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# Systems Modelling and Simulation in the Product Development Process for Automotive Powertrains

## Engineering Doctorate Executive Summary

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# Summary

This submission is a summary of the ten submissions that form the Engineering Doctorate Portfolio.

The aim of the portfolio is to demonstrate the benefit of applying systems modelling and simulation in a modified powertrain product development process.

A description is given of the competitive pressures that are faced by motor manufacturers in the global automotive business environment. Competitive pressures include a requirement for reduced time to market, exacting product quality standards, manufacturing over-capacity that increases fixed costs and compromises profit margins, and legislation that is increasingly difficult to meet. High-level strategic responses that are being made by manufacturers to these pressures are presented. Each strategic response requires organisational changes and improved approaches to the way in which day-to-day business is conducted. Computer Aided Engineering (CAE) is presented as an approach that can help to improve the competitiveness of motor manufacturers by reducing product development time and the level of hardware prototyping that is required.

An investigation in five engineering companies yielded a number of observations about the use of CAE and its integration into product development. Best practice in the implementation of CAE in the product development process is defined. The use of CAE by a leading motor manufacturer in powertrain development is compared with the best practice model, and it is identified that there is a lack of coherence in the application of CAE. It is used to tackle specific problems but the use of CAE is not integrated into the product development process. More importantly, it was found that there is limited application of systems modelling and simulation, which is a critical technique for the effective integration of vehicle systems and the development of on-board vehicle control systems.

Before systems modelling and simulation can be applied in powertrain development, an appropriate set of tools and associated modelling architecture must be determined. An appraisal of a range of different tools is undertaken, each tool being appraised against a set of criteria. A combination of Dymola/Modelica and MATLAB/Simulink tools is recommended as the optimum solution. Dymola/Modelica models of the vehicle plant should be embedded into Simulink models that also contain controller and driver models. MATLAB should be used as the numerical engine and for the creation of user environments.

Transmission calibration is selected as a suitable pilot example for applying systems modelling and simulation in powertrain development. Best practice in CAE implementation and the systems modelling and simulation architecture are validated using this example.

Simulation models of vehicles equipped with CVT and discrete ratio automatic transmissions are presented. A full description of the operation of the transmission system, of the simulation model itself, and of the validation of the model is presented in each case. The potential benefit of the CVT model in transmission calibration is demonstrated. A Transmission Calibration Simulation Tool (TCST) is described within which the discrete ratio simulation model is encapsulated. The TCST includes a user environment in which the simulation model can be parameterised, a variety of simulation runs can be specified, and simulation results are processed. Development of the TCST requires an objective measure of driveability effects that are influenced by the transmission shift schedule. A method for objective assessment of driveability is developed, correlated, and implemented as an integral part of the TCST. This element of the TCST allows trade-off exercises to be conducted between fuel economy and driveability.

The development of a transmission calibration based on experimental testing is compared with a similar exercise based on simulation testing. This study shows that, if the TCST is properly integrated into the transmission calibration process, the vehicle test time taken to optimise the calibration for fuel economy could be reduced by six weeks, and a week of calibrator time could be saved. Thus, the aim of the submission is fulfilled, since the benefit of applying systems modelling and simulation in the powertrain development process has been demonstrated.

It is concluded that a consistent approach is required for effectively integrating systems modelling and simulation into the product development process. A model is proposed that clarifies how this can be achieved at a local level. It is proposed that in the future, the model is applied whenever systems modelling and simulation is introduced into a powertrain department.

# Acknowledgements

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# 1. Introduction

The motor industry is highly competitive and constantly changing. A number of factors are creating this market environment. For instance, customers are becoming increasingly discerning and their expectations of new vehicles are increasing. Legislation is putting pressure on the industry to generate innovative solutions to safety, recycling, exhaust emissions and fuel economy. Global production over-capacity is compromising the efficiency of many manufacturers. Maintaining competitiveness and profit margins under such circumstances requires that manufacturers develop excellent products in a highly efficient manner. Excellent products could be defined as those that precisely meet customer requirements.

Once a product concept has been conceived, the Product Development Process (PDP) determines the order, timing and nature of activities that are undertaken to deliver the product to the market. The PDP, and the discipline with which the specified activities are performed, is the main influence on the quality, cost and time of product development. Thus, an effective PDP is critical for a company to develop excellent products in a highly efficient manner [1]. There are several dimensions of activity that are related to the PDP, including the definition of product concepts, the organisation of the PDP tasks, human resource allocation, project management and leadership, tools that are used, etc. [1]. It is important to get each of these aspects functioning well in order to obtain an efficient PDP.

The work described here focuses on how Computer Aided Engineering (CAE), and in particular systems modelling and simulation, can be used to enhance the PDP and hence improve product quality whilst reducing time and cost. Systems modelling and simulation is a technique that can be used to predict the behaviour of complete, complex systems. Narrowing the focus still further, the development of one vehicle subsystem, the powertrain, is considered here.

This submission is a summary of the Engineering Doctorate Portfolio. The aim of the portfolio is to demonstrate the benefit of applying systems modelling and simulation in a modified powertrain product development process. Objectives of the portfolio are as follows.

1. Assess the effectiveness of the current application of CAE in powertrain development of a major automotive manufacturer.
2. Produce recommendations for the application of systems modelling and simulation in powertrain development.

3. Apply systems modelling and simulation to real powertrain development problems and demonstrate the benefit of using the technique.
4. Demonstrate the savings that can be gained by modifying the powertrain development process to incorporate the use of systems modelling and simulation.

Part of the work described in this portfolio was undertaken in Rover Group, which at the time was a subsidiary of BMW. BMW purchased Rover Group in 1994. Rover Group consisted of four brands: Rover Cars, Land Rover, MG and Mini. There were three models of Rover Cars, the '75', the '45' and the '25'. Mini and MG were both single model brands. BMW divided up the Rover Group brands in 2000, selling Land Rover, Rover and MG brands and retaining the Mini brand.

Other aspects of the work described in this portfolio were undertaken in conjunction with Land Rover, which since June 2000 has been a subsidiary of Ford Motor Company. Land Rover is a worldwide leader in the manufacture of Sports Utility Vehicles (SUVs). There are currently four Land Rover products. The Freelander is the smallest, and aimed at customers who desire car-like attributes in a vehicle that can also competently tackle off-road scenarios. The Defender has the same functional orientation as the original Land Rover. The Discovery has a good level of specification and many technical innovations, which ensure that it performs well on- and off-road. The Range Rover is the flagship of the Land Rover range, competing firmly in the luxury car sector but maintaining a full level of off-road capability.

A clear trend in the automotive industry is a gradual increase in the proportion of new cars that are sold with automatic rather than manual transmissions. In European markets, for instance, 8% of cars sold ten years ago had automatic transmissions, compared with 14% today. The figure is expected to reach 25% by 2005 [2]. In North America today, 84% of cars are sold with automatic transmissions. Sixty four percent of new Land Rovers are sold with automatic transmissions. As Land Rover sales in the US increase [3], automatic transmission vehicles will represent a growing proportion of overall sales volume. Ensuring that the application of automatic transmissions in Land Rover vehicles is of the highest quality is clearly very important for the company's business success. The aspect of the powertrain development process that deals with the application of automatic transmissions in the powertrain system is transmission calibration. For this reason, the examples selected to meet objectives three and four of the Engineering Doctorate Portfolio are drawn from transmission calibration.

The structure of the Engineering Doctorate Portfolio is illustrated in Figure 1. The portfolio consists of four work packages that are designed to systematically tackle the aim of the portfolio. Each contains one or more submissions. A brief summary of each submission can be found in Appendix B.

The portfolio submissions in Work Package 1 consider the way in which CAE should be integrated into the powertrain product development process to maximise its effectiveness. The first submission in this work package was previously examined as an MSc Dissertation and its role in the Engineering Doctorate Portfolio is largely to set the scene. The submission in Work Package 2 focuses on how to apply systems modelling and simulation in powertrain development. Work Packages 1 and 2 were conducted in association with Rover Group.

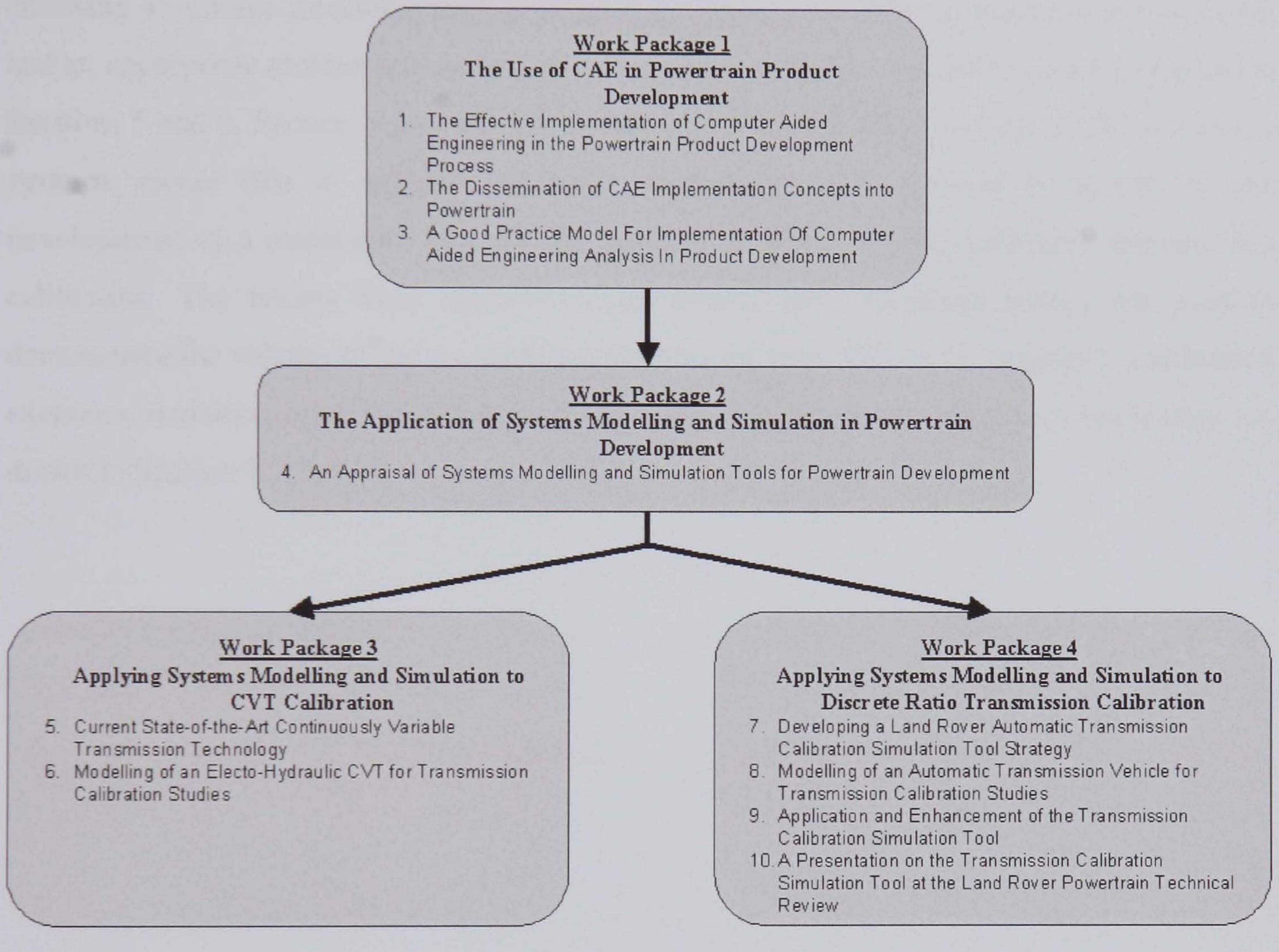

*Figure 1 – Engineering Doctorate Portfolio Structure*

Work Packages 3 and 4 give examples of the application of concepts that were developed in the first two work packages. The submissions in Work Package 3 report on the application of systems modelling and simulation to Continuously Variable Transmissions (CVTs). Current state-of-the-art CVT technology is reviewed, the systems modelling of a push-belt CVT and its application in a vehicle model for transmission calibration studies is reported. Work Package 3 was conducted in association with Rover Group.

