Integration of form and function: the Ricardo InPacT powertrain

SP Edwards
Ricardo Deutschland GmbH, Germany
NS Jackson
Ricardo plc, England
IJ Penny, C Rouaud, J Dunn, J Dalby and SD Porteous
Ricardo UK, England

ABSTRACT

Historically, the powertrain has been the combination of individual products, e.g. the engine, transmission, final-drive and, more recently, an electrical machine, suitable for a particular market and vehicle application. These individual products have often been specified in isolation, considering initially one market and/or vehicle application. More recently, with globalisation, the specification of these products has been adjusted to allow their modular combination across a range of markets and vehicle applications.

The InPacT project pushed this trend further, identifying ways to achieve more integration of the powertrain technology, giving improvements in the performance versus cost trade-off through integration of both 'process and product' plus 'form and function'. Achieving such integration cannot happen 'over-night', significant changes are required: therefore, the problem statement was constrained initially, to step through the process, generate innovation, provide examples and devise a timeline for when such change to full integration may be achieved.

When applied to the powertrain of a D/E class passenger car, it was found that there is potential in 2020 to improve the carbon dioxide emissions (CO_2 in g/km) versus powertrain cost trade-off by between 10 to 20% compared to a conventional powertrain. In particular, the ideas that can only be realised through physical integration of the powertrain could result in a potential saving of about 15 g/km CO_2 over the New European Drive Cycle (NEDC) in such a vehicle. Furthermore, there are packaging and weight savings that could possibly be realised.

In this paper the process used, the innovations devised and the resulting powertrain design plus simulated performance are presented.

1 INTRODUCTION

The Integrated Powertrain (InPacT) research programme was initiated to address the need for greater integration of engine, transmission and hybridisation technologies to meet future vehicle requirements while embracing emerging trends in manufacturability and modularisation. The objective of the programme was to identify, define and demonstrate an integrated powertrain solution for a D/E segment passenger car suitable for 2020, with affordability as a key requirement. Constraints were placed around this objective: the target CO_2 level was 90 g/km (NEDC cycle basis, but with full compliance with World-harmonized Light-duty Test Procedure (WLTP) cycle and US 5-Mode requirements) for the D/E segment vehicle; and the on-cost should be no more than €40 per g/km CO_2.

Preliminary characteristics of the powertrain had been defined in earlier brainstorming activities: the fuel should be gasoline, however, learning that crossed over to other fuels was to be protected; and an automatic transmission was to be included; together with some (limited) degree of hybridisation.

In this paper the results of the first phase of the programme, the concept study, are reported briefly. This phase followed a five step procedure through to the concept sign-off gateway: 1. Drive cycle energy audit; 2. Facilitated brainstorms and key stakeholder workshops to generate ideas; 3a. System and sub-system activities to explore ideas; 3b. Formation of (integrated) system concepts; 3c. Evaluation of system concepts relative to targets and objectives; 4. Reporting, Detailed Planning and Costing; 5. Gateway.

2 DERIVATION OF SPECIFICATION FOR A 2020 POWERTRAIN

2.1 A state of the art D/E class powertrain and outline vehicle specification

When discussing a D or E class vehicle specifications with various manufacturers, different requirements are given, primarily based upon different geographic markets and their expectations. Therefore, a few, different vehicle specifications were used in order to derive the requirements for a state of the art D or E class vehicle powertrain. On this basis the outline specifications were derived. These baseline vehicles are named and summarized in Table 1, together with the outline vehicle specifications derived for the future powertrain in relation to a US application (hence the units).

Table 1. Chosen baseline powertrains and outline vehicle specifications

Vehicle Specifications	Std American D-Class	Performance E-Class	Eco-Badged A	Eco-Badged B
Vmax [mph]	120	150	100	100
Vmax 6% grade with tow [mph]	120	150	70	70
Acceleration 0-60 [mph]	8,5	<7.0	9,0	10,0
Kerb weight [lbs]	3.300	3.680	3.000	3.000
Max towing weight [lbs]	1.000	~1,200	800	800
Peak power [bhp]	170	245	140	140
Peak torque [lbs-ft]	170	260	170	140
CO_2 [g/km]	90	90	90	70
FC [mpgUS]	61	61	61	78
Cost delta max [US$]	2.500	2.500	2.500	3.200
Current examples	Toyota Camry	BMW 528	Lexus ES300h	
Engine configuration	2.5L I4 NA	2.0L I4 T/C	2.5L I4 Atk'n	
Transmission	6sp M/T	8sp A/T	Powersplit CVT	
CO_2 [g/km]	163	158	134	
FC [mpgUS]	33	34	40	

Note: € per (g/km CO_2) ratio maintained

2.2 Energetic analysis of a D/E-class vehicle powertrain

When reconceiving the powertrain, it is important to look at the requirements for that powertrain initially, before deriving solutions based on prior knowledge and practice. Therefore, an energetic analysis of the powertrain requirements was undertaken to illustrate the possible different ways of looking at the drive cycle requirements for power delivery to the wheels. In the first instance the WLTP cycle was chosen and the behaviour of a typical European E class vehicle over this cycle was modelled (mass 1900 kg; c_d 0.3; frontal area 2.3 m^2; tyre rolling resistance coefficient 0.007).

