied to determine its impact on optimisation results. Values of c_{elec} were chosen as 396, the nominal calculated value and 198, half the nominal value representing a major reduction in costs that might be imagined due to increased numbers being produced.

6 Investment Cost vs Operating Cost

This aim of this was to identify the relationship between investment costs and operating costs (as defined by fuel costs, since maintenance costs have been neglected for this study[3], and to investigate the impact of reducing the cost of the electric components, C_{elec}.

The vehicles were evaluated over the ECE-EUDC drive cycle, initially with the nominal $c_{elec} = 396$sfr/kW, and the results are presented below. The value of c_{elec} was then halved and the optimisation rerun.

[3] as previously noted the TCS figures demonstrate that maintenance costs are not easily predictable.

Characteristic Data			
	Ford Focus	Peugeot 307	Toyota Prius
Fuel	Diesel	Gasoline	Gasoline
Drive Type	Conventional	Conventional	Hybrid
IC Engine Power	85kW	80kW	53kW
Electric Motor	-	-	Siemens 33kW
Electric Generator	-	-	15kW
Cost	27450chf	24000chf	38800chf

Table 3: Characteristic vehicle data used for cost model.

6.1 The Impact of Clustering

This optimisation was run both with and without clustering, to determine the impact of the clustering. The NDF for the case without clustering is shown in Figure 11 with the NDF from the clustered optimisation superimposed and the NDF's from the clustered optimisation are shown in Figure 12 . Several points are labeled on Figure 11 and the corresponding independent variable values are shown in Table 4.

From the algorithm standpoint the NDF found with the clustering is slightly better than without - the results shown are for approximately 20000 function evaluations for each case. The overall best solution, as defined by $C_{inv} + C_{operating}$, (labeled at point **C**) is slightly better than the best point found without clustering (point **B**) although the difference is small (approximately 200sfr).

A close inspection of the absolute best values shows that a conventional SI vehicle has the miniumum investment cost (point **G**), while the minimum operating cost is a modified Insight. The lowest combined cost, $C_{operating} + C_{inv}$, is similarly an Insight based vehicle (point **A**).

More important than the very small difference in overall costs, the clustered case provides a lot more useful information. With the optimisation being run without clustering no information could be obtained about the vehicle configurations not on the POF. Either individual optimisations for each vehicle type would be needed or the investment cost / operating cost would need to be artificially modified to penalise the winning vehicles. Either of these solutions implies many more evaulations (up to 8 times as many to run each vehicle type separately).

	Config.	ICE (kW)	Final Drive	SOC_{high}	SOC_{low}	Motor (kW)	Battery Modules
A	Insight	51.2	1.1	0.7	0.6	3.4	15
B	Insight	52.8	1.1	0.5	0.4	2.1	10
C	Insight	52.7	1.1	0.6	0.3	1.5	11
D	SI	55.6	1.1	-	-	-	-
E	SI	54.7	1.2	-	-	-	-
F	SI	54.4	1.4	-	-	-	-
G	SI	53.1	1.5	-	-	-	-

Table 4: Variable values for points A-G in Figure 11 from the optimisation of investment cost vs operating cost over the ECE-EUDC cycle.

6.2 Discussion

A complete set of graphs showing the variables for each of the vehicle configurations is given in **??**.

Overall Behaviour Figure 12 seems to show the clear dominance of the Insight configuration. The Insight and the Prius both have advanced engines [12], so can be argued to have comparable ICE costs. However, the Insight is a two door, two

[12] VTEC in the case of the Insight and Atkinson cycle for the Prius

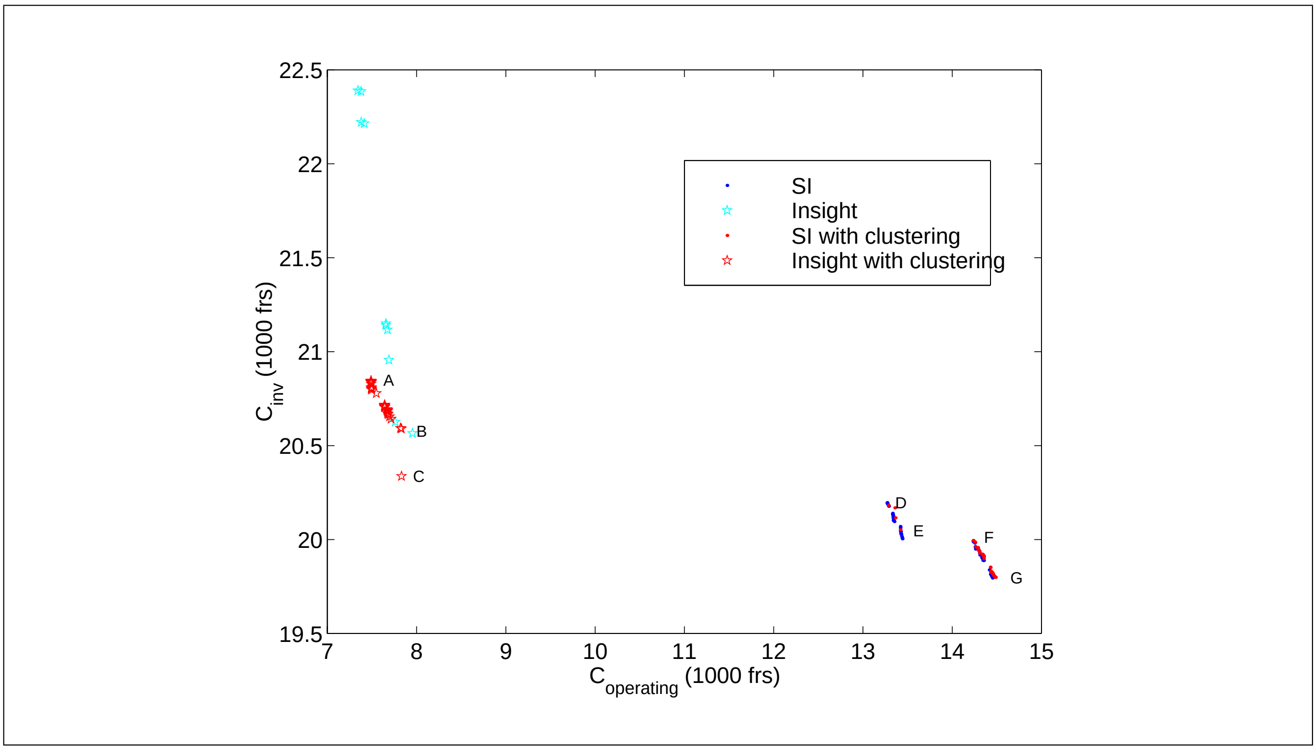


Figure 11: Investment vs Operating Cost (without Pollution) over the ECE-EUDC cycle with 0-60mph 12s acceleration. Comparison of the NDFs between the optimisation with and without clustering, showing slightly better performance with clustering.

person vehicle, in contrast to the other vehicles which are taken as small four person vehicles, and the Prius which is a four door sedan. In addition to this the Insight has a light weight Aluminium structure.