The submissions in Work Package 4 report on the approach that was taken to applying systems modelling and simulation to discrete ratio transmission calibration. In this example, considerable attention is paid to the importance of addressing the product development process when applying systems modelling and simulation. A strategy for applying systems modelling and simulation in the calibration process is developed and implemented. Work Package 4 was conducted in association with Land Rover.

The structure of this submission mirrors the structure of the Engineering Doctorate Portfolio. In Section 2, a description of the global automotive business environment clarifies the motivation for using CAE. The use of CAE in the powertrain product development process is the focus of Section 3. In Section 4, the focus narrows to consider the use of systems modelling and simulation tools in powertrain development. A set of criteria is devised for choosing a systems modelling and simulation package, a number of packages are assessed, and an appropriate architecture is devised based on the findings. The architecture is applied in Sections 5 and 6. Section 5 presents a Continuously Variable Transmission (CVT) in-vehicle systems model that is suitable for basic calibration tasks. Section 6 reports on the development of a simulation tool for the purpose of discrete ratio automatic transmission calibration. The results from extensive experimental and simulation testing are used to demonstrate the validity of the model that underpins the tool. The tool is applied to calibration exercises, including basic vehicle shift schedule driveability quality exercise. Conclusions are drawn in Section 7.

# 2. The Global Automotive Business Environment

The motor industry is one of the most significant global industrial sectors [4]. Three of the four largest companies in the world by revenue are motor manufacturers, and there are eleven motor manufacturers in the top fifty [5]. Around the world, there are approximately 250 companies engaged in some way in the manufacture of light motor vehicles [6]. It is estimated that by 2006, the largest six manufacturers will be accountable for 61% of global production, and the largest fourteen manufacturers for 90%. In 1999, approximately 52.9 million cars were sold around the world. Competition in the motor industry is extremely intense. Sales growth rates in established markets are minimal [7], thus growth in market share for one manufacturer means the erosion of sales for another. In emerging markets, sales growth rates are significantly higher, but have generally not met the expectations of ten years ago. These are some of the factors creating a highly competitive business environment for motor manufacturers.

In this section, specific competitive pressures, and their implications, are described in more detail. The purpose of outlining competitive pressures acting on motor manufacturers is to provide a thorough business-level justification for the work that is presented in this portfolio. Manufacturers are responding to the pressures in a variety of ways, and a number of important responses, for instance improving the product development process, are outlined. A technique that can be used to enhance the product development process is Computer Aided Engineering (CAE). The particular, strategic role that CAE can play in assisting companies to respond to competitive pressures is described.

## *2.1 Competitive Pressures*

Motor manufacturers, like all businesses, aim to maximise their shareholders' financial rewards. This is achieved through maximising profitability and growing the company. A requirement that underlies all the competitive pressures described in this subsection is for companies to improve profitability by increasing revenues and reducing costs. Competitive pressures tend to threaten profitability by increasing costs and reducing revenues.

Competition in the motor industry requires manufacturers to reduce new product time to market and enhance product quality; whilst dealing with toughening legislation; and the effects of global over-capacity. Each of these is discussed in turn in the following paragraphs.

### Time to Market

The total number of sales, and therefore the return on investment, for a new product is strongly related to the product development time [8]. Traditionally, motor manufacturers have had new product lead times of up to 60 months, but some manufacturers now claim to be able to deliver new products to the market in as little as 26 months [9]. In the future, it is possible that lead times will reduce still further.

New products must be brought to market quickly, but they must also be free from faults at launch. Product recalls due to faults are extremely expensive for manufacturers. Ford, for example, lost four billion dollars through product recalls during 2000 and 2001 [10]. Customer perception of the product quality can also be adversely affected by product recalls, and this can have a detrimental effect on future sales of the product and its overall success in the marketplace.

### Product Quality

Advances in product design and manufacturing processes means that most modern cars are produced to a high quality [4]. Differentiation on the basis of quality is, therefore, increasingly difficult. Build quality has ceased to be a motivating factor for vehicle purchase – in today's market it is a requirement for entry. Thus, ensuring that design and build quality is present in its products is a vital consideration for motor manufacturers. The rapid pace of development in the field of electronics has made components cheaper. Once features that would mark out a car as a luxury derivative are expected on base models.

Product quality, therefore, is starting to take on a different meaning. For instance, quality is becoming more closely associated with vehicle functionality, an area in which significant competitive advantage can be gained. During times of increased oil prices, for example, customers become very concerned about the fuel economy of their vehicles [11]. The VW Golf has used the fuel economy and power of its recent turbo-diesel 'GTI' model as its key marketing approach [12].

### Manufacturing Over Capacity

Globally, there is significantly more automotive annual production capacity than the number of vehicles that are sold. This means that the majority of manufacturing plants operate below the capacity for which they were designed. Fixed costs are incurred on unutilised capacity, but there is no revenue stream to cover the costs. In 1990, capacity utilisation was approximately 80%. By 1999, this had fallen to approximately 69% [6].

The mismatch between capacity and sales volumes has arisen from consistently optimistic estimates of future sales volumes, both in established and emerging markets. Often, predicted volumes of new products, which underpin capacity planning decisions, are based on a requirement for product profitability, rather than on what the market will sustain.

Legislation

Legislative pressures are focused on three areas in automotive development: vehicle safety; recycling; and fuel economy and emissions [13]. The latter is of greatest concern from a transmission calibration perspective.

In Europe, emissions legislation is becoming harder to meet. The next level of emissions legislation, Stage IV, will be realised in 2005. In some markets, principally Germany, tax incentives are offered by national governments for vehicles that voluntarily meet the future emissions targets ahead of the legislated requirement [14]. This has become a competitive advantage for those manufacturers that are able to meet the legislation early. In the US, Corporate Average Fuel Economy (CAFE) requirements are applied to the entire range of vehicles offered by manufacturers. In a recent review, the National Academy of Sciences recommended to the US government that the CAFE standard should be raised by 47% over the next 10-15 years [15].

A further area of legislation, which affects distribution rather than the product, is the European block exemption on new car sales. In 2002, the exemption, which permits motor manufacturers to retail their vehicles exclusively through approved dealerships, expires. This will dramatically increase price competition and reduce sales revenues [16].

## *2.2 Motor Manufacturers' Strategic Responses*

The competitive pressures described in the previous subsection represent significant challenges that motor manufacturers must meet. Survival requires manufacturers to become more nimble and efficient in every area of their business operations, and particularly in the way that they engineer new products.

A number of business strategies are being employed by motor manufacturers to improve competitive position. Many strategic alliances have been formed, through the common means of mergers and acquisitions, or through partnerships focused on specific projects. Manufacturers are enhancing their marketing strategies and redefining their relationships with customers. Manufacturing strategies are being adjusted in an attempt to improve efficiency. Changes are being made to product strategy so that products better suited to market requirements can be introduced more quickly and efficiently. Each of these four strategies is discussed at an introductory level in this subsection.

Strategic Alliances

During the 1990s, there was a frenzy of take-overs and mergers in the motor industry. The result is that six firms share 70% of the global market [17]. There are two important motivating factors behind this trend. Firstly, consolidation establishes economies of scale.

Manufacturers are able to specify common components, subsystems or platforms for vehicles of different brands thereby adding considerably to the volumes of purchased parts. Larger volumes tend to result in lower unit costs, and hence the opportunity to improve vehicle profit margins. Secondly, consolidation allows manufacturers to rapidly access sectors of the market that might otherwise prove elusive. It may often be cheaper, more efficient and faster to acquire a company that already has an established brand and appropriate products than to develop new products in-house. Ford's strategy of forming a 'Premier Automotive Group' (PAG), consisting of Lincoln, Volvo, Jaguar, Land Rover and Aston Martin is an example of this strategy [18].

Some manufacturers, for instance PSA, have resisted the prevailing trend for consolidation, but have established strategic partnerships to enable them to respond to changing expectations in the marketplace [19]. This strategy allows manufacturers to enter market sectors from which they might otherwise be excluded, and leverage their core technologies for increased profitability.

### Enhanced Marketing Strategy

Marketing is concerned with the public perception of products and with developing a favourable relationship between the manufacturer and the customer. Electronic interaction with customers via the Internet is likely to be a facilitator for enhanced customer relationships [6]. Another important marketing strategy is 'brand management'. Under brand management, each vehicle is designed with distinguishing features that relate to the product's brand image and differentiate it from its competitors. Whilst each vehicle is designed to suit its own brand image, common engines, transmissions and chassis components, as well as minor components, can be used across brands to give manufacturing economies of scale [18].

### Enhanced Manufacturing Strategy

Motor manufacturers deploy a wide range of manufacturing and quality strategies in their attempt to become increasingly competitive. These include location, capacity and equipment decisions, but also extend to e-commerce solutions, restructuring and rationalisation. E-commerce systems are being used to electronically order parts from suppliers, time parts delivery and schedule vehicle build in response to a customer placing an order [20,21]. On-line auctions are being used to enable manufacturers to choose between suppliers for automotive parts supply. Exchanging information electronically dramatically reduces the volume of documentation that is required in business transactions [22]. Many companies are reducing overhead costs by reorganisation and rationalisation, with the objective of improving profitability. Strategic alliances can give rise to rationalisation opportunities, as partners can share common components, providing the possibility of combining manufacturing facilities [23].

Enhanced Product Strategy

Without desirable products, the most efficient motor manufacturer will not be able to compete in today's market conditions [8]. For instance, at the start of the 1990s, Chrysler was in a precarious competitive position, with a financial crisis, falling sales and outdated products. The company was able to reverse its fortunes by producing a range of popular products [24].

Developing new vehicles is a very costly exercise. Since the market demands regular product offerings to maintain a smooth revenue flow, then economical and rapid methods for developing new vehicles are needed. Three product strategies that are widely being adopted by manufacturers are platform engineering, enhancing the product development process, and increased outsourcing of component design and supply.

Platform engineering involves the sharing of powertrain and chassis subsystems between different vehicles. Engineering a new vehicle from a platform that already exists is substantially quicker and more cost effective than developing a new vehicle from scratch. Volkswagen is the leader in platform engineering, and it is anticipated that it will have a volume of approaching 3.7 million vehicles from two platforms by 2005 [6].

Manufacturers are seeking to improve the product development process, as well as the products themselves. Two key strategies are, firstly, to increase the level of supplier involvement in developing new products [10], and secondly, to reduce the level of prototype hardware testing during vehicle development through the use of Computer Aided Engineering (CAE). Vehicle prototypes are costly and time consuming to manufacture, and reducing their number provides obvious time and cost benefits.

Manufacturers have gradually been increasing the number of vehicle components that are purchased from a third party supplier. Components such as transmissions that were traditionally designed and built in-house are now outsourced to global suppliers. With the increasing complexity of bought-in subsystems, manufacturers require the assistance of suppliers in integrating the subsystems into their products. Engineering competencies are moving from manufacturers to suppliers, with the manufacturers retaining responsibility for overall systems integration, defining overall vehicle attributes to suit its brand, and managing programmes. The benefits of this strategy, are simplified product cost control, reduced development time, and reduced risk for the manufacturer.

## 2.3 The Strategic Role of Computer Aided Engineering

The effective use of computers is important for agile product development. A variety of computer tools and techniques are used in engineering product development, for example, electronic interaction with customers and suppliers, Electronic Product Data Management, Computer Aided Design, Computer Aided Manufacturing, and Knowledge-Based Systems could all be classed as computer tools. Computer Aided Engineering (CAE) analysis is a particularly important method for reducing the level of hardware prototyping during product development and improving understanding of the system. Using CAE analysis, the behaviour of a physical system can be predicted through computer simulation, which generally requires the numerical solution of a set of governing equations [25]. CAE can play a role in the implementation of each of the four strategies discussed in the preceding section, those being strategic alliances, enhanced marketing strategy, enhanced manufacturing strategy and enhanced product strategy.