It was noted that, although the WLTP cycle is much more transient than NEDC-type cycles, it still does not have high accelerations (the maximum is 1.8 m/s^2 or 0.18G) nor demand the power levels seen in the real world vehicle performance requirements. For example, the power requirement to achieve a credible 0-100 kph (0-60 mph) time, 120 to 150 kW is about 30 times greater the average WLTP cycle power requirement: 4 kW (motoring 11.8 kW, braking -8.8 kW, moving 4.8 kW) (see Figure 1). Therefore, in addition to optimising the powertrain to provide the power profile expected from transient legislative drive cycle, much higher power levels need to be provided (by some means) to satisfy the vehicle performance characteristic requirements.

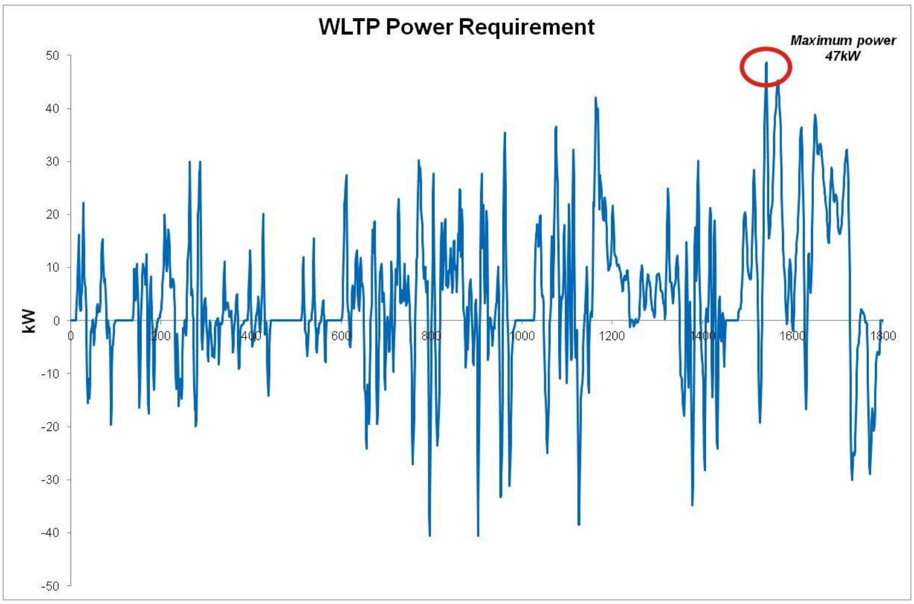


Figure 1. Example results from the vehicle energetic analysis

Further analysis was undertaken to extract indicative values for energetic parameters over different possible cycles. These are illustrated in Figures 2 and 3. It was noted that, for example, the maximum increase rate of power requirement is 10.6 kW/s; although less time is spent at high power levels, significant energy must be delivered; most braking energy in the 0 to 20 kW range, which sets the requirements for the energy storage rate; and that the ideal points for highly efficient operation vary between the different test cycles, which is of particular importance for stepped power split concepts with effective "mechanical" points.