Figure 13 shows the vehicle mass shown plotted against the sum of investment and operating cost,$C_{inv} + C_{operating}$, and clearly shows the Insight to be the lightest and the Prius the heaviest, even more so than the series hybrids.

The Prius is probably unfairly punished in that no weight was added to the structure of any of the other vehicle types to account for an increase in drivetrain component weight - so the series hybrids are unrealistically light. Since fuel use and hence operating costs are directly related to vehicle mass [13] it is to be expected that a lighter vehicle will outperform a heavier one. This is alleviated to some extent in the hybrid vehicles since some of the energy can be recuperated, but still poses problems on continual climbs.

In general the parallel hybrids are heavier than the conventional vehicles due to the electric motor and batteries. Similarly the series hybrids are heavier than the parallel hybrids because of the extra need for a generator.

The lowest investment cost is for a conventional SI vehicle, the lowest operating cost for the Insight configuration. The Insight also has the minimum overall cost ($C_{inv} + C_{operating}$). The Insight does in fact have a very low level of hybridization - it is nearly a lightweight conventional car with advanced engine - the electric motor helps out with maximum acceleration.

Conventional Vehicles The conventional vehicles show a simple relationship between engine size and operating cost (see points **D,E,F,G** in Figure 11). A smaller ICE must (in general) operate at a higher speed in order to generate the same power, with a corresponding increase in final drive ratio. This results in a reduced C_{inv} but at the expense of fuel economy and hence $C_{operating}$.

Series Hybrids Figure 12 shows that the series based hybrids are considered unfavorable, with much higher investment cost than any other vehicle configuration, and with operating costs higher than the equivalent alternative configurations. In general the series hybrids have a small (around 12-14kW) ICE with similarly sized generator, and a large motor. The ICE runs most of the time and the large battery storage is used to meet the intermittent loads. As the motor power decreases the

[13] A reduction of n kg in vehicle weight can be considered to translate directly to a fuel economy of m *see OTA report - cant remember figures*

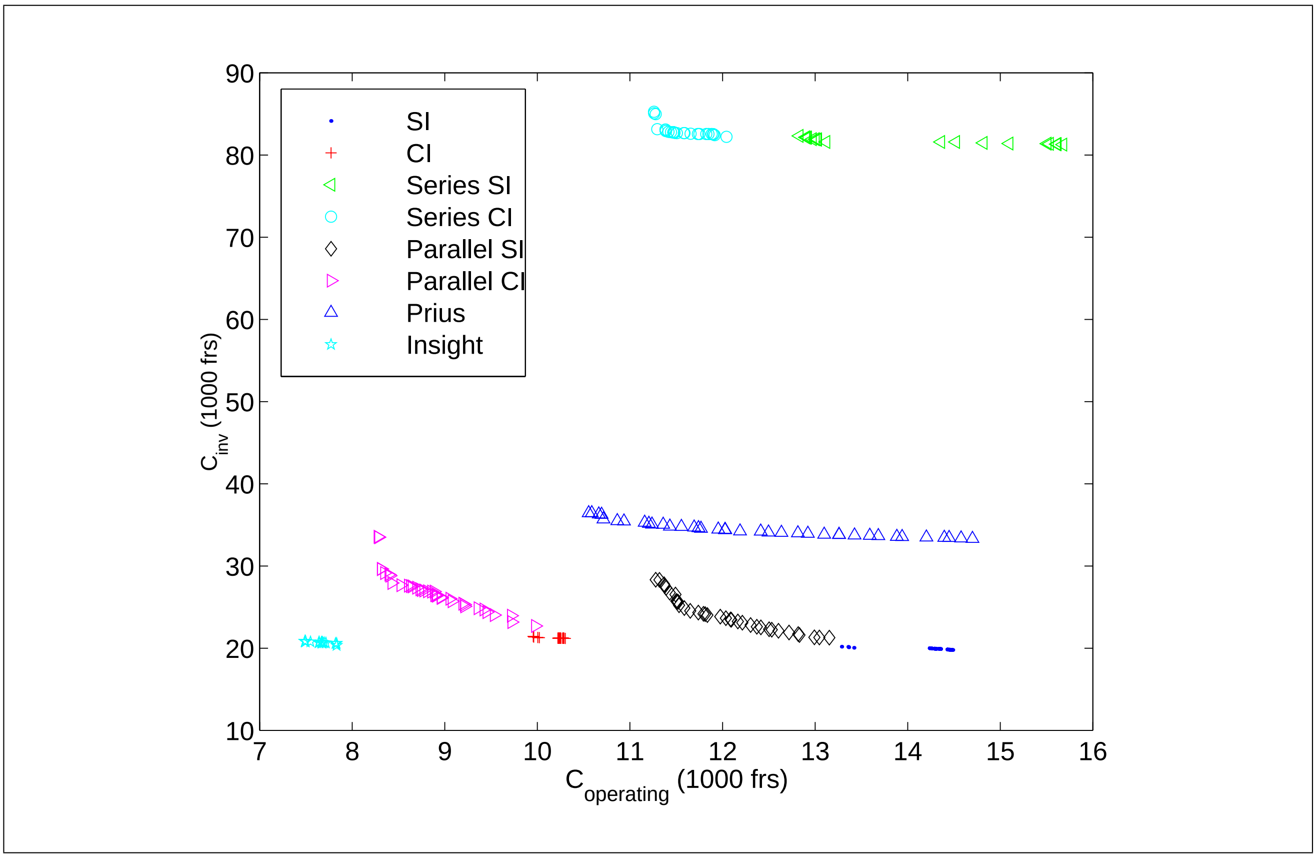


Figure 12: Results of the optimisation of investment vs operating cost (no pollution) over the ECE-EUDC cycle with 0-60mph 12s acceleration.

generator power drops and hence the ICE power drops accordingly - all of these contribute to reducing C_{inv}. As with the conventional vehicles smaller ICE means higher ICE speed and so higher fuel consumption and hence higher $C_{operating}$.

Parallel Hybrids The parallel hybrids are clearly more favorable, as might be expected since they do not suffer from the drivetrain losses experienced by the series hybrids. The ratio of electric motor power to ICE power (the degree of hybridization) is shown against the operating cost for each of the parallel hybrid configurations in Figure 14.

This shows clearly the tradeoff between investment cost and operating cost. A large motor with appropriately high number of battery modules and small ICE produce a high C_{inv} and low $C_{operating}$, since the ICE is operated at high efficiency with the motor meeting the acceleration requirements. As the motor size is reduced, the number of battery modules can also be reduced but the ICE power must increase to meet the demand and cope with the acceleration, hence increased fuel consumption and $C_{operating}$. As the motor size becomes very small (very small degree of hybridization), the NDFs for the parallel hybrids approach those for the conventional vehicles.