Whenever strategic alliances are formed that involve co-operation between partners in developing products, systems must be established for communicating engineering specifications, designs, and ideas. Typically, Computer Aided Design (CAD) electronic models are exchanged to communicate dimensional engineering data. CAE models can be a complementary mechanism for communicating functional design and engineering data. They may be encapsulated to allow co-operation without unwanted disclosure of confidential information. Exchanging CAE models of physical components would ensure, for instance, that partners are working to similar assumptions.

One aspect of enhanced marketing strategy is developing a distinct brand for each product. Brand image is particularly true of premium products. CAE analysis can assist engineers to tailor a product to reflect its brand values, particularly when the required brand image of a product can be defined in objective, engineering terms. For products that have a different brand image but are based on the same platform, CAE can assist in identifying the engineering changes that are required to differentiate between the vehicles.

E-commerce in the automotive industry is benefiting manufacturing strategy. CAE analysis can support E-commerce in two ways. Firstly, component function specifications can be captured and electronically distributed to suppliers in the form of a CAE model. Secondly, suppliers can submit proposed component or subsystem solutions electronically in the form of CAE models for engineering appraisal by the manufacturer. Thus, CAE enables a more informed selection of solutions at the outset of product development and supports E-commerce.

Enhancing product strategy is concerned with improving the desirability of products and making the development process more efficient. Two strategies that help to realise the goals of accelerated product development, reduced development costs, and increased frequency of new product offerings are giving suppliers greater responsibility in new product development, and integrating CAE into the product development process [26, 27].

Outsourcing the design and development of a number of vehicle subsystems places a demand on motor manufacturers to be increasingly effective at integrating the subsystems. Engineering skills must evolve and different tools and techniques are required to support such a systems integration approach. Manufacturers must be able to ensure at every stage of vehicle development that its attributes will meet pre-defined targets. Some CAE techniques, in particular systems modelling and simulation, can assist in obtaining an optimal solution for complete systems rather than just subsystems or components, which strongly supports the integration of outsourced subsystems.

As shown in Engineering Doctorate Portfolio Submission One, when it is properly integrated into a product development process, CAE can offer a number of general advantages over traditional, prototype based engineering product development approaches:

1. **Reduced Physical Prototyping**. Traditionally, a process of build-and-test has been used for the development of products. Analysis and simulation helps engineers to develop a first subsystem or component design iteration that is likely to meet design requirements. Physical prototyping can be accurately targeted and used for confirming analysis of the design [28]. Reducing physical prototyping has two major knock-on benefits. Firstly, significant time can be removed from the Product Development Process (PDP). Ford estimates that it can cut the development time for suspension systems in half using a CAE approach [29]. Secondly, cost savings can be made. High costs are associated with the build-and-test cycle [30]. Physical prototypes can be particularly expensive and by reducing the number, CAE can have a direct impact on the PDP cost.

2. **Improved Understanding of the Physical System**. Physical testing yields limited information since it is limited to that which can be measured through instrumentation. Analysis and simulation, however, provides engineers with a detailed insight into the behaviour of the subsystems or components they are designing. Improved understanding of system behaviour in turn leads to a higher quality solution, supporting enhanced product strategy. An aeronautical example of this benefit is the application of CFD to the development of a vertical take-off and landing jet [31]. The flow of the up-thrusters was creating negative lift when the aircraft was hovering close to the ground, but using CFD to optimise the up-thrust flows eliminated the problem.

3. **Increased Number of Design Iterations.** Making changes to designs in the virtual realm is generally less time consuming and more economical than making changes to physical prototypes. In the same time and for the same cost, therefore, more design iterations can be tested, giving a more optimal solution and a greater opportunity for innovation. Solution quality once again benefits. Design issues can be addressed and resolved earlier in the PDP using CAE [32].

4. **Optimisation of Complete Systems.** In the virtual realm, complete systems can be modelled and, if the appropriate platform is available, optimised. Parameters can be changed that would be impossible to manipulate using hardware prototypes.

Thus, CAE can directly contribute directly to an improvement in product development process efficiency, and can also support other strategies that motor manufacturers are adopting in response to competitive pressures.

## *2.4 Conclusion*

The highly competitive global automotive business environment, manufacturers that are able to bring new products to market most quickly gain a great advantage over their competitors. Customers expect vehicles to exhibit excellent build quality, which has become an 'order qualifier' or prerequisite when providing a new product offering. An additional pressure is that, on a global basis, there is an over-capacity in vehicle manufacturing plants. As a result, amortised fixed costs are higher for each vehicle, and profit margins are reduced. Besides business competitive pressures, it is becoming increasingly challenging to meet government automotive legislation. Manufacturers that are most efficiently able to generate solutions to the increasing legislative requirements will gain a significant competitive advantage.

In order to remain competitive and profitable in this environment, manufacturers have devised a variety of business strategies. Developing strategic alliances; evolving the nature of the manufacturer-customer relationships; adopting new technologies for efficient vehicle production; and improving products themselves and the way that they are developed are some of the most important strategies that have been adopted.

CAE models and analysis can contribute to supporting the implementation of each strategic response listed in the preceding paragraph. In particular, if CAE is effectively implemented in the product development process, it can serve to improve the efficiency of the process, reducing time and cost. Efficiency improvements can be achieved because the implementation of CAE allows a reduction in the use of physical prototypes, an improved understanding of the physical system, an increased number of design iterations, and optimisation of complete systems.

# 3. The Use of CAE in Powertrain Product Development

In Section 2, it was identified that competitive pressures in the motor industry are forcing motor manufacturers to change their approach to product development. Reduced time to market, improved product quality and reduced cost are requirements, and to be successful, the product itself must be innovative and profitable. Reducing hardware prototyping and adopting a systems approach to engineering are two ways in which the motor industry is responding [33]. Computer Aided Engineering (CAE) was introduced as being a critical resource in the modern automotive product development process.

This section reports on the first work package in the Engineering Doctorate Portfolio. Current applications of CAE in powertrain development are reported. Research that was conducted in five different engineering companies in different sectors is summarised and used, in conjunction with published literature, to distil a set of principles that define CAE implementation best practice. The implementation of CAE in the powertrain development process of a leading automotive manufacturer is appraised against the best practice model that has been developed, and conclusions are drawn.

## 3.1 The Application of CAE in Powertrain Development

CAE is used to mathematically predict the behaviour of physical systems, which generally requires the numerical solution of a set of governing equations [34]. There are a number of CAE techniques that range from the design analysis of components to the behaviour of integrated systems. In this report, CAE refers to the techniques listed below.

- **Computational Fluid Dynamics (CFD).** CFD uses a 3-dimensional mesh and Navier-Stokes fluid dynamics equations to predict fluid flow. Examples of typical powertrain applications include engine intake manifold air dynamics, engine combustion chamber internal flow, exhaust gas flow and catalyst thermal response, and coolant circuit flow.
- **Finite Element Analysis (FEA).** FEA is used to analyse materials for stress, thermal performance, and mechanical response. FEA is applied in the engineering design of most powertrain mechanical components.
- **1-D Gas Dynamics.** This technique is used to predict the flow of a fluid around a circuit. Pipes, orifices and volumes can be modelled. A typical powertrain application is the optimisation of engine intake manifold gas dynamics.
- **Multi-Body Systems (MBS).** MBS analysis is used to analyse the behaviour of hinge-jointed structural systems that are under load or excitation. The mass of elements is

lumped, but a coordinate system is defined to give relative positions of each element. Powertrain applications include the modal analysis of transmissions, and a full representation of driveline dynamics.

- **Systems Modelling and Simulation.** Systems Modelling and Simulation is a technique that is particularly optimised for simulating the behaviour of systems made up of different types of subsystems, e.g. an automatic transmission, which has hydraulic, rotational mechanical and electronic control elements. Lumped parameter models are created. Powertrain applications include performance, emissions and fuel economy prediction, vehicle driveability studies, design studies, control algorithm development, and engine and transmission calibration.
- **Computer Aided Software Engineering (CASE).** CASE tools provide systematic procedures for developing embedded real-time systems. The technique can be used to accelerate the development of controller software. CASE tools can facilitate the automatic generation of machine-level code from controller models. CASE is used in powertrain in the development of engine and transmission controllers.
- **Hardware-in-the-Loop Applications (HIL).** HIL is used to test a piece of hardware (often an electronic controller), with the system that is being controlled modelled and running as a simulation on a computer. The proper operation of the hardware can be tested. Rapid controller prototyping is a similar CAE application, where a controller can be designed and implemented in the virtual realm without building physical prototypes. In this case, a controller can be modelled and run along with the physical system. Typical powertrain applications are controller development and verification, and dynamic engine test-beds.

All these CAE techniques are used to simulate the function, or attributes, of designs at the system, subsystem or component level. Thus, CAE is distinct from Computer Aided Design (CAD), which is used for defining the geometry or fit of designs, and from Computer Aided Manufacture (CAM), which is used to realise designs held within CAD. CAD/CAM are widely used techniques and are now being linked by Virtual Reality, which can give a complete digital mock-up of a vehicle [35, 36]. CAD/CAM and Virtual Reality are outside the scope of this portfolio.

Figure 2 shows the current usage of different CAE techniques in one major automotive manufacturer. The techniques that are listed on the left hand side of the matrix diagram are ranked according to the level of detail in the CAE models. At one extreme, systems modelling and simulation represents the interaction of subsystems. At the other extreme, combustion flow analysis is a specific and detailed application of CFD. Along the top of the matrix diagram, different activities in product development are listed. Solid dots on the diagram indicate that a technique is used extensively in a product development activity, and white dots indicate that it is used to a limited extent. An interesting pattern is that in the advanced phases of product development (research and pre-development), there is a bias towards the use of systems tools, and in series development the bias is towards more detailed analysis. This reflects the requirement to define a product at a system level in the early phases, and the emphasis on detailed design during series development.

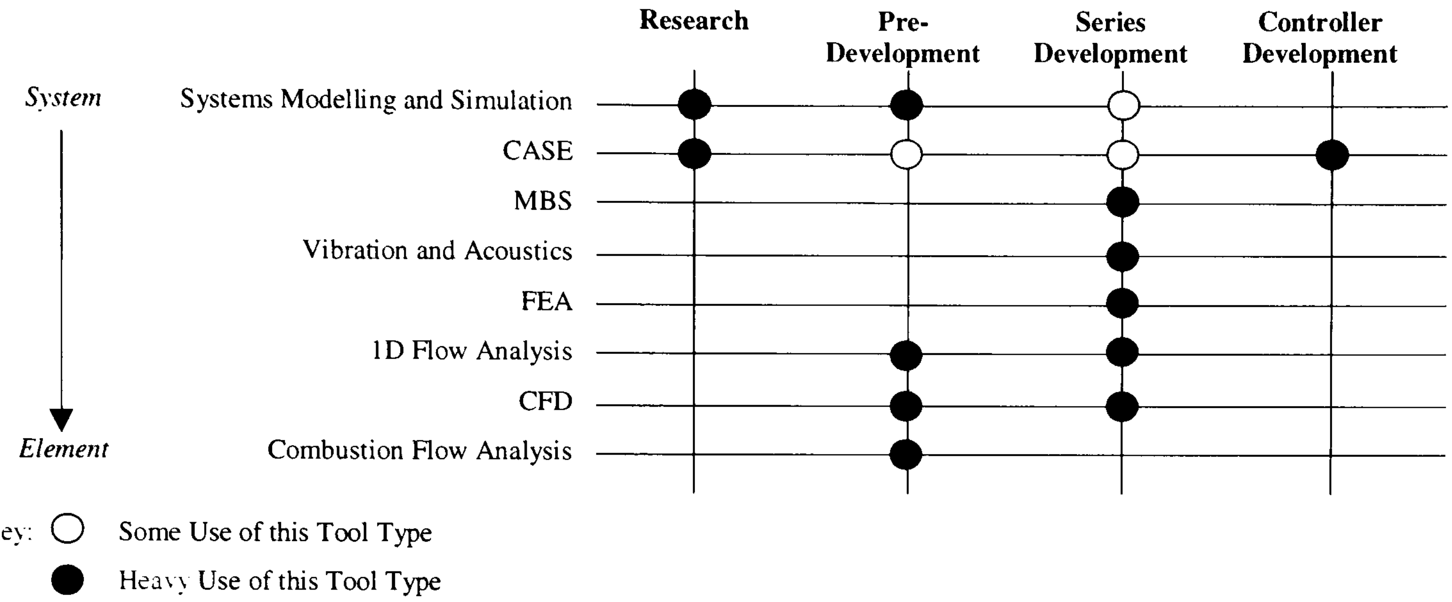

*Figure 2 – Application of CAE at in a Major Automotive Manufacturer*

Previous literature has examined the application of CAE analysis tools and techniques to specific problems [37, 38, 39, 40]. On the other hand, a great deal has been published on the automotive product development process, and its most appropriate configuration [41, 42, 43]. It is widely recognised, as stated in Section 2, that CAE analysis is essential for reducing hardware prototyping, and that prototyping is a critical part of the product development process [44]. There are relatively few papers, however, that consider the proper integration of CAE into the product development process to yield optimum benefits, although Smith et al give one example [45]. Therefore, the work package described in this section concentrated on how CAE should be effectively implemented in the product development process.