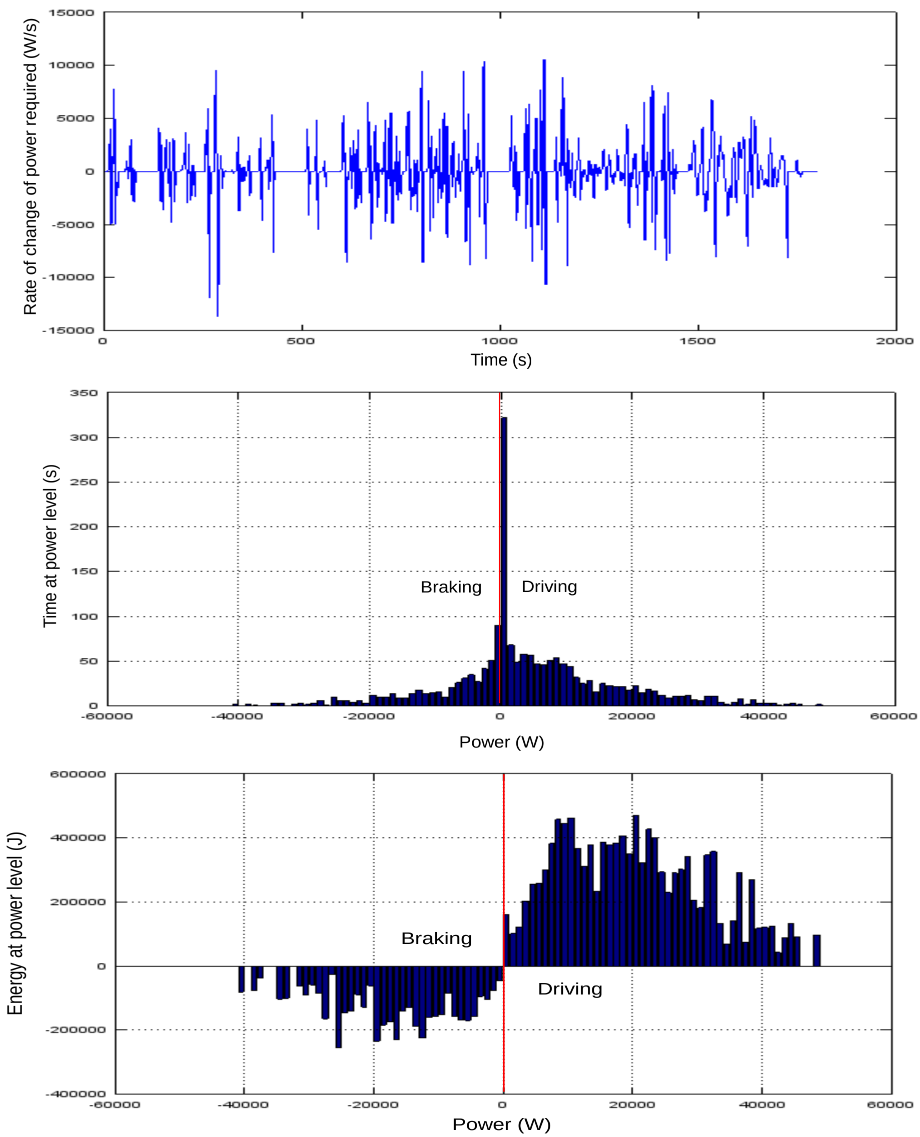


Figure 2. Example results from the vehicle energetic analysis – looking at the WLTP with different parameters

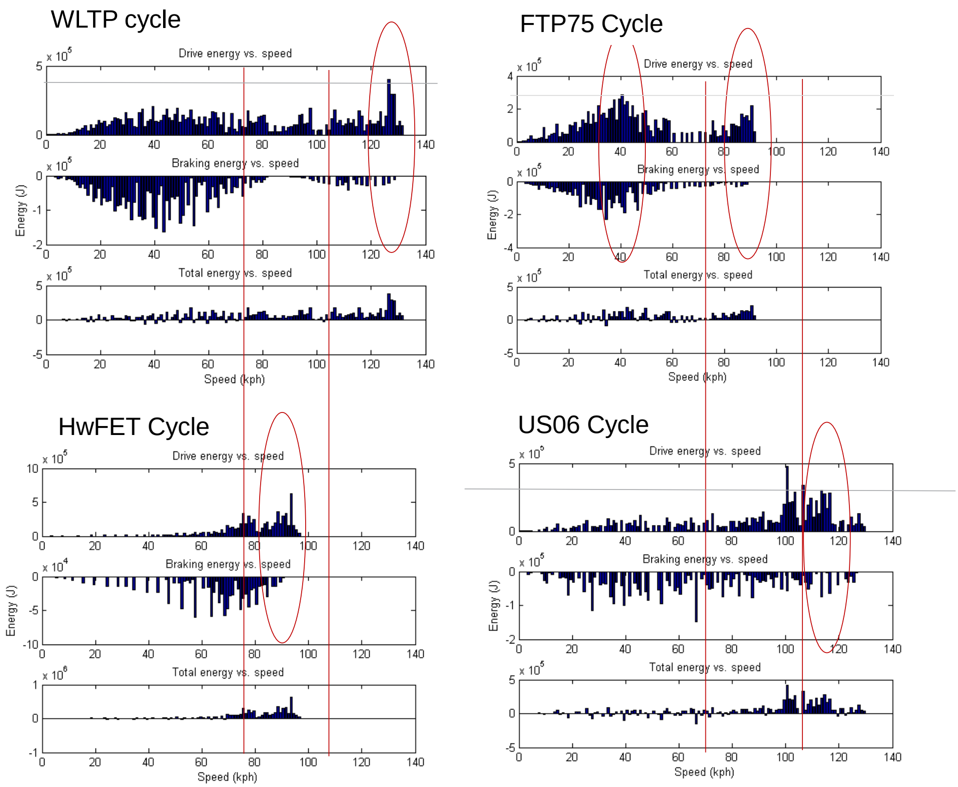
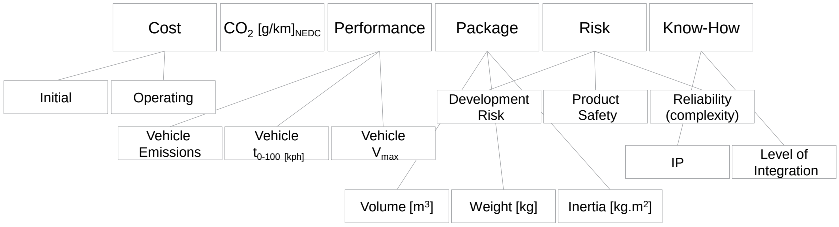


Figure 3. Example results from the vehicle energetic analysis – looking at the ideal points for efficient powertrain operation (circled in red) over different test cycles

3 GENERATION OF IDEAS TO IMPROVE THE POWERTRAIN THROUGH INTEGRATION

Naturally, as with any concept study, a multitude of new ideas needed to be generated. This was achieved through several workshops, with cross functional, locational and generational teams using a range of directed brainstorming and group passing techniques (1). For example the following questions were used as prompts: What could we do to the combustion engine, in order to make best use of the latest transmission technology?; How should we apply the transmission plus hybrid technology, to make best use of the latest engine fuel consumption map characteristics?; What could we do to maximise the powertrain energy recovery whilst minimising the non-motive power demands, such as A/C, water pumps etc.?; How should we mechanically integrate the complete powertrain package for reduced cost? The Analytical Hierarchical Process (AHP) was used to help evaluate the ideas. The criteria and their hierarchy, in order to weight the importance of the criteria and the value of the ideas, are summarized in Figure 4. The outputs from the brainstorm were captured in Pugh Matrices and 'Idea Specification' documents for subsequent analysis by the technical lead team.