The final drive ratio drops as the motor size increases, since this reduces engine speed and hence reduces fuel use.

The SOC_{max} and SOC_{min} show in general a less smooth trend than the other variables,although both the CI and SI based configurations follow the same trend.

Prius The Prius is slightly odd in that it makes use of a generator to control the power flow between the batteries and wheels. The ICE and motor show the same trend as the parallel hybrids - increasing ICE power, decreasing motor power results in lower C_{inv} but higher $C_{operating}$ as described above. The generator power drops approximately in line with the motor, although less smoothly, as does the number of battery modules. There is a clear change of operation at small motor power (high ICE power), with the generator size dropping suddenly and the number of battery modules jumping to near the maximum (see Figure 15). This will allow the ICE to charge the batteries for much of the working part of the cycle, with the batteries then providing extra torque via the motor when needed at high loads. The Prius shows slightly better operating costs than the simple parallel SI hybrid and better than the series hybrids.

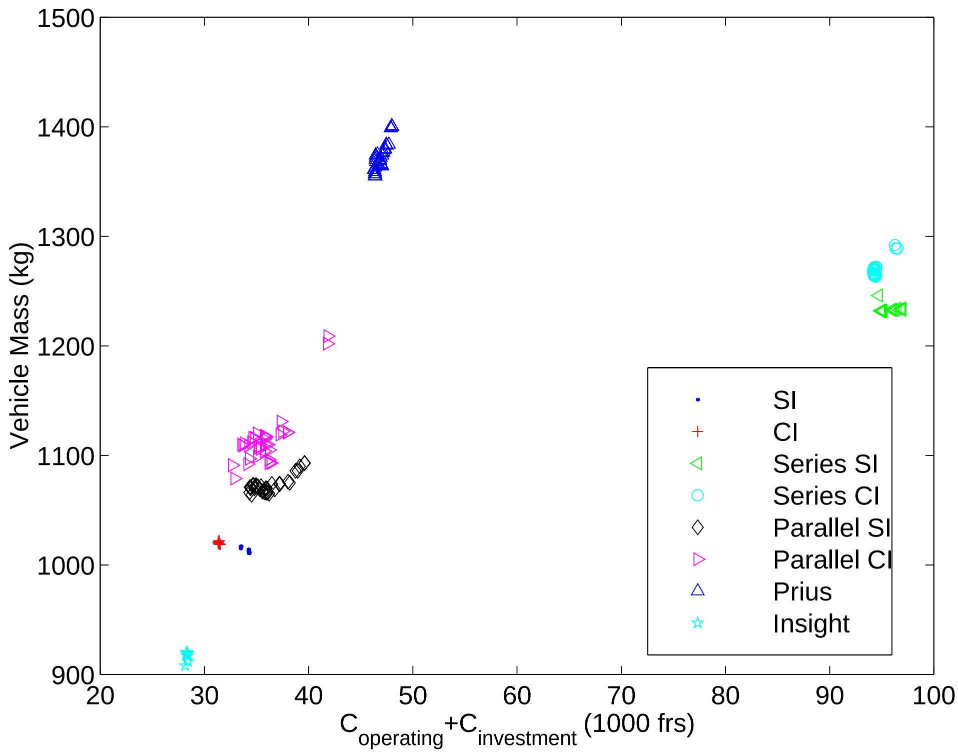


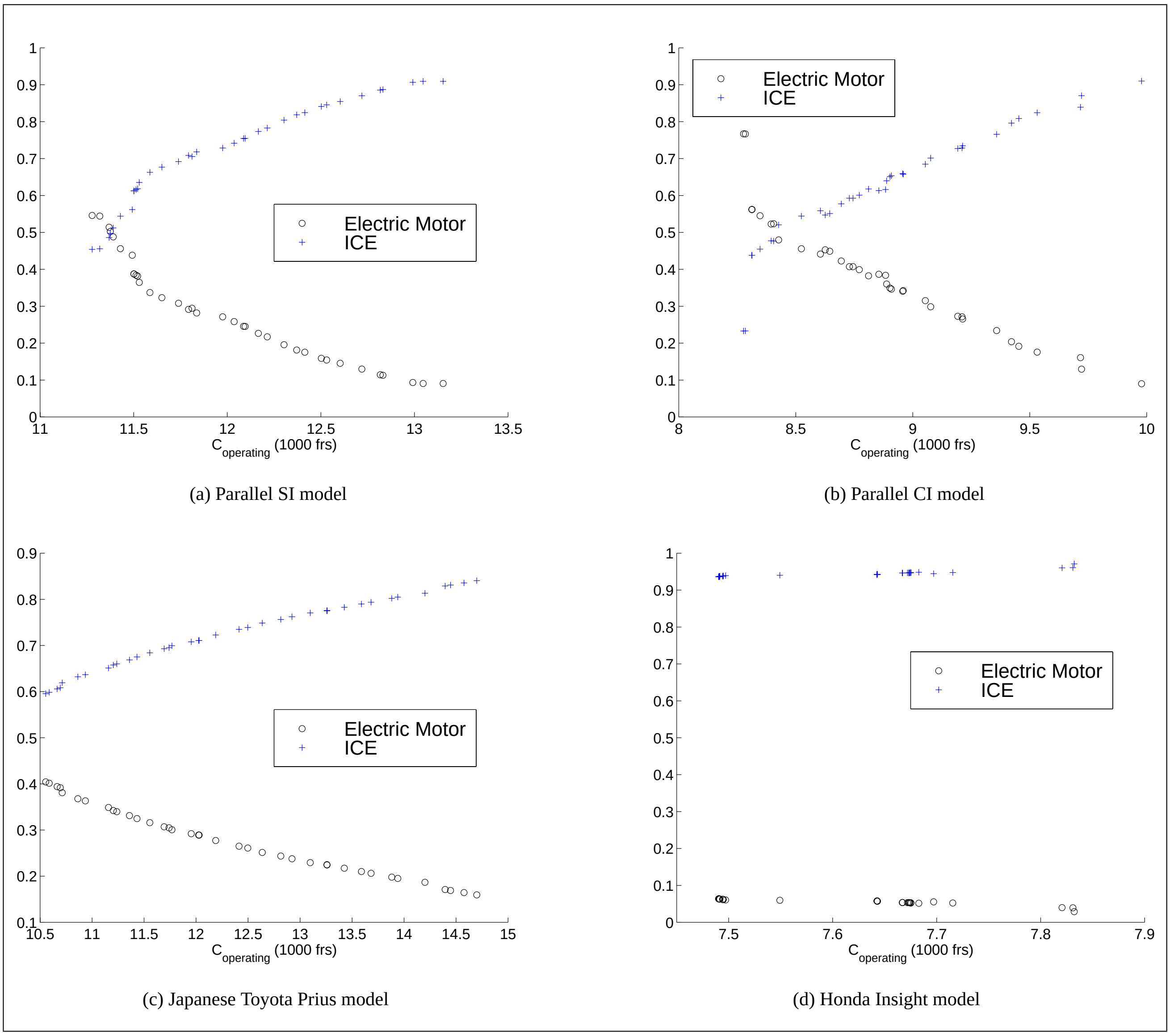
Figure 13: Vehicle Mass from optimisation of investment vs total costs (no pollution costs)

6.3 Reduced Costs for Electric Components

Reducing the value of c_{elec} will lower the investment costs of all of the hybrid vehicle configurations. It was not necessary to re-optimise the problem - by decomposing the investment costs and recalculating the new costs the new curves could be reconstructed, and the resulting set of solutions ranked to provide a new set of NDFs.