## *3.2 Implementation of CAE in the Product Development Process: A Cross-Industry Study*

Research was undertaken into the implementation of CAE in five companies in different engineering sectors. Findings from the research are outlined in this section. Having made observations from each company, implications for how CAE analysis is used in product development are drawn out in the analysis at the end of this section.

### *3.2.1 An aerospace company*

Aerospace is a highly competitive industry, especially in the commercial sector, with a number of well-matched competitors in a limited market. Product reliability and safety are critical factors. CAE analysis is an important technology in the development of aerospace products, with FEA and CFD being the most important methods.

In the company that was investigated, a department has been established outside the main functional departments, which is responsible for process, technique and tool development. The effect has been a continued development and coherent implementation of CAE analysis. The department is able to respond to the expressed needs of customer product development departments and initiate the adoption of more sophisticated analysis techniques. A robust Product Data Management (PDM) system has been developed to support CAE analysis. A technique for the synthesised optimisation of distributed systems is being implemented, which can bring together different CAE analysis tools. Optimum solutions to complex problems can be obtained, for example, balancing fluid flow and structural integrity of a wing section. The need for synthesised analysis is particularly clear in the aerospace company, since components often operate under extreme conditions. Such components must be optimised for weight, performance and cost.

Despite the fact that the application of CAE analysis in the aerospace company is advanced, and a number of vital issues are addressed, CAE analysis is still not thoroughly integrated into the PDP. The effect of implementing CAE analysis without realising a wholesale change in the PDP has been that product quality has improved, but there is little change in product time to market.

### *3.2.2 An off-highway transmissions company*

Off-highway transmissions are complex systems that involve the integration of hydraulic, electrical, electronic and mechanical components [40]. The transmission is itself a subsystem, which is integrated into a number of different products. The off-highway transmissions company has only a few hundred employees in the transmissions division, all located in the same building.

The company has the capability to analyse individual gears and shafts, but its ability to model and analyse gear/shaft/bearing interactions is underdeveloped. There are insufficient systems integration capabilities. A policy of placing a workstation on every desk has been pursued, providing flexible computing facilities, but since CAE analysis is not incorporated into departmental design procedures, it is not consistently applied in the PDP.

### *3.2.3 A heavy goods vehicle transmissions company*

An HGV transmission is a product that is very different in nature, application and operating conditions from an off-highway transmission. HGV transmissions are utilised in a wide variety of different OEM products. Systems integration is therefore, once again, a critical consideration.

Overall, use of CAE analysis in this company is crude. Observations relate primarily to the effect of poor CAE analysis implementation.

There is no coherent strategy in the application of CAE analysis. The ad-hoc approach creates difficulties in obtaining financial approval for purchasing CAE Tools, it prevents the build-up of sustainable momentum in the use of analysis, and it discourages confidence in analysis results. The prevailing engineering mentality remains one of physical prototyping.

A strong research department makes extensive use of CAE analysis methods and tools, but they are not transferred into the development process. The effect is that potential reductions in physical prototyping are not realised.

There is limited validation of CAE analysis results. By way of example, dynamic test rigs that could potentially significantly reduce the level of vehicle testing are under-utilised because the vehicle models that drive the rigs are crude. Engineers have lost confidence in the results.

Some of the HGV transmission company's products include electronic control systems. Systems integration is an important aspect of developing these products, and it is currently undertaken manually. One team is responsible for mechanical development and a separate team develops software. Systems engineers bridge the gap between the two teams. Ideally, systems modelling tools would be used to develop systems in an integrated manner.

### *3.2.4 A white goods manufacturer*

White-goods markets are dynamic and driven by trends and price. Product development must be rapid, low cost and develop solutions that are robust, durable and within specification. White goods products are systems comprised of different types of subsystems, for example washer/dryers and dishwashers, which are dynamic systems with electronic control.

Despite market conditions that would seem to encourage the use of CAE analysis, actual use by the white goods manufacturer is limited. Design is undertaken using a CAD system, which generates parameters for some Finite Element structural analysis. MBS modelling is starting to be used for vibrational analysis, for instance to eliminate undesirable modes. Rapid prototyping is used in the development of washing machine controller strategies. Functional specification changes can be made in a spreadsheet, which is a familiar environment for the engineers. Changes can be rapid-prototyped, and their effect determined experimentally. This is an example of CAE analysis being applied in an appropriate, localised manner, which results in an accelerated development process.

### *3.2.5 An automotive electronics company*

The electronics industry is perhaps the fastest-moving industry in the world. Product time-scales are very short and competition is stiff, which means that the product development process must be rapid and produce excellent solutions. The sophistication of the product and the development time pressure makes the effective use of CAE analysis imperative.

The PDP has been fundamentally readjusted to allow effective implementation of CAE analysis. Development of integrated electronic systems is now completely reliant on CAE analysis. Four to five years ago the development process was manual. In union with significant changes to the PDP, the full benefits of CAE analysis are enjoyed.

As a result of the effective implementation of CAE analysis, the company is now presenting its products differently to customers. Integrated electronic modules can be delivered in the virtual realm as a model, allowing customer needs to be met more accurately and more quickly. Despite a thousand-fold increase in complexity, development time for electronic modules has been reduced dramatically through the integration of CAE analysis into the PDP.

CAE analysis tools in this company generally have common standards for communication and can be integrated using scripts. Integration is a secondary consideration to utilising the optimum package for each application, but has made a significant contribution to its effectiveness.

This company has development sites around the world. Engineers separated by large distances must work together on projects. CAE analysis tools have been configured to facilitate this situation, with effective product configuration and project management systems, making globally distributed development possible.

Support for CAE analysis is provided at two levels. At a central level, CAE strategy is set and libraries are developed for use across the company. At a local level, there are CAE champions, who encourage effective use of CAE in the engineering process, at a ratio of one for every five to eight engineers. Thus, a strong support structure has been created to facilitate the use of CAE analysis. In-house development of CAE tools in the company is restricted to those that are required but unavailable commercially, and those that bring a distinct competitive advantage to the company.

### *3.2.6 Analysis of cross-industry study*

A set of observations on the on the implementation of CAE in five different companies has been presented in the preceding subsections. From these, implications for the effective implementation of CAE analysis in product development can be drawn.

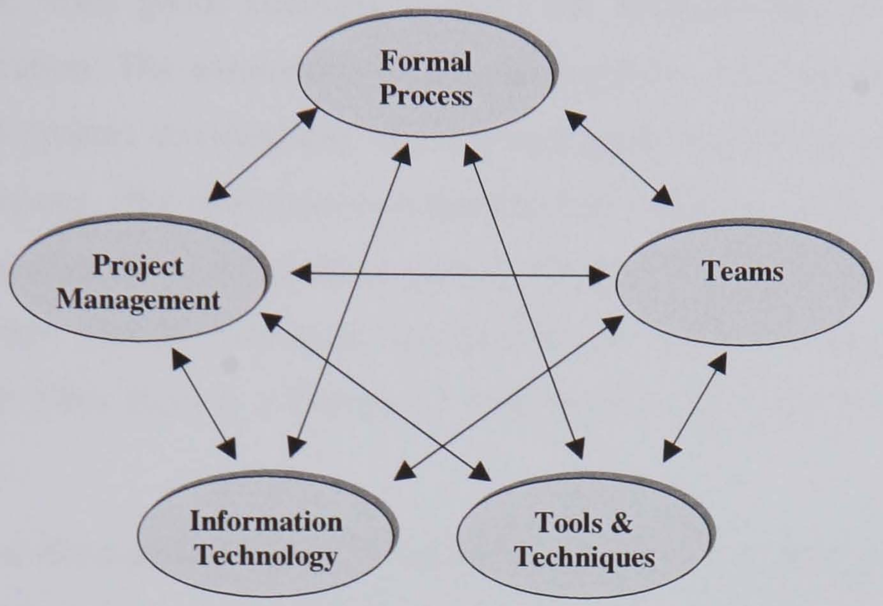

*Figure 3 – Organisational Factors that Affect Product Development*

Figure 3 shows that effective product development depends on a number of inter-related organisational factors [46]. An interaction between CAE analysis (part of 'Tools and Techniques') and the formal PDP must be defined. Reorganization of the formal PDP to facilitate optimum use of CAE analysis is an approach that has yielded excellent results for the automotive electronics company. A virtual realm definition of the functionality of complete products is developed at the outset of the PDP, from which requirements for subsystem design are cascaded. This has brought about radical reductions in time to market. The aerospace company makes extensive use of CAE analysis but it has not reorganised its formal PDP. Whilst quality is improved, time to market remains unchanged. Implications for effective implementation of CAE analysis are that, to obtain full benefit from the techniques, the formal PDP must be reorganised. Published literature indicates that Ford Motor Company has intertwined CAE analysis methods such as CASE, Behavioural Modelling, FEA and CFD into its formal PDP [47]. In fact, CAE analysis is leading the design process and company-wide policy is in place to ensure that an integrated CAE analysis approach is achieved [48]. CAE analysis should be used extensively at the outset of the formal PDP, where most cost and time can be saved. In the electronics industry, it has been shown that approximately 75% of manufacturing costs are determined by the engineering design and that two-thirds of design costs are committed early in the PDP [32].

An observation in the HGV transmissions company was that the potential benefits of CAE analysis are not realised because it is not included in local procedures. By contrast, experience from the white goods company shows that even very basic CAE analysis is effective and can reduce product lead-time when it is applied consistently at a local level. Only when it is integrated into departmental processes and coherently applied will CAE analysis be effective in reducing time to market, reducing cost, and improving quality.

A lesson from the white goods company is that CAE analysis must be appropriate in its fidelity and application. The automotive electronics company required tools that supported global, distributed product development, but this was quite unnecessary in the off-highway transmissions company. The importance of having CAE analysis tools that are geared to specific needs, user-friendly and that the engineers can trust is illustrated in the experience of these two companies. Careful validation will prevent the situation where engineers do not trust CAE analysis. Thus, there is a demand for both an effective global strategy and effective local application.

Another interaction illustrated in Figure 3 is between Tools & Techniques and Teams. Thus, there must be a connection between the application of CAE analysis and the structure of the organization. In both the aerospace and the automotive electronics companies, the centralised departments give a coherent strategic direction in the use of CAE analysis, provide training, develop library models, develop CAE tools in-house that offer a significant competitive advantage, etc. The central support departments maintain inter-operability between software and hardware, whilst allowing each department to adopt solutions appropriate for its situation. Knowledge must be effectively transferred from the central departments to local departments. In the case of the HGV transmissions company, the lack of coherence in the use of CAE analysis can be partly attributed to the lack of a central support department. The poor flow of knowledge from the research department into the product development areas highlights the need for local CAE champions, like those used in the automotive electronics company.

The automotive electronics company best illustrates the interaction between CAE analysis and Project Management. Engineers distributed around the world are now able to work on the same project, linked by software that simulates virtual co-presence. Appropriate software is an enabling technology that allows high levels of flexibility in the management of projects.

