Integrated Powertrain Design and Control

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At the heart of every vehicle is the powertrain. The characteristics of the powertrain have a major influence on many crucial vehicle attributes - performance, economy, driveability, emissions, even safety and cost of ownership. Against this background vehicle powertrains are becoming increasingly complex as the scope offered to improve vehicle attributes is explored. All this must be achieved while reducing component costs, reducing development times and increasing durability. These conflicting goals are driving far reaching and exciting changes in the way powertrains are designed and controlled. Integration is a key theme, which although requiring significant effort, is capable of delivering surprising improvements in every area of powertrain performance.

Developments can be considered in two strongly related areas, powertrain hardware and control systems –

Powertrain Hardware

The degree of refinement, efficiency and capability evident in today's IC engines when mated to an advanced transmission will ensure their survival in mainstream production for the foreseeable future. The sums invested in the R&D and manufacturing of these systems over the last century has led to a high level of sophistication even when compared to the elegant fuel cell electric powertrains in development. The prime mover itself is developing in a number of areas to ensure its continuing dominance in the coming years.

Prime Movers

Diesel, gasoline and renewable fuelled engines are all being actively developed in new schemes designed to meet the requirements of both the ever-rising expectations of the customer and increasingly demanding environmental considerations. In a number of respects the development of Diesel and gasoline engines seems to converging. In five years a number of direct injection, compression ignition, lean burn and highly complex arrangements may require careful inspection before the nature of their fuel becomes evident. A major common goal is the raising of part load efficiency. At its best a modern Diesel engine is hard to beat for energy conversion efficiency but automotive duty cycles ensure that most engines operate inefficiently at part load for much of their life. Here again the modern Diesel engine is the best available device but gasoline technology is improving quickly. Another major goal is improved power to weight ratios leading to a host of high specific power outputs and downsizing schemes. In this respect the gasoline engine has traditionally had the advantage due to the high piston speeds achievable. Inevitably emissions, cost and durability goals must all be achieved in conjunction with the primary goals. Subjective driveability is no less critical but is perhaps the most difficult attribute to characterise early in the design process.

From an integrated powertrain perspective it is interesting to note that almost all of the engines in production or development (with the notable exception of Toyota's Prius engine) are designed to meet the shortcomings of a conventional stepped ratio transmissions (automatic or manual). A relatively choice of available transmission ratios requires that the engine has a broad speed range to allow matching to road speed. Conversely, a transmission engineer may argue that it is the engine's restricted speed range that necessitates a large number of ratios in the transmission. One of the intriguing possibilities offered by wide range CVTs and hybrid powertrains is that the speed range and torque envelope of the engine can be reduced, leading to savings in rotating inertia, friction and mass and better optimised engine processes.

An essential feature of any engine used in an integrated powertrain is the ability to control engine torque output via an electronic controller rather than as a function of the driver's pedal position.

Electronically controlled Diesel engines have been offering this capability since the early 1990s. As air fuel ratio can be allowed to vary over a wide range rapid and effective electronic torque control can be achieved through modulation of the injected fuel quantity. A conventional gasoline engine requires an electronically controlled throttle plate in addition to control over fuelling and air fuel ratio must be controlled within tight limits to ensure satisfactory operation of the catalyst. Such systems are now commercially available and being introduced into volume applications.

Transmissions

In parallel with the development of prime movers activity a growing array of new and emerging transmission technologies are also competing for the attention of the major manufacturers. Many of these concepts will find niche marketing opportunities leaving a select few to take the major share of the volume passenger car market. The **manual transmission** will still account for the major share of passenger vehicle sales in most European markets for the medium term. The most obvious enhancement in this area has been the emergence of six speed manual gearboxes with Mercedes-Benz, Fiat, PSA and Renault among those who consider this a useful development, usually when matching a small engine to driver demands for brisk performance. It seems unlikely that more than six speeds will be used due to excessive shift busyness and confusing shift patterns. A raft of less visible improvements have contributed to efficiency, noise, shift quality and durability. Manual transmissions are clearly not part of an integrated powertrain system but are often used as the basis of "robotized" systems.

There are already a number of applications of **Automated Manual Transmissions** in production. These tend to be installed in small passenger vehicles where full CVT or AT is hard to justify economically, difficult to package and potentially inefficient. There are also examples of other vehicle types using automated manuals. Performance cars such as the Ferrari 360 Modena exploit the perceived racing heritage and a number of light goods vehicles such as the new Ford transit and Mercedes-Benz Sprinter vans present reduced driver workload as a selling point. For most applications the goal is to combine the economy of a well-driven manual transmission with the ease of use and comfort of a conventional automatic transmission. This is to be achieved while retaining the simplicity and economies of scale of an established manual design. Most manufacturers have therefore added actuators to an existing transmission, leading to the term Automated Manual.