The Insight remains the most favorable configuration (mild hybrid) until a drop in cost of electric components to around 25% of the current value, at which point the CI parallel hybrid takes over, due to the greater degree of hybridization.

If the Insight is removed from contention then the best solution becomes the conventional CI vehicle, and the parallel hybrid CI vehicle will become favourable if the cost of electric components drops to around 55% of the current value.



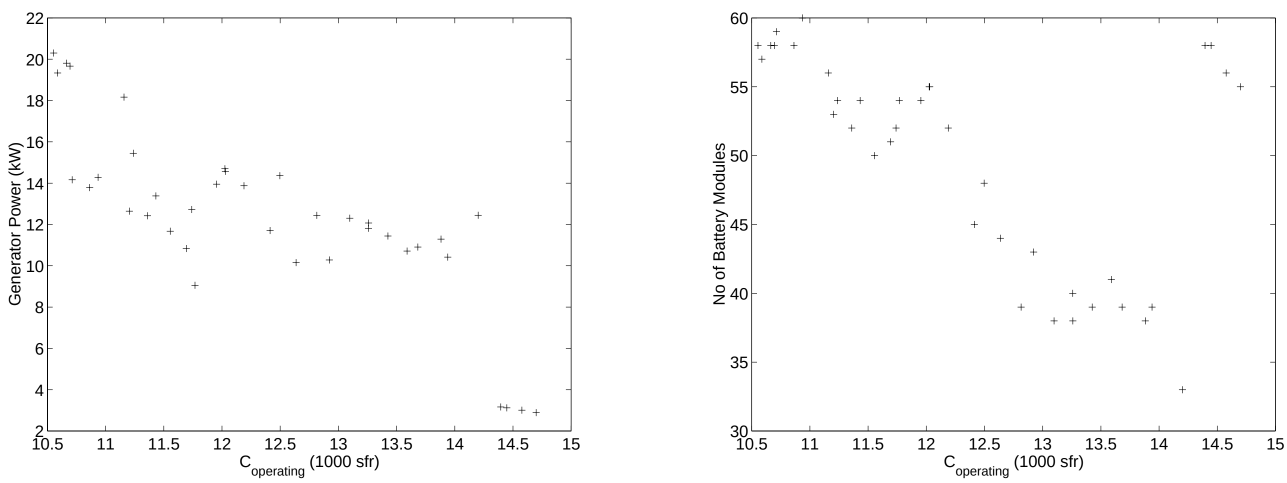
(a) Parallel SI model

(b) Parallel CI model

(c) Japanese Toyota Prius model

(d) Honda Insight model

Figure 14: Degree of hybridisation shown against operating cost, from the optimisation of investment vs operating cost.



(a) Generator Power (b) Number of Battery Modules

Figure 15: Generator and number of battery modules for Prius configuration from optimisation of investment cost vs operating cost

7 Total Cost vs Pollution Cost

This was to investigate the impact of applying the pollution costs used in the district heating model to the domain of transport. The Insight is not included in this optimisation because engine emissions data was not available.

7.1 Pollution Cost Calculations

Pollution costs were limited to the cost of $\mathrm{CO_2}$ and NO_x and the values used were the same as in the district heating network optimisation, notably 13.8 sfr/kg for NO_x and 0.03 sfr/kg for $\mathrm{CO_2}$.

While the NO_x emissions are produced directly from the ADVISOR model, the $\mathrm{CO_2}$ emissions were calculated from the fuel use as:

$$M_{\mathrm{CO_2}} = (0.640 * 44/12)M_{gasoline} \tag{6}$$

where 0.640 represents the carbon content (in kg) of one litre of gasoline.

7.2 Results

Figure 16 shows the NDFs for the optimisation of $C_{inv} + C_{operating}$ and C_{pol}. Figure 17 shows the same information without the series hybrids with labels at certain sites. Variable values at the labeled points are given in Table 5.

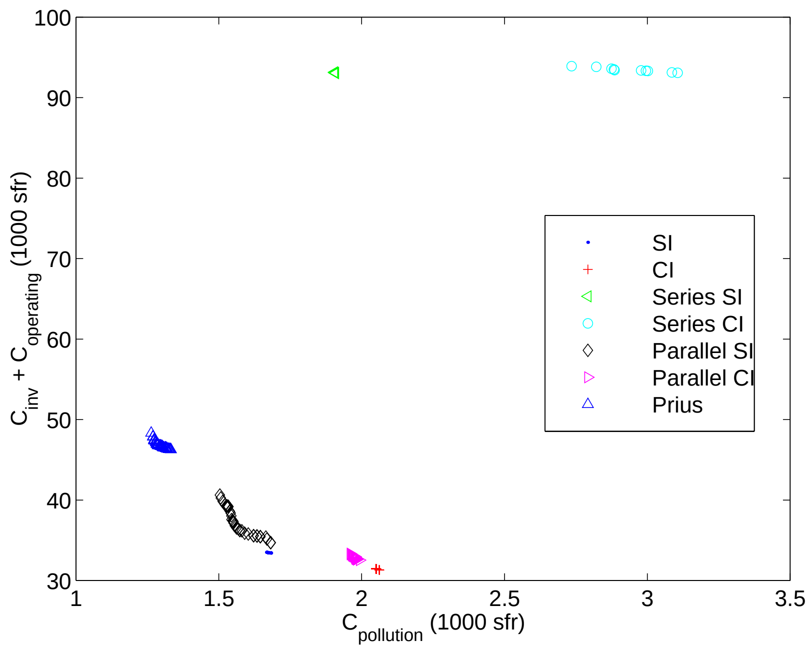


Figure 16: Results of the optimisation of investment and operating cost vs pollution cost

For the specific pollution costs considered the calculated pollution costs are so low as to be insignificant compared to the overall investment and operating cost over the supposed life time — indeed comparing the results to the operating cost shows that it can be expected to have only a limited impact. This is in contrast to the heating domain where the optimum solution is very sensitive to pollution costs. This is largely due to the already high level of taxes imposed on the fuel prices, that already acts to improve fuel economy and swamps the direct pollution costs.