Most engineering products consist of a number of interacting subsystems. In the off-highway transmissions company, CAE analysis would be more effective if tools were available to simulate the interaction of different components in the transmissions to obtain an optimised solution. The aerospace company has addressed this issue by opting for an optimisation package that concurrently runs different CAE analysis tools on different platforms and obtains an optimised solution. The automotive electronics company uses script files to integrate different tools. A common communications protocol is another way to allow heterogeneous CAE analysis tools to become inter-operable [49] – it requires that all the tools selected have an interface to the protocol. Tools that can model interacting systems are a vital aspect of effective CAE analysis implementation.

Support structures for CAE analysis include hardware computing resources and PDM. The off-highway transmissions company has deliberately opted for flexible computing resources, providing every engineer with a workstation. Without the hardware resources, CAE analysis cannot be effectively implemented. The aerospace company leads the way in providing a carefully constructed PDM system. PDM must keep pace with and support the use of CAE analysis tools if they are to be effective.

### *3.3 Implementation of CAE in the Product Development Process: A Best Practice Model*

Findings from the cross-industry study have been translated into a 'Good Practice Model'. They are presented in this section as recommendations for the effective implementation of CAE analysis in product development.

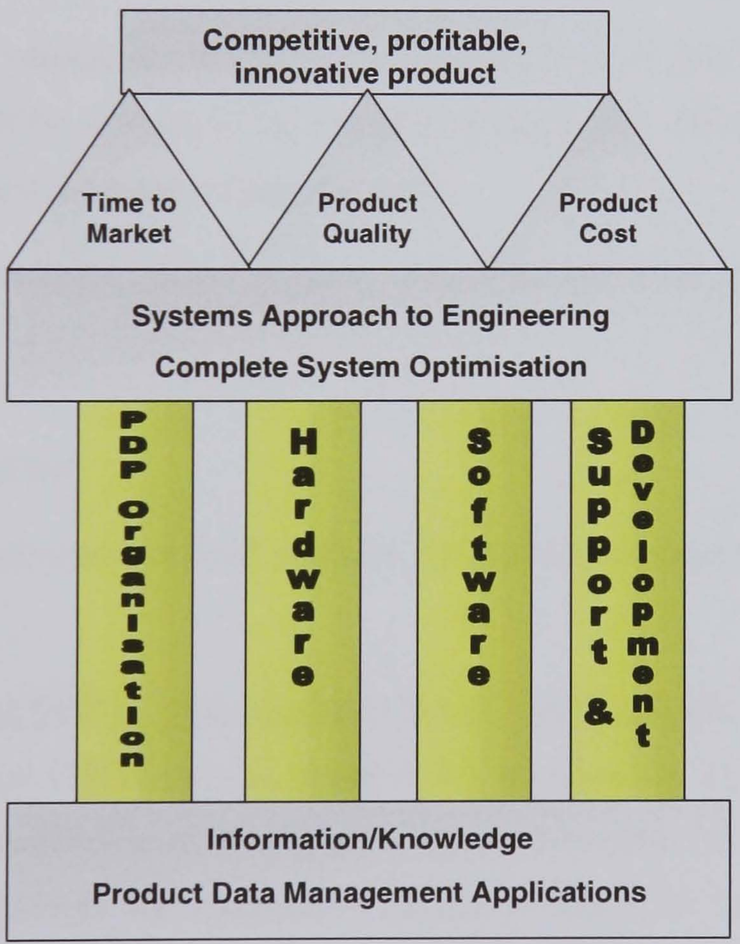

*Figure 4 – CAE Implementation Good Practice Model*

Figure 4 illustrates the model structure, which is in the form of a Greek temple. The model has five 'layers', each of which is supported by the layer below it. In Section 2, the market forces acting on motor manufacturers were described. Excellent products are required in order for a company to remain competitive. In this model, excellent products are described as 'competitive, profitable, innovative products'. Delivering products to the market of this nature is the top layer and the ultimate goal of product development. The next layer is 'time', 'quality' and 'cost'. Minimising time and cost whilst maximising quality is the means by which the first layer can be supported. The third layer is a 'systems approach to engineering' and 'complete systems optimisation'. This relevance of this layer arises from observations made about the aerospace and automotive electronics companies. They recognise that the complete system must be considered from the outset of engineering development (a systems approach). Traditionally, integration of a complex system was undertaken using physical prototypes, but time pressures mean that for many companies it is becoming unfeasible to make extensive use of physical prototyping [50].

Structured CAE analysis supports the first three layers described above. CAE analysis applications should support a systems approach [49], whereas traditionally they have been focused on the optimisation of individual components or subsystems. Four areas need to be addressed for effective CAE analysis implementation: the interaction with the formal PDP organization, hardware, software, and support and development. These form four pillars and the fourth layer of the model.

The fifth layer of the model, the foundation of the structure, is information, knowledge and PDM. An effective PDM system is an essential foundational element underpinning CAE analysis, but it is outside the scope of this portfolio.

In the following subsections, 'good practice' principles are recommended for each of the CAE analysis pillars.

### *3.3.1 PDP organization*

To maximise the effectiveness of CAE analysis, the techniques must be appropriately applied in the PDP.

Re-organise the formal PDP to allow optimum use of CAE analysis. As has been previously stated, reorganising the PDP makes it possible to capitalise on the full potential of CAE analysis [50]. In fact, implementation of CAE without addressing the organizational issues of PDP configuration will limit the competitive advantage that CAE analysis can deliver [51]. The nature of the rearrangements that are required depend on the particular company situation. The product should be engineered as a complete system from the outset of the process. To pass through each stage-gate in the PDP, a certain level of design fidelity should have been achieved [52]. It should be possible for the design to pass through the stage-gates even if aspects of it exist only in the virtual realm. The ultimate aim of CAE analysis is to develop products in the virtual realm and minimise physical prototyping.

Thoroughly integrate CAE tools into the PDP. Using CAE analysis methods in an optimum way requires that they feature in global and local company procedures. Specific methods should be written into company procedures.

Apply CAE analysis early in the PDP. It is far easier to effect change in the product at early stages in its development than at later stages [1]. Results from CAE analysis should be made available early in the PDP, when they are most useful in influencing engineering decisions and can assist in filtering out bad concepts.

### *3.3.2 Computer software*

A CAE analysis software architecture is required that will support a systems approach to engineering and complete systems optimisation. Software is critical in the integration of CAE analysis tools. It should allow analysis and simulation of each subsystem in physically separated locations and in different disciplines. Deploying an effective software architecture that will meet current and future needs is particularly important.

Software should model individual subsystems and form part of a complete, inter-operable system. A conflict exists between two requirements of CAE analysis software packages: (i) to perform complete systems optimisation, and (ii) to develop individual subsystems. Ideally, the same CAE analysis tools and models should be used for both requirements. At least, there should be an exchange of information between systems at the two levels. CAE analysis software packages must be coherent and inter-operable at the same time as offering the best-in-class performance in their primary application [50]. The preferred software package can be used for each application and they can be interfaced for complete system optimisation.

Software should support the global distribution of engineers. When companies have product development sites that are distributed around the globe, engineers on any site must have access to up-to-date product information and access to common CAE analysis software packages. Software must cater for heterogeneous and physically remote computing environments [49], enhance communications, and provide concurrent change management capability [53]. Software that facilitates remote visualisation for tracking designs is beneficial, for example, an intranet web browser for viewing the latest level of analysis results at a system or subsystem level.

Software should be of an appropriate level of sophistication. CAE analysis specialists require software with a high level of functionality, whereas periodic users need software that is easy to use. If there is a trade-off in software selection between packages that are user-friendly and those that focus on performance, the software that is most appropriate for the application should be selected.

Develop bespoke software only when it offers a significant competitive advantage. Bespoke software packages are developed for a unique application, often in source code such as FORTRAN or C++. If a tool supports a core competence, or if no appropriate tool is commercially available, in-house development is preferable.

### *3.3.3 Computing hardware*

Computing hardware, like software, should support a systems approach and complete system optimisation. Hardware is an enabling technology required to deliver CAE analysis. A hardware infrastructure is required that will facilitate globally distributed product development for multinational companies.

Establish an effective, high bandwidth network. Operations must be able to span computers, and two or more computers should be capable of running different programmes whilst interfacing with one another. Bandwidth is the key constraint on network speed, and so should be maximised [51]. Reliable communication across networks underpins a systems approach.

Use a flexible mixture of different types of computers for CAE analysis. Traditional supercomputers, scaleable parallel processor machines and workstations all have their place, and should be utilised in order to minimise analysis time. Although desktop processing has slower calculation times than centralised supercomputers, the total processing times can be faster because the resource is continuously available to the user. Parallel processing increases computing power and helps to support complete systems optimisation.

Install reliable and affordable servers for storing and retrieving data. Large volumes of data are generated during CAE analysis, including model data, simulation and analysis results data. Data storage facilities must be in place that will deal with this high level of demand.

Optimise the graphical capabilities of computers. Whilst an analysis or simulation is running, the engineer can be gainfully employed in another task. The only cost is the processing time of the computer. Pre- and post- processing, however, consumes both computer and engineers time, so should be as rapid as possible. This requires good graphical capabilities.

### *3.3.4 Support and development*

CAE analysis must be strategic at a global level and effective at a local level. Those developing models require specialist skills, and the entire engineering population requires general CAE analysis skills. A clear support and development structure at both global and local level is required to ensure that these requirements are met.

Establish a global, centralised support and development department. The primary task of a centralised support department is to ensure strategic, coherent application of software and hardware across the organization. Latest CAE analysis tools and techniques should be investigated and implemented. Technical specialists should be operating in the central support department to enhance and develop systems to meet customer needs. Developing and maintaining library models in a central support department enhances the effectiveness of CAE analysis since engineers can use validated models without investing the time in their development. The central support department should be a source of technical support for engineers using CAE analysis. Centralised training should be provided at three levels. Firstly, concepts of the systems approach must be communicated. Secondly, training in practices of inter-disciplinary working is necessary to support the systems approach. Thirdly, technical training in using CAE analysis tools and techniques is required.

Establish local, departmental support structures. At a local level, CAE analysis should be woven into the fabric of the organization. Local CAE analysis champions should be appointed within each department who ensure that the methods are thoroughly and appropriately integrated into departmental procedures. CAE champions have three tasks. Firstly, the champion implements the coherent global strategy at a local level, ensuring that CAE analysis tools used at a departmental level are part of the global strategy. The champion works with engineers to ensure that CAE analysis methods are applied with an appropriate level of fidelity, that they are applied consistently, and that results are validated. Secondly, the champion feeds local needs back to central support. Thirdly, the champion ensures that local training needs are met.

Engineers rather than analysts must be responsible for CAE analysis to encourage its integrated application. A change in the role definitions and performance metrics of engineers may be necessary to encourage this thinking.

## 3.4 Implementation of CAE in the Powertrain Product Development Process

A detailed investigation was conducted in which the use of CAE in the powertrain development process of a major automotive manufacturer was compared against the Best Practice Model. A number of gaps were identified between best practice and current practice. The most significant gaps that have been identified are described in the following list.

- There is no systems 'top-down' approach to product development to support an integrated systems approach to engineering. Most CAE analysis is focused on optimising individual subsystems rather than pursuing complete system optimisation. This is manifest in a limited and ad-hoc application of systems modelling and simulation techniques.

- Software is designed to analyse or simulate individual subsystems and does not form part of a complete, inter-operable system. There is no common simulation backplane to interface tools.
- In-house packages are often used or developed regardless of whether they contribute to competitive advantage or whether commercial packages are available that offer the required functionality.
- Support departments fail to ensure a coherent application of software and hardware across the organisation.
- Support departments do not develop library models for use by engineers.

At a local level, CAE is applied effectively in this company, although there is an excessive use of in-house tools. Gaps between best practice and current practice exist in the coherence of tools rather than in the tools themselves, and result in 'islands of CAE'. CAE techniques are used to solve specific problems during product development, but not as a driving force through the product development process. Action is required to improve coherence since it is essential for future competitiveness.

## 3.5 Conclusion

In this section, the application of CAE in powertrain development has been introduced, a study into the use of CAE in five companies has been presented, and best practice for the effective implementation of CAE has been derived. The critical advantages of CAE over traditional design methods are: reduced physical prototyping, improved understanding of the physical system, an increased number of design iterations and optimisation of the complete system.