From a system integration perspective these systems give the scope to optimise shift patterns and achieve most of the gains in fuel economy predicted for a CVT. This is illustrated by the Fiat Ecobasic concept car, which has integrated control of the engine with that of the auto-shifting manual to achieve impressive fuel consumption potential of 3 litre/100km. In such schemes there are potential problems with shift quality as these gains are only achieved where shifts are scheduled automatically. Here the torque interruption necessary with single clutch arrangements can become intrusive, unlike a manually initiated shift, where the driver anticipates the torque interruption. There are also emissions considerations as one of the worst events during a typical drive cycle is the rapid transient surrounding a gearshift. To overcome these problems several manufactures are re-examining the twin-clutch concept pioneered by AP in the early 1980s. One example is DaimlerChrysler’s ESX3 concept car, fitted with a 6-speed, twin-clutch AMT. This is possibly the best available compromise between cost, comfort, economy and emissions compliance for the small to medium vehicle sector.

Continuously (and Infinitely) Variable Transmissions have been developed since the dawn of motoring in an attempt to produce the ideal transmission. Practical CVTs have consistently failed to live up to the ideal and are only on the last five years starting to fulfill their true potential. One of the enduring problems of CVT is that drivers have become used to the behaviour of stepped ratio powertrains and find some CVT control strategies unsettling at first. This issue is now partly remedied by CVTs that can emulate stepped ratios such as the MGF and Nissan Primera. Clearly use of this manual override detracts from fuel economy and emissions compliance. Also a better understanding of subjective driveability has been incorporated into modern control strategies.

Another barrier to CVTs wider uptake has been the historical torque limitations imposed by early systems. This problem is receding as VDT and now LuK, producer of Audi's multitronic, can offer transmissions suitable for typical V6 or V8 engines. The efficiency of CVT powertrains has historically been poor, although modern installations can deliver better figures than manual equivalents. The major improvement has been the introduction of electronic control, which for the first time allows precise matching of engine and transmission operating point to driver demand. Driveability at start from rest has been an issue with belt drive CVTs, early models had wet clutches with simple control strategies, later installations use electronic control or often include a torque converter to give the subjectively pleasing torque multiplication effect at pullaway.

The infinitely variable transmission, as developed by Torotrak, does not require a start from rest device due to its split power arrangement. This advantage contributes to the demonstrated fuel economy savings of 15% or more compared. The variator used by Torotrak is a full toroidal traction drive, one of the more successful examples of a host of traction variators. Another popular class of traction drive is the semi-toroidal, such as that developed by NSK (Powertoros) and used in the Nissan Gloria and Cedric. Critical to the success of modern traction drives is the availability of high purity steels developed for the rolling element bearing industry which allow high contact stresses and long life in automotive applications. Another key feature is the purpose developed lubricant which separates the moving parts, and through which power is transmitted. Traction drive technology is readily scaleable to allow its use in the very largest automotive applications. Other types of traction drive such as the Milner CVT, which resembles a variable geometry deep groove ball bearing, are aimed at the low power market such as scooters where hybrid dry belts are the main CVT in use currently.

Hydrostatic CVTs and IVTs have been used in off road applications for many years. Efficiency and noise issues have prevented their use in automotive powertrains although the latest agricultural CVTs claim remarkably high efficiencies due to careful design and development of the hydraulic units. On similar theme Borg-Warner are developing a transmission for the US light truck market, which could become a serious competitor for traction drives.

Conventional automatic transmissions continue to improve both in terms of efficiency and the number of ratios offered. A modern six speed automatic with integrated engine control is an expensive solution but can offer truly class leading driveability and performance with better than average fuel consumption and emissions. As such their market share is increasing. 80% of ZF's production for passenger cars is automatic gearboxes.

Hybrid Powertrains will radically change the requirements for the transmission and engine. Most of the systems described above can form part of a hybrid powertrain. Their combination with various load-leveling devices such as flywheels or electric motor/generator/battery sets offers the potential to decouple the energy conversion process from the duty cycle of the vehicle. Consequently the IC engine can run at optimum efficiency for a higher proportion of its operation and be subject to less external disturbance. The major challenge once again is system integration. The various components in the powertrain must be carefully coordinated to maximise the benefits. Given that every time energy is converted from one form to another a significant proportion is lost, advanced optimisation will be required both in system and control strategy design. The Honda Insight, with its IMA (Integrated Motor Assist) augmenting an otherwise conventional powertrain is an early example of the solution likely to be adopted by a number of manufacturers in the short to medium term. The emergence of 42-volt vehicle electrics makes the integration of electric motor/generators, turbochargers and engine ancillaries a viable proposition for future advanced powertrains.