The cheapest, but most polluting solution is a conventional diesel car, while the least polluting but most expensive is the Prius[14] configuration. Indeed, only the diesel series hybrid configuration is more polluting than the conventional diesel configuration, as might be expected since it makes use of the IC diesel engine continually during the cycle.

[14] The Insight was not considered here since no emissions were available.

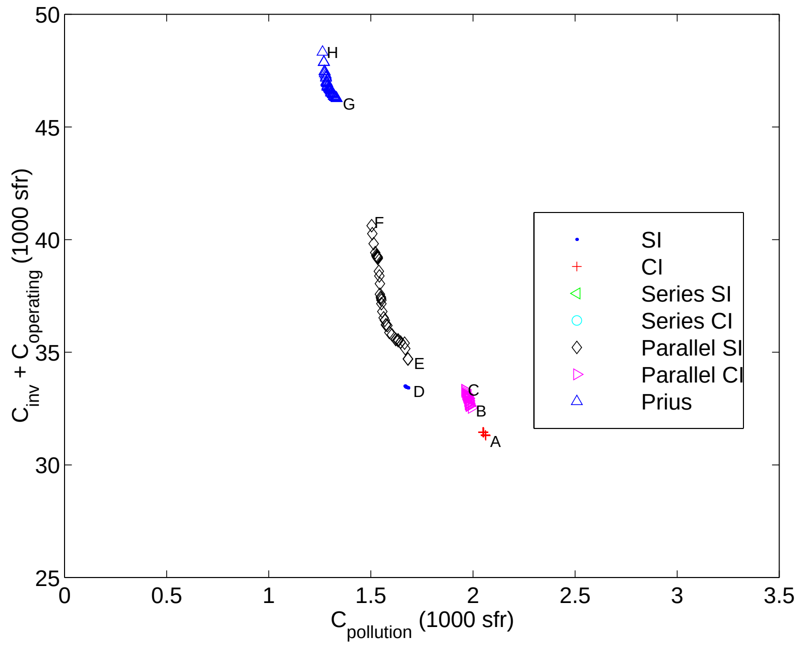


Figure 17: Results of the optimisation of investment and operating cost vs pollution cost

		ICE (kW)	Final Drive	SOC_{high}	SOC_{low}	Motor (kW)	Battery Modules
A	CI	52.6	0.8	-	-	-	-
B	Parallel CI	46.3	1.0	0.6	0.4	6.2	14
C	Parallel CI	43.3	1.0	0.6	0.4	10.4	16
D	SI	54.3	1.2	-	-	-	-
E	Parallel SI	49.8	1.1	0.6	0.3	6.6	14
F	Parallel SI	25.7	1.1	0.6	0.5	34.5	30
G	Prius	50.8	5.0	0.6	0.6	26.3	54
H	Prius	43.7	4.8	0.6	0.6	33.0	56

Table 5: Variable values for points labeled in Figure 17 from the optimisation of fuel economy over the US06HWY and ECE-EUDC cycles.

The overall best solution as defined by $C_{inv} + C_{operating} + C_{pol}$ is also the conventional CI vehicle. The pollution cost must be increased five fold before there is a change towards conventional SI vehicles, and nearly thirty fold before there is a change towards a hybrid CI vehicle. It should be stressed, however, that the pollution costs do not include particles or hydrocarbons or any of the many other potentially harmful emissions[6].

7.3 Discussion

Conventional vehicles Both the SI engine and CI engine vehicles show very little tradeoff between pollution cost and total cost. In the case of the SI engine vehicle approximately 40% of the investment and operating cost is operating cost (fuel cost), and this contributes to approximately 65% of the pollution costs (CO_2). The small tradeoff is due to a small (0.5%) change in engine size that allows the engine to be more fuel efficient while keeping the NO_x nearly constant. This is due to the specific characteristics of the engine efficiency and NO_x maps and can only happen over a very small change in engine size.

For the CI engine vehicles only 30% of the investment and operating cost is the operating cost and this contributes to only 35% of the pollution costs, the majority being due to NO_x. The more significant NO_x costs dominate the pollution cost and account for the tradeoff - a bigger engine produces more NO_x. This is again due to the specific characteristics of the engine maps.

Series Hybrids vehicles The series vehicles suffer from high cost due to the generator and large motor costs. This aside the pollution costs are higher than the equivalent conventional vehicles since the ICE spends more time running at high efficiency. The SI series hybrid shows almost no tradoff. As for the conventional equivalent the pollution costs are dominated by CO_2 and so follow closely the operating costs (the two objectives are very nearly the same). The CI series hybrid pollution costs are due mainly to the NO_x costs - small ICE gives low operating costs and investment costs but high NO_x costs, and conversely. The electric motor size is fixed by the cycle requirements, and the generator more or less fixed by the ICE size, so there is little room for manoeuvre.

Parallel Hybrid vehicles Both the SI and the CI parallel hybrids show the same trend - smaller ICE and bigger electric motor gives improved fuel economy and lower pollution, and this is clear in Figure 18. It is more noticeable in the case of the SI engine since the CI engine hybrid is penalised by the increased NO_x production of more efficient CI engines. The CI hybrids tend to have bigger ICE (and a lower degree of hybridization), since the diesel ICE are themselves more efficient. Consequently they have fewer battery modules.