TOP LEVEL											
N= 6						Overall weighting=	1,00				
	Cost	CO_2	Performance	Package	Risk	Know-How	Nth root of product	Eigen Vector	Consistency Index	Local Weighting	Global Weighting
Cost	1	1	3	5	5	7	2,84	0,34	6,15	0,34	0,34
CO_2	1	1	3	5	5	7	2,84	0,34	6,15	0,34	0,34
Performance	1/3	1/3	1	3	3	5	1,31	0,16	6,26	0,16	0,16
Package	1/5	1/5	1/3	1	3	3	0,70	0,08	6,39	0,08	0,08
Risk	1/5	1/5	1/3	1/3	1	1	0,41	0,05	6,28	0,05	0,05
Know-How	1/7	1/7	1/5	1/3	1	1	0,33	0,04	6,14	0,04	0,04
							8,43	1,00	0,05	1,00	1,00

Figure 4. The AHP hierarchy used in and the weighting derived for the evaluation of the ideas generated within the workshops

Over one hundred individual ideas were generated via the workshops. Detailed review of these ideas identified thirty six as being particularly relevant, these were called "nuggets". Consolidation of the nugget ideas then took place: thirty-six became fourteen sub-systems concepts, which could be applied with an integrated powertrain. A 'one-pager' was generated for each consolidated sub-system concept. This document gave a description of the idea(s), the pros and cons (including whether they could or could not be combined with other nuggets), and an estimated CO_2 and cost change. The data for the CO_2 and cost change estimates were generated through simulation and design analysis. The sub-system concepts were ranked by scoring against the Pugh matrix criteria and their € per g/km CO_2. A summary of these concepts is represented in Figure 5. Their estimated € per g/km CO_2 individually is shown in Figure 6.

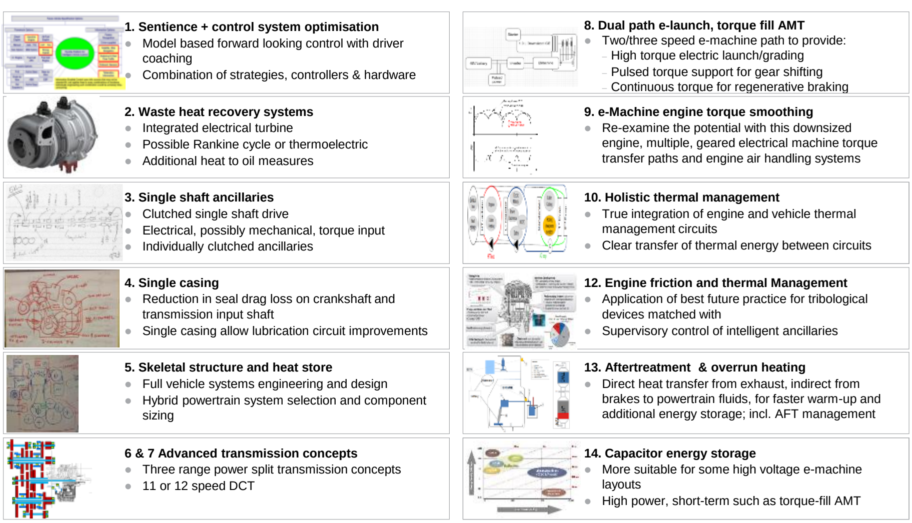


Figure 5. An overview of the sub-system concept ideas generated for evaluation in the InPacT research programme