Control Systems

For a number of years it has been possible to demonstrate that considerable benefit may be derived from operating the engine and transmission in an integrated manner [**1**], using a single controller to interpret the driver's wishes and instruct the engine and transmission controllers in turn. The goal of integration is to find the optimum operating mode for the whole powertrain, not just separate parts of it. This is true whichever combination of engine and transmission are employed, although CVTs are particularly suited to flexible, combined control. Manual gearboxes and clutches are the most mechanically efficient, however automation is required to reduce the effect of the element which detracts most from their efficiency: the driver.

Integration issues

Crucial to the success of such systems are the basic specifications of the major components and the design of the overall powertrain control strategy. Perhaps the most difficult aspect of this approach is the requirement that the powertrain be treated as an integrated system, itself an integral part of the vehicle as a whole. Failure to explicitly recognise this consideration at all points in the design and development process inevitably results in potential improvements being overlooked. One of the major practical difficulties in achieving such a working philosophy is the sheer size and diversity of today's automotive organisations, which traditionally cluster their specialists into teams responsible for different vehicle subsystems.

The difficulties are accentuated by the trend for OEMs to procure some or all of their transmissions and an increasing proportion of engines from outside vendors. As the OEMs shift their emphasis to finance, marketing and servicing, they will tend to want to leave transmission and engine design and tooling to suppliers and collaborators, who can spread the load of increasingly complex development over a larger volume. Against this background powertrain control and calibration will take on an increasingly important strategic role due to its ability to define the character of the vehicle. There is a clear requirement for OEMs to retain control of this process even as they delegate the development of mechanical aspects of the powertrain.

System Architecture

A major enabling technology allowing effective integration of systems from a range of suppliers has been the advent of CAN bus and similar digital communication links, now almost universally fitted to ever more powerful electronic control units. Complex time critical control tasks can be distributed among a group of controllers co-operating via such a bus. Various configurations may be employed, a supervisory controller could govern the separate engine and transmission control systems, which would be retained. Another configuration would be to make one of the latter the master and one the slave. Another would be to make them share the functions of overall control. The strategy adopted will depend largely on which group takes the lead. Often it is the transmission control engineers who are responsible for system integration due to their inherently cross disciplinary position within an organisation. One of the best examples of such a master slave approach is found in the Torotrak IVT system shown schematically in Figure 1. Here a comprehensive algorithm running on the transmission controller interprets driver pedal input as a demand for tractive effort and calculates the optimum engine operating point to fulfil this demand. The engine and throttle are then carefully co-ordinated via data bus to execute the manoeuvre while the transmission controller is also responsible for the closed loop hydraulic control of the transmission. In this way the transmission controller determines in its entirety the response of the vehicle to driver inputs.

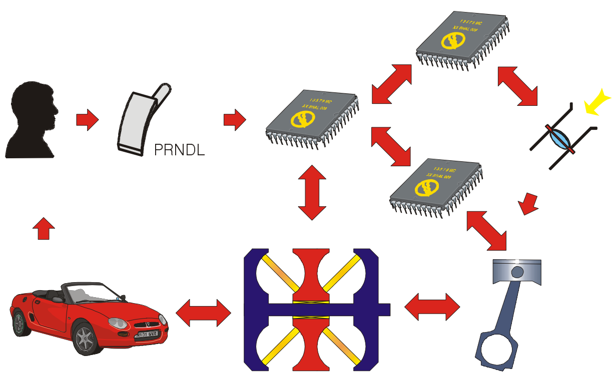

Figure 1 - The Torotrak system uses an advanced transmission controller
which also supervises the action of the engine controller

An example of another integrated powertrain concept can be found in the Fiat Ecobasic concept car is powered by the Multijet diesel engine, with second-generation common rail mated to a robotized gearbox using the Fiat/Magneti Marelli Selespeed system. The combination of the two, plus the low vehicle weight and advanced aerodynamics, gives the Ecobasic a fuel economy better than 3 litre/100 km, with a top speed of 160 km/h. Again the transmission controls the engine.

Emissions, Fuel consumption and Driveability

It has long been accepted that the use of an integrated powertrain control approach allows the driver's power demand to be implemented in the most fuel-efficient manner [**2,3**]. However, this does not achieve the best exhaust emissions performance, which must be considered as a priority in order to meet legislative limits. Driveability must also be considered from the outset as an essential objective if the resulting powertrain is to be commercially attractive.