Research into five companies yielded a number of observations about how they implement CAE analysis. By correlating the approaches of the companies to the effects on their product development, points of good practice in the structured application of CAE analysis have been derived. Aerospace and automotive electronics companies were found to be the most advanced in their application of CAE analysis. Useful lessons were also learnt from examining the use of CAE analysis in an off-highway transmissions company and an HGV transmissions company. Recommendations are presented in a 'good practice model', which has at its core four pillars: organization of the PDP, software requirements, hardware requirements, and support and development.

The formal PDP should be reorganised to cater for the effective use of CAE analysis. Practically, this requires the definition of products as complete systems in the virtual realm early in the PDP. CAE tools should be thoroughly integrated into the PDP. Integration of CAE into the product development process is critical if it is to reduce development time and cost, and improve product quality. The effectiveness of CAE is compromised if it is treated as an 'optional extra' to the standard development process. CAE provides a different basis from which to make engineering decisions during product development. Approaches to resolving engineering problems need to be fundamentally adjusted to make best use of the technique, and only when it is applied in conjunction with a fundamental change in the development process can it provide the required reduction in development time. Thus, CAE is a key technique that can be used in enhancing the product development process.

Software should be selected that can model individual subsystems and that forms part of a complete, inter-operable system. Supporting the global distribution of engineers requires appropriate software and there should be a balance of performance against user-friendliness. In specific circumstances, it may be appropriate to use software developed in-house.

Hardware that can support a systems approach and distributed working must be specified. This includes an effective, high bandwidth network that allows a flexible mixture of different types of computers to be used for CAE analysis. Reliable and affordable servers are essential for storing and retrieving data, and the computer graphical capabilities should be optimised.

Support and development of CAE should be strategically arranged at global (organization-wide) and local (departmental) levels. At a global level, the support structure should ensure coherent application of appropriate current software and hardware across the organization. At a local level, CAE champions should be appointed to ensure that local solutions fit within the strategic global framework.

The current practice in the powertrain department of a major automotive manufacturer has been compared with the best practice model. An important conclusion is that CAE is widely used, but in an ad-hoc manner that is focused on solving specific problems. There is a lack of a systems approach to powertrain development, and the associated systems modelling and simulation technique has not been widely deployed. CAE should be integrated into global and local processes to improve the coherence and effectiveness of its implementation.

In light of the gap between the current implementation of CAE in powertrain development and best practice, and the identified lack of a systems approach, the remaining work packages focus on the application of systems modelling and simulation in the product development process. A critical concern is the effective integration of this technique into the product development process.

# 4. Recommendations for the Application of Systems Modelling and Simulation in Powertrain Development

Systems modelling and simulation, one of the CAE techniques introduced in Section 3, was found to be under-utilised in the powertrain development process of a major automotive manufacturer. Systems modelling and simulation is the mathematical representation of a physical or electronic system for the purpose of predicting its behaviour. Close and Frederick [54] define both 'system' and 'mathematical model';

> *System:* a system is a collection of interacting elements with cause and effect relationships between the elements.
>
> *Mathematical Model:* a description of a system in mathematical terms. By creating a mathematical model, it is possible to solve the mathematical equations and simulate the system's behaviour.

Systems modelling and simulation can be applied to a wide range of product development tasks in powertrain development. Typical applications are:

- Performance, fuel economy and emissions prediction [55, 56, 57, 37]
- Driveability (driveline torsional analysis, response of vehicle to driver pedal inputs) [58, 59, 60]
- Powertrain controller calibration [61, 62]
- Controller strategy development (e.g. engine, transmission and driveline controller design) [63, 64, 65]
- Component development [66]
- Research and concept studies [67]

This section reports on the second Engineering Doctorate portfolio work package. A set of criteria for assessing systems modelling and simulation packages for powertrain applications is developed. A number of candidate packages are assessed against the criteria. Finally, a solution that is suitable for powertrain applications, in the form of a systems modelling and simulation architecture, is proposed.

## 4.1 Criteria for Assessing Systems Modelling and Simulation Packages

In order to make a fair and rigorous assessment of alternative systems modelling and simulation packages that are available on the market, a set of criteria that defines Powertrain requirements is required. This is especially true since different packages have widely varying design and operating concepts, which can make direct comparison difficult. The criteria must reflect not only current but also anticipated future powertrain applications for systems modelling and simulation.

Considering the typical applications of systems modelling and simulation in powertrain development in more detail, a selection of current and potential future powertrain systems modelling and simulation applications are as follows.

Performance, fuel economy and emissions prediction

Current: Vehicle acceleration times and maximum speeds. This includes diesel engines with turbochargers, which require the accurate modelling of the engine air path.

Vehicle drive cycle fuel economy. Again, engines with turbochargers must be considered.

Emissions predictions using steady-state emissions results.

Future: Improved fidelity of simulation models and accelerated execution speed.

Driveability

Current: Consistency of shift schedules.

Future: Assessment of shift quality, which requires a full dynamic model of the automatic transmission.

Simulation of torsional behaviour of driveline under a variety of vehicle operating conditions. Effects that are also of interest include all terrain vehicle behaviour.

Powertrain controller calibration

Current: Calibration of shift schedules, in particular optimisation of shift schedules for fuel economy and consistency.

Calibration of cruise control, which includes consideration of the resume rate and the functioning of the controller.

Calibration of petrol and diesel engines, which are becoming increasingly complex with the introduction of many new features (e.g. variable vane turbochargers and cylinder port deactivation).

Calibration of driveline components.

Future: Extensive use of simulation to dramatically reduce the level of vehicle testing. An increasing number of vehicle tests will be simulated.

### Controller strategy development

Current: Testing potential functional modifications to the engine controller strategy.

Verification of controller software and On-Board Diagnostics (OBD) using Real-Time Hardware-in-the-Loop techniques.

Define extreme vehicle system operating conditions for controller hazard analysis.

Future: Development of Real-Time Hardware-in-the-Loop capability to enable more extensive test-bench development of controllers.

Integrated control of powertrain and chassis subsystems.

### Component development

Current: Sizing of driveline components based on a calculation of their duty cycles using simulation models. Duty cycle information can be used as boundary conditions for distributed parameter simulation models.

Definition of transmission and final drive ratios.

Future: Definition of a wider range of powertrain components based on a combination of lumped and distributed parameter simulation.

Determining optimal torque converter characteristics.

### Research and concept studies

Current: Evaluation of alternative driveline concepts, such as mild hybrids.

Future: Principle method for assessing suitable concepts for future products.

Although this is not a comprehensive list of applications, it is presented to provide an impression of the diversity and complexity of powertrain tasks that are to be tackled using systems modelling and simulation. The set of criteria should be focused on these tasks to ensure that a suitable solution for powertrain development is devised.

Important sources when developing the criteria were published literature, private communications with systems modellers, and discussions with development engineers and team leaders. Different aspects of a package need to be assessed, namely, its mathematical or numerical basis; its interfaces with other software; the way in which it handles data; its user interface; powertrain components that might be available in a library; and controller design tools. These aspects are dealt with in turn in the following subsections.

### 4.1.1 *Mathematical Basis of the Package*

Jones [68] identifies that automotive powertrain modelling places significant demands on the mathematical capabilities of systems modelling and simulation tools. Powertrain systems are relatively stiff systems. For example, the frequency of driveline shuffle is in the region 1 to 10 Hz whereas the angular rotation of the engine can be up to 100 Hz. In addition, discrete events such as clutch engagement and disengagement cause discontinuities in the power flow to the driven wheels. The criteria in this section define the requirements for the mathematical capabilities of a systems modelling and simulation package (Figure 5).

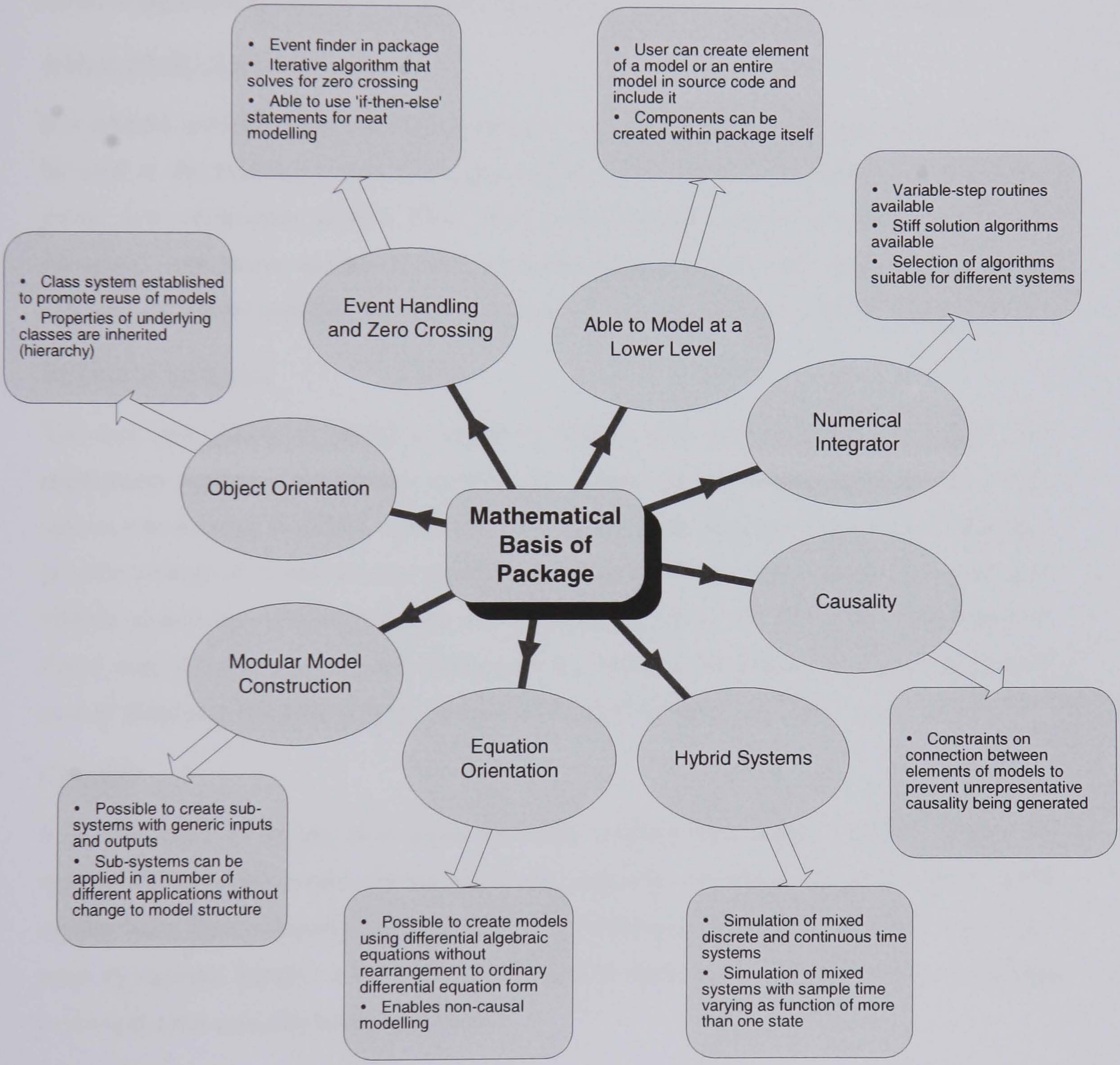

*Figure 5 - Mathematical Basis of Package Appraisal Criteria*

Event Handling and Zero Crossing

Powertrain systems are often variable state systems. Clutch engagement and disengagement is a primary cause of changes in state, and automotive powertrains often contain a number of clutches. System modelling and simulation tools should allow easy representation of such state events by the use of conditional statements or their equivalent. In addition, the numerical integrator should be equipped with an event finder to determine the time at which state events occur.

Zero-crossings can create instabilities or inaccuracies during simulation if the numerical integrator is not effective in identifying the time of their occurrence. For instance, if the exact time at which a backlash engagement occurs cannot be identified, the position of the element at the next time step may be simulated as being beyond its physical limit of travel. An iterative algorithm should be available to identify zero crossing points during simulation.