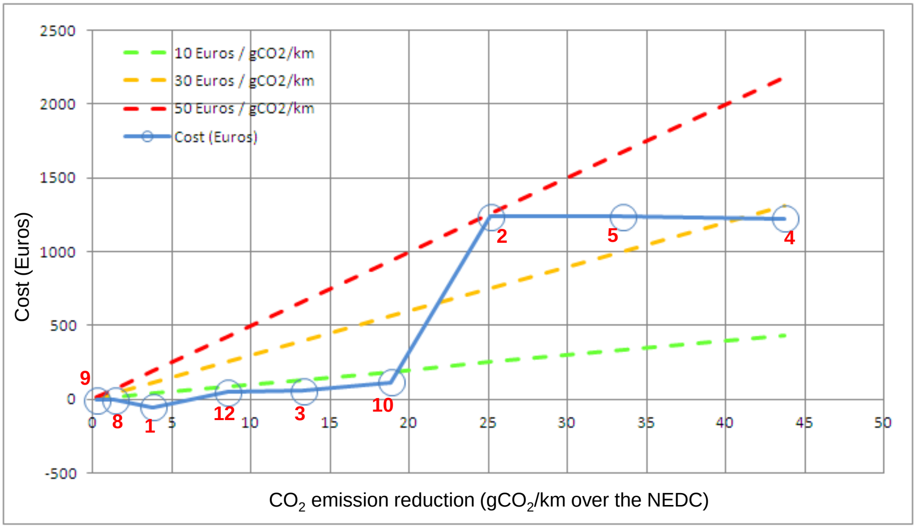


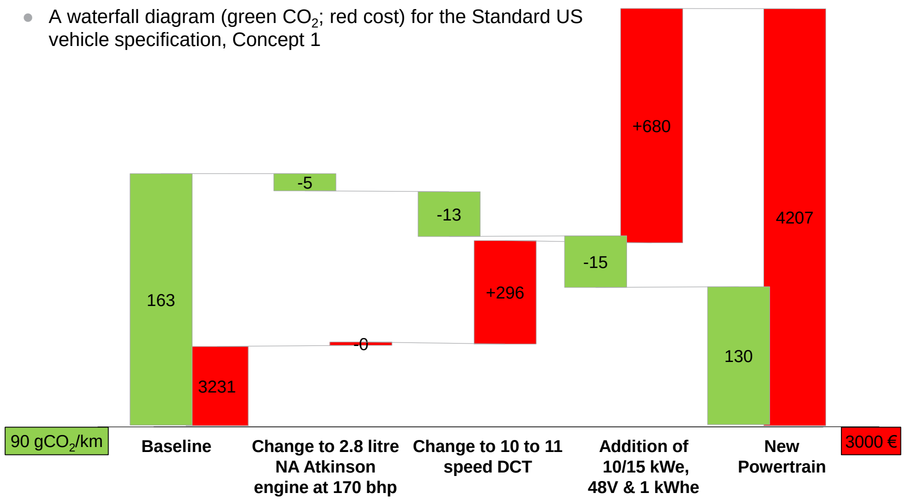
Figure 6. An overview of the sub-system concept cost versus CO_2 reduction trade-offs (numbers refer to sub-system concepts as given in Figure 5)

4 DEVISING AND EVALUATING THE POWERTRAIN SPECIFICATIONS

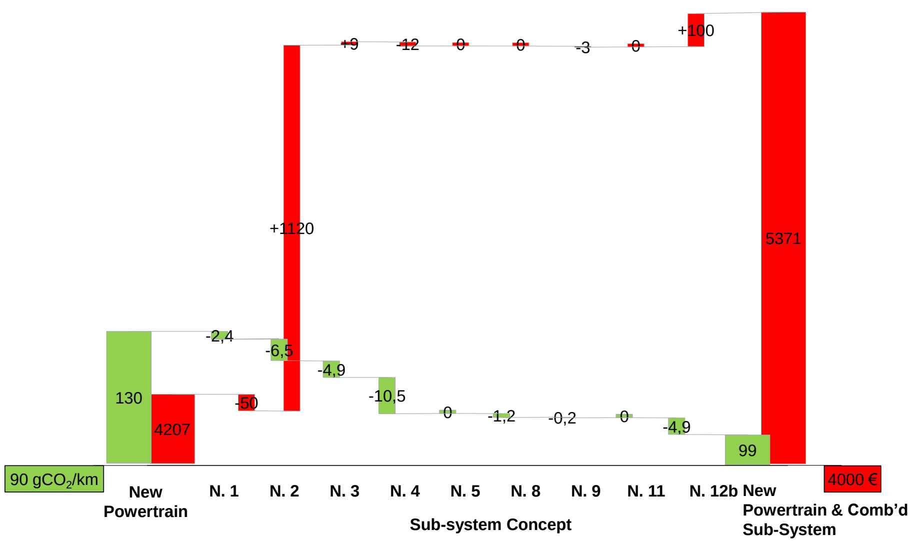
Naturally, with so many ideas, sub-system concepts and vehicle specifications the number of possible combinations was enormous (almost three hundred thousand just including the sub-system concepts and vehicle specifications). However, the sub-system concept outline specifications were combined to give a range of powertrain concepts for each of the vehicle specifications shown in Table 1. The combination was prioritised based upon the relative cost to CO_2 effectiveness of the individual sub-system concepts and the vehicle specifications. Subsequently, the likely cost change and CO_2 improvement values of each the combined sub-system concepts was estimated. Hence the likely cost change and CO_2 value improvement of each of the powertrain concepts could be made.

4.1 Estimation of cost versus CO_2 trade-off

Overall, twenty four vehicle and powertrain concepts were considered in detail. Here, the specifications for the power creation (engine), power transfer (transmission) and power vectoring (electrical machine and battery storage system) were derived comprehensively. For each concept a "waterfall" diagram, showing the procession toward the programme objectives was generated: an example of such is shown in Figure 7 (Parts (a) and (b)).



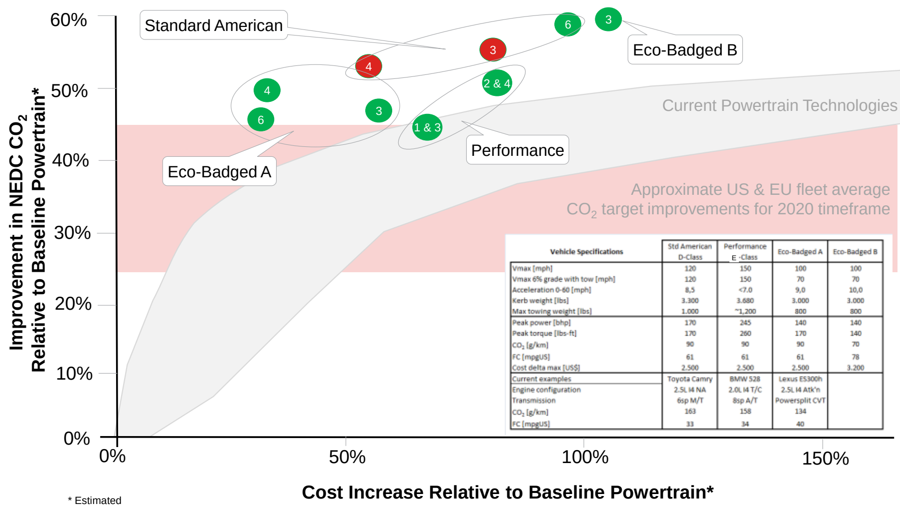
Part (a). The engine, transmission and electrical machine



Part (b). The individual sub-system concepts employed

Figure 7. The CO_2 and cost progression towards the programme targets for one concept by way of example

Following the more comprehensive analysis, it was determined that not all of the twenty-four concepts would achieve the programme targets. For each of those concepts that was deemed to have the potential to meet the targets, the relative change in cost versus that of CO_2 was plotted, for the powertrain, in a similar manner to that which is common practice for engine technologies. This step was important in order to determine whether, through integration of form and function, any benefit over and above that possible through known individual technology applications could be identified. This summary plot is given in Figure 8.