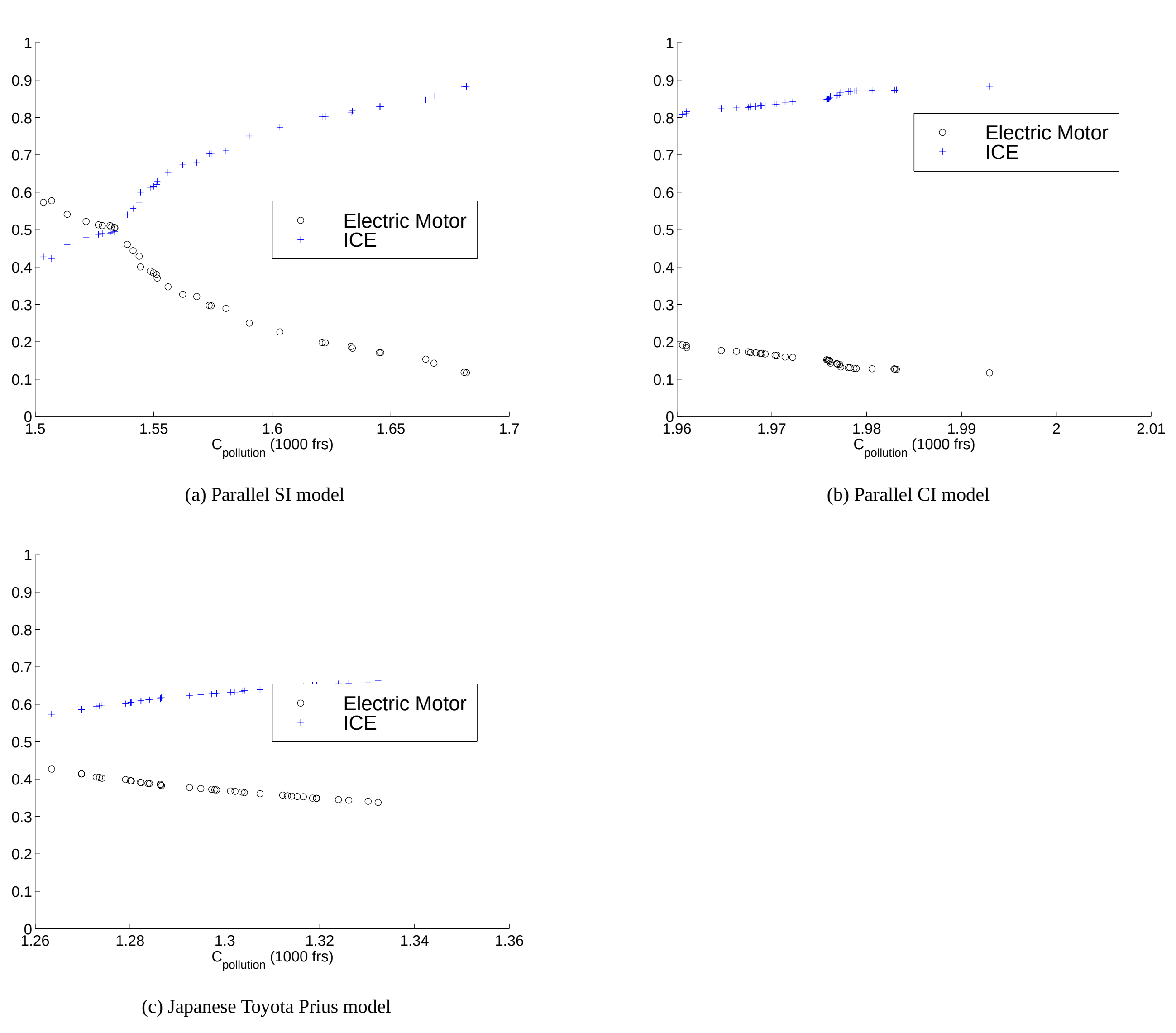


Figure 18: Degree of hybridisation shown against operating cost, from the optimisation of investment vs operating cost.

Prius The Prius configuration follows the same trends as the SI parallel hybrids. Reducing the ICE size improves fuel economy and so reduces CO_2 but at the cost of increased NO_x - however the CO_2 effect is dominant, hence reduced engine size leads to reduced pollution cost. Investment increases because of the larger proportion of power from the electric motor (see Figure 18) hence larger investment.

7.4 Effect of Decreased c_{elec}

The NDFs for the optimisation with $c_{elec} = 198$sfr are shown in Figure 19. Halving the c_{elec} used in the calculation of C_{inv} brings the cost of the electrical components down to nearly the same as the cost of the ICE engines.