### Able to Model at a Lower Level

If a systems modelling and simulation package comes equipped with built-in models that can be used as the building blocks for larger models, it should also be possible for the user to create new component models. This implies that models created in source-code can be integrated into larger models in the simulation package. Sufficient basic built-in model elements should be available for the user to build up unique models for various applications.

### Numerical Integrator

The user may choose to model a variety of systems with different frequency ranges. The appropriate numerical integration method will depend on the unique characteristics of the system that is being modelled. Systems modelling and simulation packages should, therefore, provide a range of numerical integrators from which to choose. The complexities inherent in vehicle powertrain systems mean that no single type of solver will be suitable for all models. Fixed step, variable step and stiff integrators are required. Integration tolerances and, in the case of fixed step integrators, step size, should be modifiable by the user.

### Causality

It is important to ensure that cause-and-effect relationships within systems models are representative, which means that the governing equations of motion for each element of the system have been correctly rearranged and interconnections between elements have been properly defined. Ideally, some constraints would be built into a systems modelling package to prevent false causality being modelled.

### Hybrid Systems

There are times when continuous and discrete elements are combined in powertrain models, which requires a systems modelling and simulation package that can support hybrid systems. Hybrid systems occur in powertrain modelling whenever electronic controllers are modelled in conjunction with the physical plant.

### Equation Orientation

Rearrangement of the governing differential equations of a system into assignment statement form is required to create models using standard programming languages. Ideally, however, in a systems modelling and simulation package, models should be defined directly using differential algebraic equations without requiring their rearrangement into ordinary differential equation form. This saves modelling effort on the part of the user. Some form of mathematical solver is required in the package that will interpret, sort and translate the equations that are entered by the user. The simulation runtime of a model will be influenced by the efficiency of the code that is produced during this process, so efficient generated code is a further requirement of these criteria.

### Modular Model Construction

The ability to use model elements in a number of contexts reduces modelling effort by encouraging model reuse and enables the central management of models that are utilised by several different users. Self-contained models should be available as 'plug and play' blocks for the construction of larger models [69]. Modularity can be introduced by the users' approach to creating models. However, the systems modelling and simulation package should impose constraints on component interconnection laws to ease the adoption of a modular approach. For instance, a rotating flange should not be directly connected to an electrical resistor.

### Object Orientation

Object orientation is an approach to computer programming that uses a hierarchy of objects. A fundamental element of object code is called a class. Each instance inherits the properties of the class from which it was derived. Object orientation offers a more sophisticated approach to modular model construction, since some of the requirements for modularity are inherent in an object-oriented environment [70]. Ideally, the model creation environment in systems modelling and simulation packages should use object orientation.

### *4.1.2 Computational Basis*

The openness and flexibility of the package, in terms of its interface with the outside world, is the subject of these criteria (Figure 6).

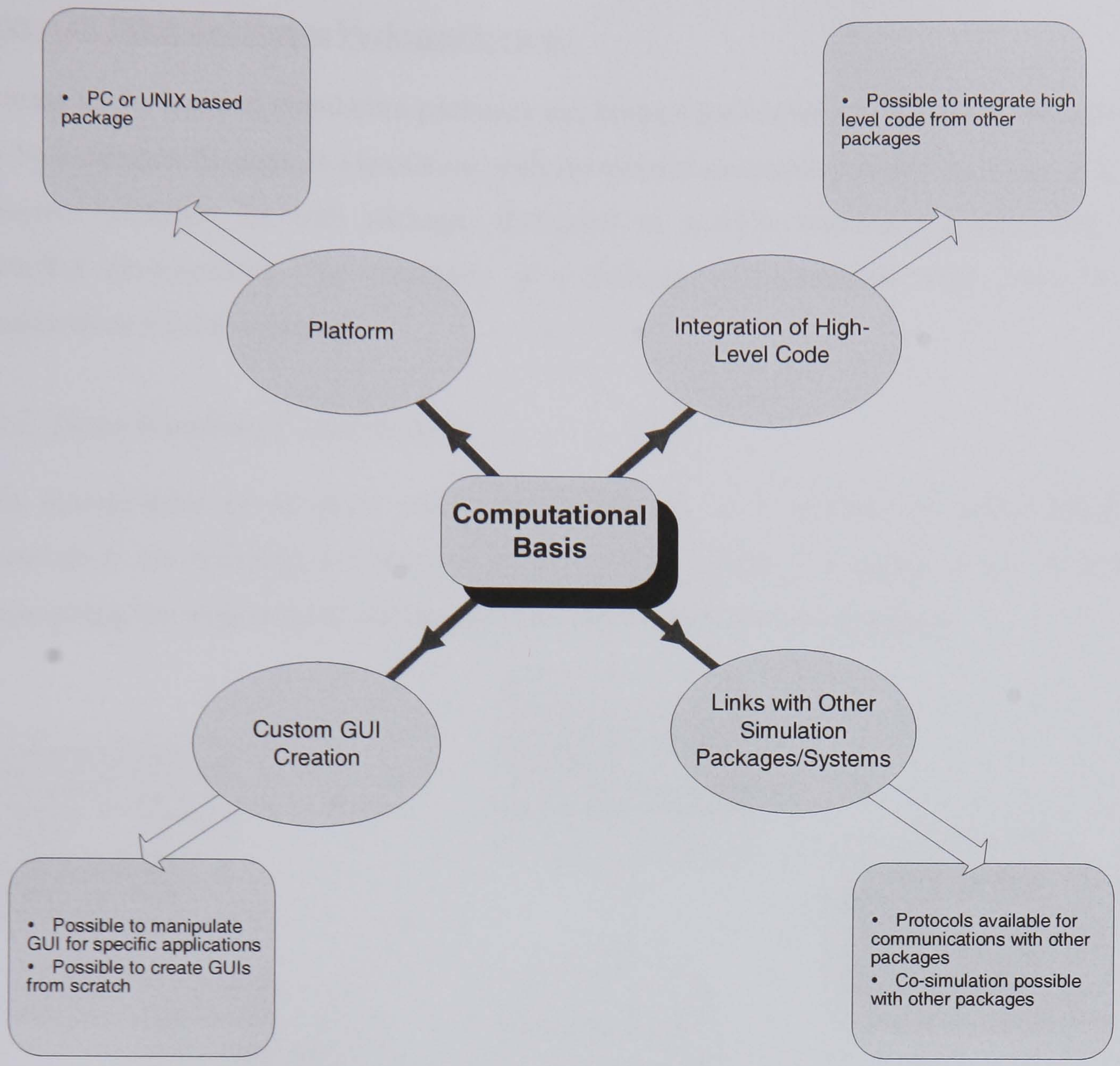

*Figure 6 - Computational Basis Assessment Criteria*

Platform

The operating system, or platform, is relevant since it can restrict the usefulness of a package. If the package only operates in Unix, then it would be difficult to run simulations on a laptop for in-vehicle calibration. The operating system that is most widely used is Windows 98/2000/NT.

Integration of High-Level Code

Integration of sections of legacy source code into a model may be necessary. For instance, legacy component models may be available in C or FORTRAN code, and in order for it to be incorporated into a new model, the systems modelling package must recognise the code.

Custom Graphical User Interface (GUI) Creation

A truly flexible package will facilitate the definition of custom user interfaces. This is particularly important if the end user of the model is not experienced in the specific systems modelling package in which the model was created. A GUI can protect underlying models from modification by users.

Links with Other Simulation Packages/Systems

Systems modelling and simulation packages use lumped parameter models. Simulation power can be extended through co-simulation with distributed parameter modelling tools, e.g. gas dynamics packages, or with packages dedicated to specific simulation applications, e.g. controller development. The capability of a package to co-simulate with others is the consideration for this criterion.

### *4.1.3 Data Handling Capabilities*

Data management is of great importance, especially if a number of users within an organisation are utilising a common set of models. Figure 7 contains a set of criteria summarising the requirements for the data handling capabilities of a package.

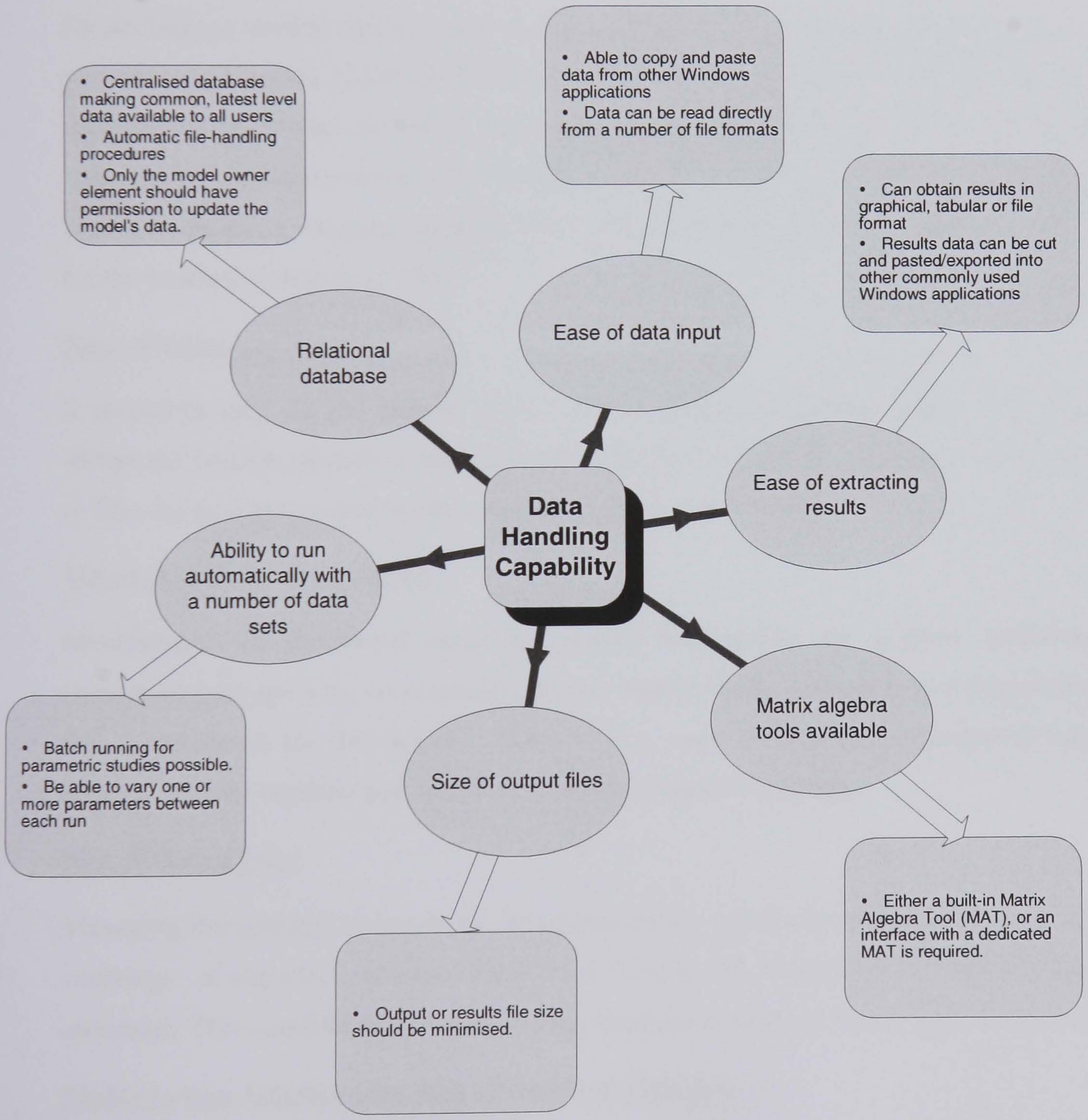

*Figure 7 - Data Handling Capabilities Assessment Criteria*

### Relational Database

Advanced data storage in the form of a complex database is not necessarily required as an integral part of a systems modelling and simulation package, but the interface between the package and a suitable data storage system is important. It should be possible to automate data handling procedures so that models can be automatically parameterised once a desired data set has been selected. In addition, data must be moved between computational packages in the computer aided design analysis environment of a company [64], and control must be maintained over levels of input and parameter data in the common models. This requirement takes on greater importance when models are used for routine tasks such as performance prediction.