Vehicle Specifications	Std American D-Class	Performance E -Class	Eco-Badged A	Eco-Badged B
Vmax [mph]	120	150	100	100
Vmax 6% grade with tow [mph]	120	150	70	70
Acceleration 0-60 [mph]	8,5	<7.0	9,0	10,0
Kerb weight [lbs]	3.300	3.680	3.000	3.000
Max towing weight [lbs]	1.000	~1,200	800	800
Peak power [bhp]	170	245	140	140
Peak torque [lbs-ft]	170	260	170	140
CO_2 [g/km]	90	90	90	70
FC [mpgUS]	61	61	61	78
Cost delta max [US$]	2.500	2.500	2.500	3.200
Current examples	Toyota Camry	BMW 528	Lexus ES300h	
Engine configuration	2.5L I4 NA	2.0L I4 T/C	2.5L I4 Atk'n	
Transmission	6sp M/T	8sp A/T	Powersplit CVT	
CO_2 [g/km]	163	158	134	
FC [mpgUS]	33	34	40	

Figure 8. The CO_2 versus cost progression trade-off for chosen InPacT concepts (numbers in circles) in relation to the Ricardo database of current and known future individual technologies

Considering the information given in Figure 8, it is seen that when applied to the powertrain of a D/E class passenger car, it was found that there is potential through integration to improve the CO_2 versus powertrain cost trade-off by between 10 to 20% in 2020 compared to a conventional powertrain. In particular, the ideas that could only be realised through physical integration of the powertrain could result in a potential saving of about 15 g/km CO_2 over the NEDC in such a vehicle.

5 DETAIL OF THE CHOSEN POWERTRAIN CONCEPT

It was found that, for a range of possible D/E vehicle specifications, a range of power creation, transfer and vectoring technologies are likely to achieve the programme targets of 90 g/km CO_2 and <40 €/(g/km CO_2).The power creation was found to be best satisfied by a three cylinder T or SGDI engine with a swept volume between 0.8 and 1.5 litres, depending on the detailed vehicle specification. The power transfer was found to be satisfied by either a 10 to 11 speed dual clutch (DC) or a 3 speed PSSM (Ravigeaux or DC) transmission (a dual path transmission also looked favourable). The power vectoring was found to be best achieved with a 10/15 kWe to 30/50 kWe electrical machine running at 48 or 220 V.

Clearly therefore, although the different vehicle concepts demand different sub-system specifications, the general solution philosophy can be the same. For a global manufacture, a 'family' of sub-system components could be devised and implemented to satisfy all market requirements. It should also be realised that these base sub-system choices appear to achieve roughly half the improvement in CO_2 and that these improvements, although obviously the result of thinking about the powertrain as a whole, are almost totally independent of the need to physically integrate the sub-system components.

5.1 Design

Design layouts were initiated for the chosen powertrain concept on the basis of application to an American D-class vehicle. An initial image from those layouts is shown in Figure 9, in which some of the features are highlighted.

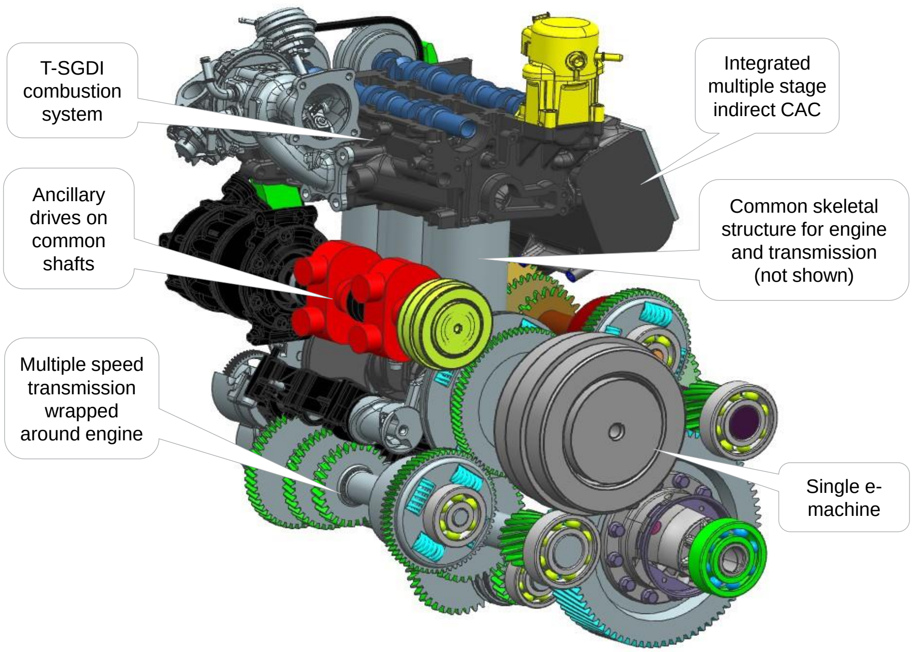


Figure 9. An initial design layout for the chosen InPacT concept

5.2 Simulation of specific features

Whilst the concept includes many innovative features, two in particular will be described further here: that of the ancillary system drive and that of the integration of the engine charge air cooling and vehicle air-conditioning systems.