This results in a change of overall best solution from a conventional CI vehicle to a parallel hybrid CI (although the extremely low pollution costs still have a minimal influence). Increasing pollution cost by five fold moves the overall best solution to a SI parallel hybrid, and an increase of 30 fold favors the Prius configuration.

The range of parallel hybrid solutions is reduced since the difference between c_{elec} and c_{ice} was the major driving force in the tradeoff between size of motor and size of ICE. This is apparent in the graphs showing the ratio of P_{elec} and P_{ice} in Figure 20.

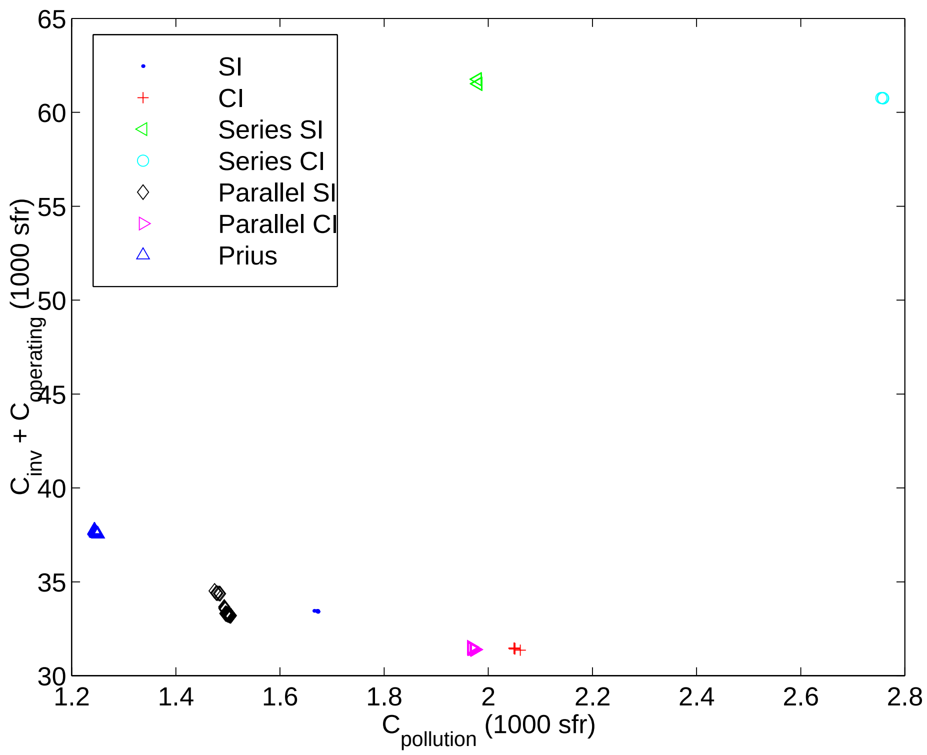
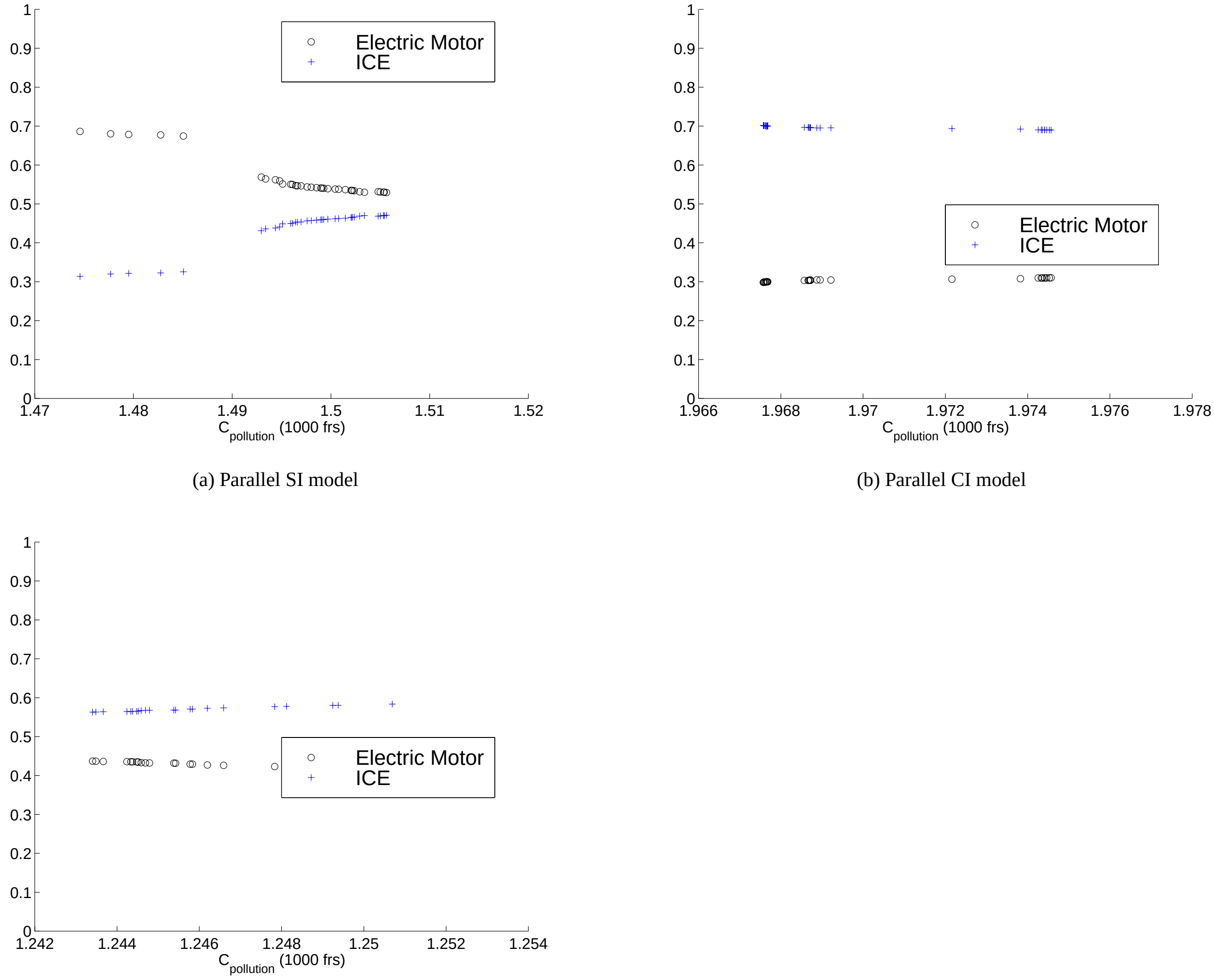