Simulation tools offer great potential for prediction of the fuel consumption, performance and emissions produced by passenger vehicles. This allows a large part of the powertrain control strategy to be designed in simulation. If this process is to be truly effective, it is also necessary to estimate subjective driveability at the simulation stage. This allows controllers to be designed, which properly consider fuel consumption, emissions and driveability. The regulated exhaust emissions are carbon monoxide (CO), unburnt hydrocarbons (HC), oxides of nitrogen (NOx) and, in the case of a Diesel engine, particulate matter (PM). Due to the nature of the various pollutants and their different origins the optimum speed and load for a given power will vary for each of the pollutant species under consideration. Figure 2 shows a contour plot of NOx production from a typical Diesel engine, superimposed is the line giving lowest NOx for each engine power output. Figure 3 additionally shows similar lines for minimum fuel consumption and HC. Clearly a compromise needs to be developed.

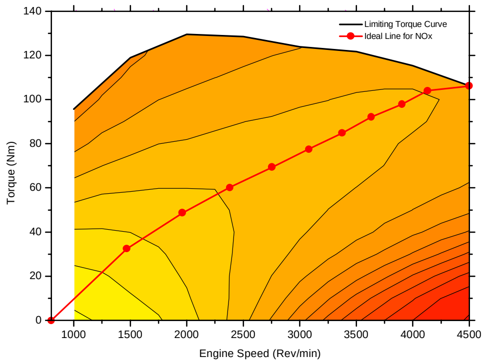

Figure 2 - Typical NOx contours for a Diesel engine with optimum line superimposed

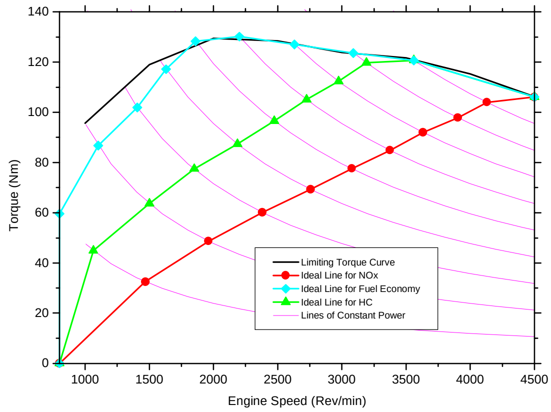

Figure 3 - Typical optimum lines for NOx, fuel economy and HC minimisation

Driveability is a subjective quality comprising many individual aspects. Many of these characteristics may be represented in simulation by a correlation between subjective appraisal data and measures performance data [**4**] as shown in Figure 4. By combining the representation of emissions, fuel economy and driveability a framework for the design of a supervisory powertrain controller may be constructed. Several methods of generating such a compromise have been developed [**5**] which rely on the user (calibration engineer) to set the relative importance of each pollutant. The engineer must retain an input to the process, although the use of an automated routine to incorporate this expert knowledge into a practical controller calibration is extremely useful. It allows the calibration engineer to concentrate on the engineering issues, minimising the complexity arising from the implementation. Formal optimisation techniques are extremely useful here as they allow the search for likely calibrations to be largely automated.

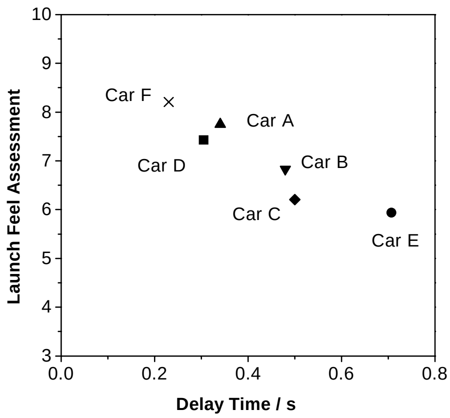

Figure 4 - Influence of delay times on a subjective launch feel assessment

Summary

The future for the powertrain industry looks exciting and demanding. It is a key system in the automotive industry and the importance of effective integration is becoming ever more pressing.

Concerning hardware, although individual applications will always emerge against the trend it is likely that in the next five years small vehicles will see a proliferation of automated manual powertrains, medium vehicles will take CVT into the mainstream and large passenger vehicles will be dominated by conventional automatic transmissions. Commercial vehicles will continue to be a large market for various forms of automated parallel-shafted transmissions. Drive by wire engines will be common in all sectors to allow the maximum potential for automation with the mix (at least in Europe) containing progressively more Diesel. It is likely that Direct Injection Gasoline engines will have effectively replaced current gasoline technology within this time frame and may make life difficult for Diesel outside Europe.

Outsourcing will be a major feature of powertrain engineering, placing the system integration activity at the core of the OEMs contribution to vehicle identity. Continuous improvement to control and calibration methodologies will allow the full potential of a given set of hardware to be accessed by all drivers on a regular basis and allow a vehicles characteristics to be tailored to suit brand objectives.

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