5.2.1 Ancillary Drives on a Common Shaft

Integrating individual ancillaries onto a common drive it is known to give packaging benefits, and if both the source of drive torque and its distribution can be carefully controlled depending upon the instantaneous needs, further benefits may be realisable. Therefore, an initial control strategy for clutching individual ancillaries in and out was devised, as shown in Table 1: by declutching ancillaries when they are not required it is possible to reduce parasitic losses and fuel consumption. The data given in Table 1 is an initial strategy: it does not account for complex real world considerations, such as thermal comfort and the air-conditioning (A/C) system operation (the A/C is simply assumed to be required at all times except during coasting, when removing the parasitic load would improve vehicle "sailing" yet have minimal impact on thermal comfort). Similarly, in this initial strategy, the coolant (water) pumps were assumed to be required at all times whilst the vehicle is moving or the engine is running: it is known that further fuel consumption reduction would be achieved by declutching the pumps during warm-up, or by cycling the pumps as required during normal operation. In the InPacT concept, the single ancillary drive-shaft was able to be driven either directly by the engine (via a gear set rather than a belt) and, consequently, indirectly by vehicle inertia whilst the engine is coupled to the drivetrain, or via the electrical machine mounted directly on the single shaft drive.

Table 2. Example single shaft ancillary drive strategies

		Single Shaft Ancillary Drive Strategy			
Vehicle state	Engine	Stopped	Coasting	Running	Running
	Vehicle	Stopped	Moving	Moving	Stopped
Required ancillaries	Oil Pump	✗	✓	✓	✓
	TX Pressure Pump	✗	✓	✓	✗
	HT Water Pump	✗	✓	✓	✓
	Vacuum Pump	✓	✓	✓	✓
	A/C Compressor	✓	✗	✓	✓
	E-Machine	✓	✓	✓	✓
	PAS	✗	✓	✓	✗
	LT Water Pump	✗	✓	✓	✓
	FEAD Belt Losses	✗	✗	✗	✗

A 1D vehicle model of an E-segment car was created using the Ricardo vehicle simulation tool called "V-SIM", which is MATLAB based. The initial model was validated against test data and then modified to create a mild hybrid vehicle with regenerative braking and torque assist functionality. This mild hybrid variant was used as the baseline against which different single shaft ancillary drive control strategies were compared. Some features, as noted above, were not included in the analysis, although they are known to give benefits. Additionally the hybrid operating strategy was not optimised in the results shown here. However, minor tuning of the hybrid strategy was carried out to ensure state of charge (SOC) neutral simulation results, which allow the fuel consumption for each model configuration to be compared fairly. As part of the single shaft ancillary drive, representative gear losses were introduced in place of the belt losses and an 80% efficiency was assumed for the electrical machine. The exception to this was the baseline case, which was assumed to still have a belt system driving the ancillaries. A range of simulations were carried out including, the ancillaries being driven exclusively by the engine, the ancillaries being driven exclusively by the electrical machine and a "smart" strategy that aimed to drive the ancillaries by the most efficient means at a given time.

Example results from the simulation are shown in summary form in Figure 10. The ancillaries "always on and always driven by the internal combustion engine (ICE)" represents the baseline case against which the other configurations are compared. The theoretical maximum fuel consumption reduction over the NEDC (with all the ancillaries switched-off) was found to be 2.7%. By selectively declutching ancillaries when they were not required, it was possible to achieve a fuel consumption reduction some way towards that limit. Using the strategy shown in Table 2 ("Smart Ancillaries") the predicted fuel consumption saving was 1.5% over the NEDC. This dropped to 1% over the WLTP cycle but increased to 2% when considering the ARTEMIS drive cycle.

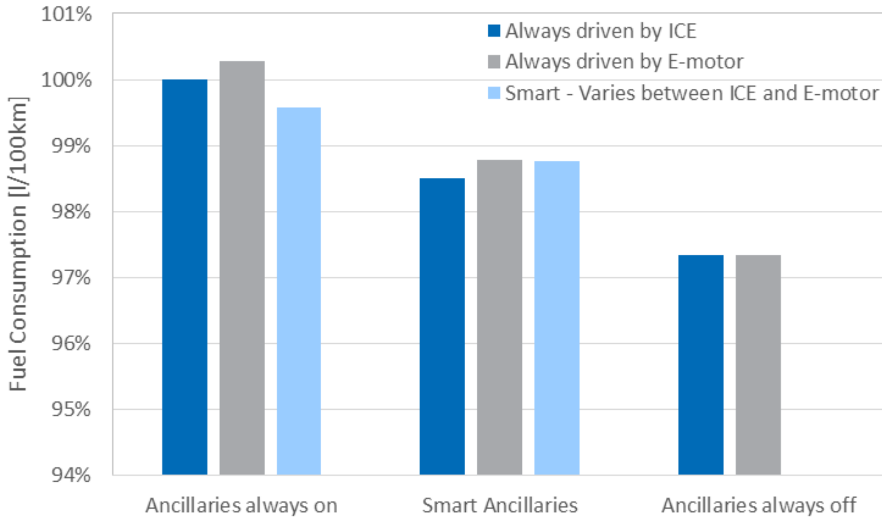


Figure 10. Relative fuel consumption values for different configurations of ancillary control over the NEDC