Figure 19: Results of the optimisation of investment and operating cost vs pollution cost over the ECE-EUDC with electric component cost reduced to 198sfr/kW.



(a) Parallel SI model

(b) Parallel CI model

(c) Japanese Toyota Prius model

Figure 20: Degree of hybridisation shown against operating cost, from the optimisation of investment vs operating cost with electric component costs reduced 198sfr/kW .

8 Total Cost vs Quantity of NO_x

NO_x emissions have been shown to have a direct impact on human health[4,5] and vehicle NO_x emissions are of particular importance because they produce NO_x in areas where it impacts directly on people. Considering NO_x vs operating and investment cost provides a clearer picture of the hybrid behaviour, particularly since the operating costs are fuel costs and so are directly proportional to the CO_2 produced.

Figure 21 shows the NDFs from the optimisation with the series hybrid not shown for greater clarity. The ratio of ICE to electric motor power are given in Figure 22. Table **??** shows values of the independent variables at the points labeled in Figure 22.

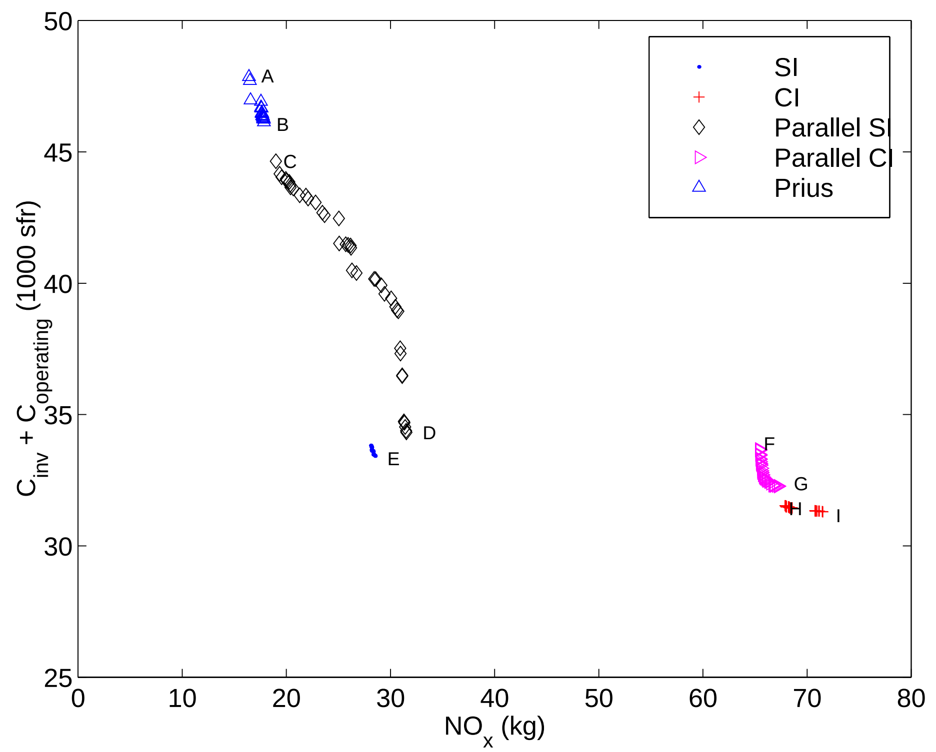
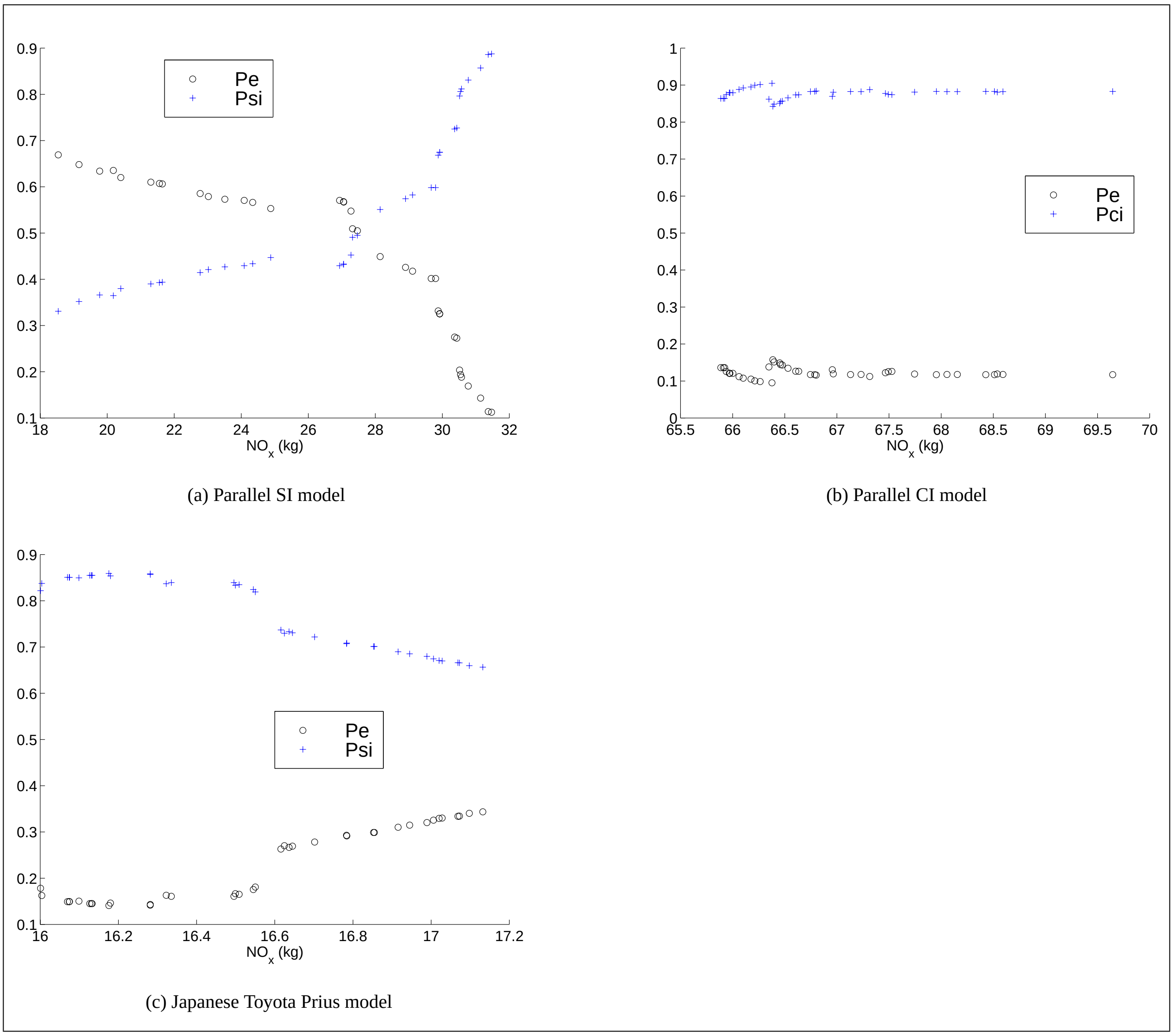


Figure 21: Total Cost vs Quantity of NO_x output over the ECE-EUDC cycle.

	config	ICE (kW)	Final Drive	SOC_{high}	SOC_{low}	Motor (kW)	Battery Modules
A	SI	54.3	1.2	-	-	-	-
B	Parallel SI	47.0	1.2	0.7	0.6	6.7	14
C	Parallel SI	53.7	1.2	0.6	0.4	7.9	14
D	Parallel SI	27.5	1.2	0.7	0.7	30.0	23
E	Prius	53.7	5.0	0.7	0.6	24.8	59
F	Prius	64.0	5.0	0.7	0.6	23.2	58
G	Parallel CI	47.4	1.0	0.5	0.4	8.2	14
H	Parallel CI	46.9	1.0	0.8	0.3	5.1	14
I	CI	51.9	1.0	-	-	-	-

Table 6: Variable values for points A-I in Figure 21 from the optimisation of overall cost vs quantity of NO_x. produced over the ECE-EUDC cycle.

The best economy and lowest investment cost hybrid can be expected to use the IC engine at its full capacity for as long as possible to reduce fuel consumption by running the IC engine at its most efficient, and to reduce the size of the IC engine. However this means high NO_x emission for the IC engine.



(a) Parallel SI model

(b) Parallel CI model

(c) Japanese Toyota Prius model

Figure 22: Degree of hybridisation shown against quantity of NO_x output, from the optimisation of total cost vs NO_x.

8.1 Results

The global Pareto front contains hybrid gasoline vehicles (**C,D**), hybrid diesel vehicles (**F,G**), conventional gasoline vehicles (**E**) and conventional diesel vehicles (**HI**). This will change if the investment cost of the hybrid electric components is reduced. The conventional vehicles tends to disappear as c_{elec} is reduced, as does the diesel hybrid.

Conventional vehicles The SI and CI conventional vehicles both follow the same trend as the total cost vs pollution cost optimisation. The SI engine vehicle follows the expected trend - as the ICE size reduces the engine runs more efficiently but produces more NO_x. The CI engine vehicle similarly follows the same trend as the total cost vs pollution cost optimisation, with a small increase in CI engine size leading to an increase in NO_x. In both cases the changes are fairly small.

Series Hybrids Again these follow the same trends as the total cost vs pollution cost optimisation.

Parallel Hybrids The CI parallel hybrid shows a reversed trend for the ICE, as does the Prius.

9 Conclusions

The most striking result is the inadequacy of the pollution costs for $\mathrm{CO_2}$ and NO_x. These result in an overall pollution cost for all the vehicles that is negligible compared with the investment cost and the cost of fueling a vehicle over its life, without even considering the maintenance costs.

This is in contrast to the district heating case where the best result is highly sensitive to the inclusion of pollution costs, and even a small pollution cost causes the solution to radically change technology.

From a political point of view, the idea of a $\mathrm{CO_2}$ tax accross all sectors (heating, transport etc) would encourage solutions such as the fully electric vehicle, where it would be advantageous to produce energy at the central power station. The current situation with high taxation already on fuels used for transport overwhelmes the additional direct cost of pollution taxes, which would need to be increased five fold to have any significant effect.

It should be noted that the direct effect of many other pollutants (for example hydrocarbons, carbon monoxide, and particulates) on health have been ignored in this study, and a health tax might be more effective, linked to the toxicity.

It would be interesting to examine in more detail the control strategies, since the SOC_{min} and SOC_{max} variables used in the optimised appeared to have only a secondary impact on the hybrid behaviour (although were probably necessary in order to find feasible solutions).

It should be noted when comparing the results from the Honda Insight model to the Toyota Prius and other simple vehicles that the Honda Insight is a two person vehicle with a light weight chassis, in contrast to the other vehicles.

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