5.2.2. Multiple stage, indirect charge air (sub-) cooling

Gasoline engine part load fuel consumption can be significantly improved by operating at increased compression ratios. However, the need for higher specific performance with engine downsizing leads to lower compression ratios because of the constraints of knock at full load. Several methods exist to realise higher compression ratio engines whilst maintaining specific power output and mitigating knock, these typically include additional valvetrain technologies and increased demands upon the boosting system. The concept selected within the InPacT powertrain was to integrate the existing A/C circuit with that of the charge air cooling, to enable increased cooling of the intake charge air, even to sub-ambient temperatures. Knock is triggered by a combination of increased pressures and temperatures in the combustion chamber, therefore reducing the intake manifold air temperatures allowed the compression ratio to be increased, whilst maintaining the same full load performance and knock intensity as the baseline engine.

A baseline engine was selected for study, which had a peak specific output of 25 bar brake mean effective pressure (BMEP) and a compression ratio of 9.5:1. Within the Ricardo WAVE engine modelling software, the Douaud and Eyzat knock model (2) enabled reference values of knock along the full load curve to be estimated. The engine models were then run to find the sensitivity of knock to compression ratio and charge air cooler outlet temperature, for a fixed combustion timing and duration. The responses, at two of the full load speeds, are shown in Figure 11.

It is seen that, if the charge air cooler air outlet temperature is reduced to approximately 20°C (293K), then the compression ratio could be increased from the baseline value of 9.5:1 to 10.5:1. If the charge air cooler air outlet temperature is reduced even further, to 10°C, then a compression ratio of 11:1 should be achievable.

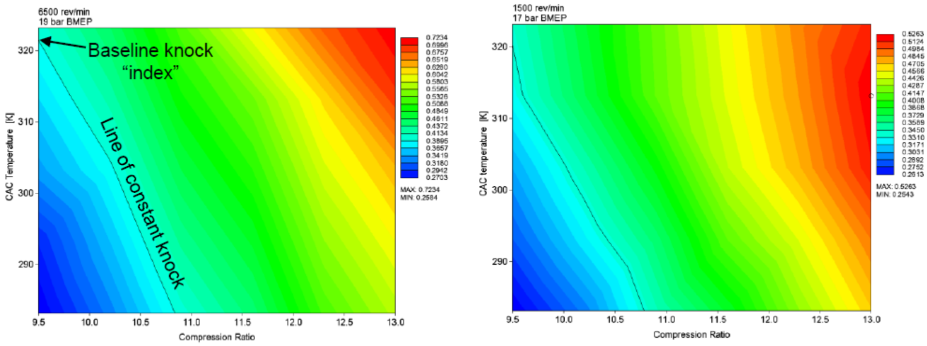


Figure 11. The variation of knock intensity to compression ratio and CAC outlet temperature at two full load conditions

A calculation was then performed to estimate the additional A/C compressor work required in order to maintain the selected CAC air outlet temperature, and this quantity was then used to adjust the fuel consumption results of engine simulation at part load. The results indicate that, even when the additional compressor work is considered, the increased compression ratio (10.5:1) and reduced charge air cooler temperatures (20°C) would give a 1 to 2% specific fuel consumption reduction in the range of 1500 to 3000 rev/min, 7 to 15 bar BMEP engine operation. The benefit of sub-cooling the charge air was found to reduce at lower simulated engine loads, since the additional compressor work began to dominate. Nevertheless, the resulting fuel consumption was still no worse than the baseline 9.5:1 compression ratio data.

7 CONCLUSIONS

The InPacT project identified ways to achieve more integration of the powertrain technology, giving improvements in the performance versus cost trade-off through integration of both ‘process and product’ plus ‘form and function’.

When applied to the powertrain of a D/E class passenger car, it was found that there is potential in 2020 to improve the CO_2 versus powertrain cost trade-off by between 10 to 20% compared to a conventional powertrain. In particular, the ideas that can only be realised through physical integration of the powertrain could result in a potential saving of about 15 g/km CO_2 over the NEDC in such a vehicle.

This benefit, when viewed in combination with the impact that such integration will have on the manufacturing and assembly techniques plus the supply chain structure in the automotive industry, needs to be critically reviewed to ensure that the benefit of integration is still sufficient.

Individual sub-system concepts, devised through the idea generation process within the InPacT research programme, show significant promise and will be pursued regardless of whether full integration of form and function is viable or not.

8 ACKNOWLEDGEMENTS

The authors would like to thank the directors of Ricardo plc for permission to publish this paper. In particular, the contributions of P Rivera, LM Sykes and CS Wren are acknowledged for the work reported here.

9 REFERENCE LIST

1. AF Osborn, “Applied imagination: Principles and procedures of creative problem solving (Third Revised Edition)”. New York, NY, Charles Scribner’s Sons, 1963.
2. AM Douaud and P Eyzat, “Four-octane Number Method for Predicting the Anti-knock Behaviour of Fuels and Engines”. SAE 780080, 1978, 15 pp.