### Ease of Data Input

Parameterising models can be a time-consuming aspect of the simulation process. In order to ease parameterisation of the model during development, it should be possible to copy and paste data directly into the model in the systems modelling and simulation package. More importantly, parameterisation of the model using various file formats should also be possible. This may require a scripting language within the package by which instructions can be given for the loading of data from files.

### Ease of Extracting Results

It should be easy for the user to access and manipulate simulation results. A plotting tool within the systems modelling and simulation package is required. The ability to export results to files for post-processing in other environments is also desirable.

### Matrix Algebra Tools Available

Manipulation of simulation input and results data within the systems modelling and simulation package may be necessary. Matrix algebra tools have an underlying architecture that is optimised for this purpose, along with a range of built-in mathematical functions. Ideally, a matrix algebra tool would be available within the package.

### Size of Output Files

Managing the quantity of data that is generated during simulation runs themselves is a further challenge – it can run to several Mbytes [71]. Ideally, the output file size would be kept to a minimum. This could be achieved by saving simulation results as binary files, for instance.

### Ability to Run Automatically with a Number of Data Sets

A common use of simulation models is to conduct parametric studies, in which a set of simulation runs is conducted to examine the effect of changing a single parameter. Changing a single parameter by hand when conducting parametric studies is very time consuming, so a batch processing function is required that will automatically update the parameter after each simulation run.

### *4.1.4 User Interface*

Jones et al [69] in 1984 identified *"a user friendly man-machine interface"* as one of the key requirements for a computer simulation facility that was under development. Today, 'Graphical User Interfaces' (GUIs) have become the standard method for controlling software packages, and this is an expectation of any systems modelling and simulation package that is reviewed (Figure 8).

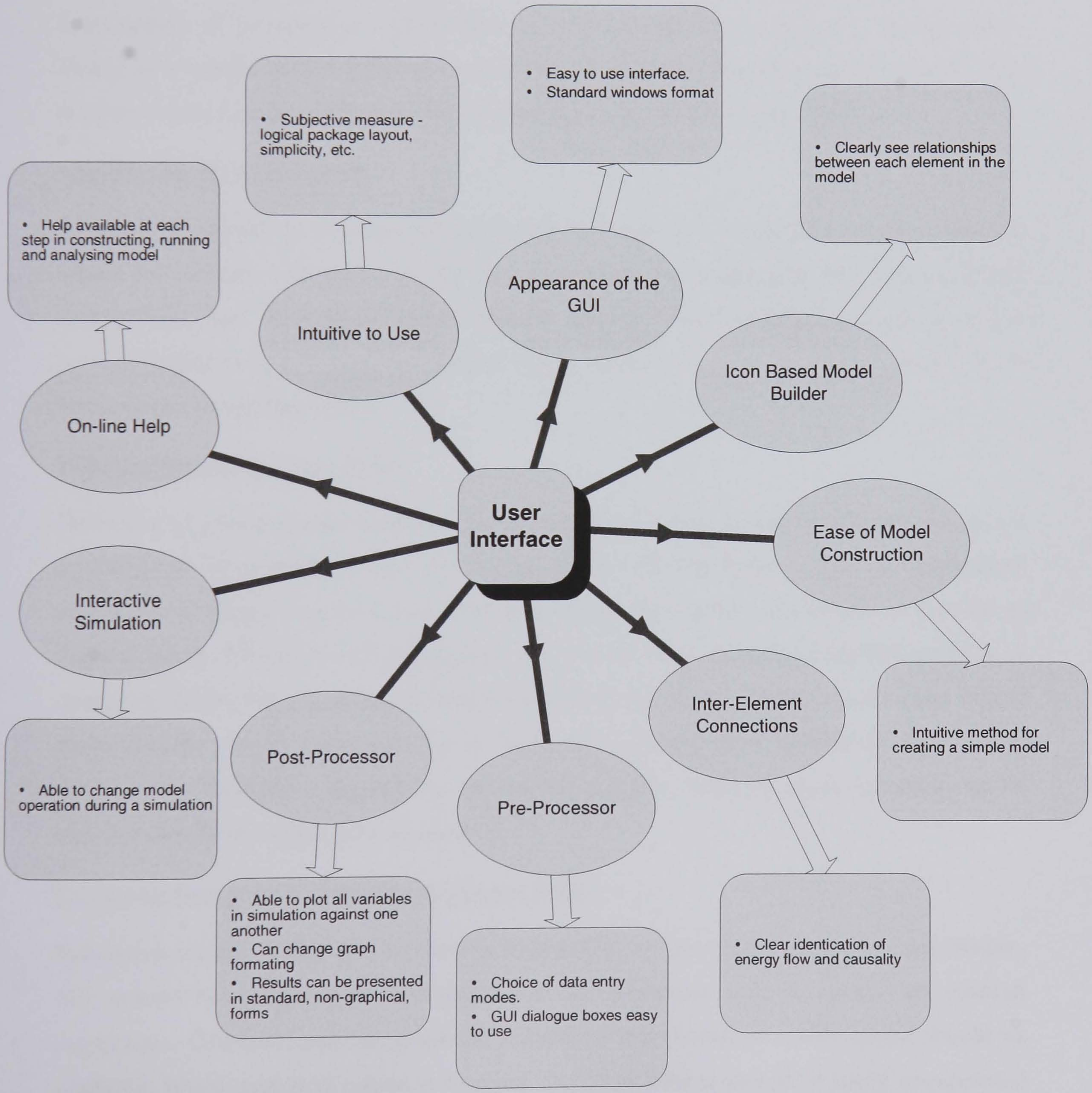

*Figure 8 - User Interface Assessment Criteria*

Functionality of the user interface is of vital importance. A systems modelling and simulation package that has a good level of mathematical and computational capability could be compromised if the user finds difficulty in utilising that capability. Four aspects of using a systems modelling and simulation package have been identified that relate to the ease of performing these functions. Criteria have been developed to appraise the performance of packages in each of the four aspects.

### Navigating around the Package

The 'Appearance of the GUI' should enable ease of use, which means that the familiar standard Windows® format should be adopted. The means by which functions are accessed should make the package 'Intuitive to Use'. This enables the user to utilise the full functionality of the package without having to learn contrived techniques. 'On-line Help' should be available at each stage in constructing, running and analysing models to ensure that the user is able to solve difficulties that are encountered whilst using the package.

### Constructing Systems Models

It should be possible to construct iconic models with ease and connections between elements should be intuitive and intelligent. These requirements are captured in the 'Ease of Model Construction' and 'Icon Based Model Builder' criteria. 'Inter-Element Connections' should be constrained in such a way that proper model causality is ensured and that energy flows between blocks are appropriate.

### Entering Parameters (Input Data)

Definition of models through parameterisation should be a smooth and flexible process, and it would ideally be possible to vary input variables while the simulation is running. This kind of interactive simulation can be useful when identifying the response of a system to specific or unusual inputs. The criteria for the package 'Pre-processor' is that there should be a choice of data entry modes. For example, data entry from a text file, from a database or by hand should all be possible. Where data is entered by hand, GUI dialogue boxes should be intuitive and easy to use. 'Interactive Simulation' should be possible, whereby input variables can be changed during the course of a simulation.

### Extracting the Results of Simulations (Output Data)

Simulation results should be presented in a form that is convenient and easy to manipulate. The criteria for the package 'Post-processor' are concerned with its results presentation capabilities. Graphical and non-graphical (tabular or text) forms of results output should be available. Where graphical output is required, the graph format should be easily manipulated and a free choice offered of which variables to plot. Exporting plots to graphical formats such as 'JPEG' and 'GIF' should be possible, so that they can be easily incorporated in presentations and reports.

### *4.1.5 Powertrain Library Components*

The criteria for specific powertrain models to operate in a Powertrain-in-Vehicle (PTIV) simulation environment have been developed in collaboration with colleagues (Figure 9)..

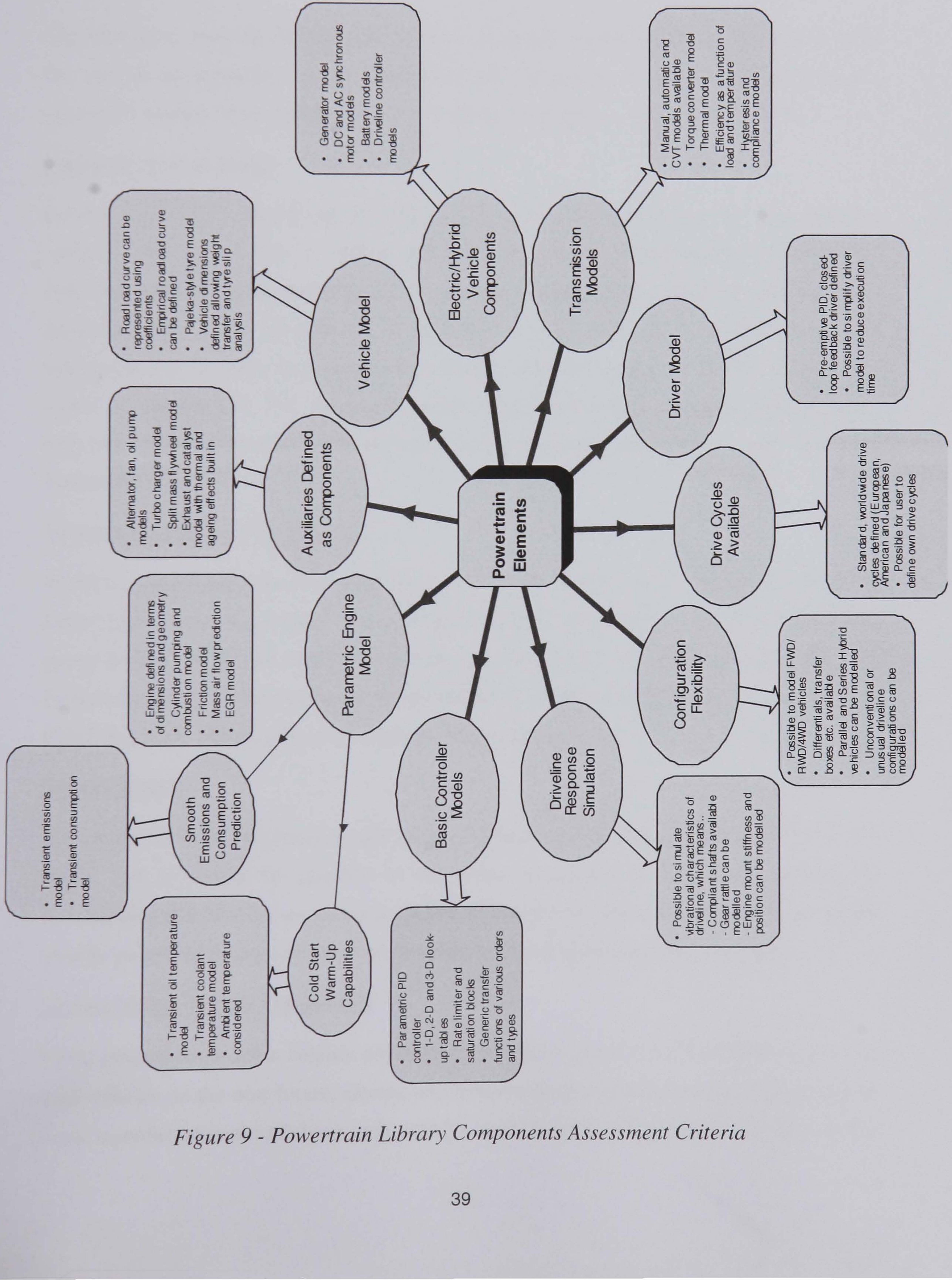

*Figure 9 - Powertrain Library Components Assessment Criteria*

When a systems modelling and simulation tool includes a powertrain component library, a comprehensive set of models should be available. Models of varying levels of fidelity should be provided for the same component where it is applicable. For instance, basic steady-state map-based engine models are acceptable for applications such as drive-cycle fuel economy prediction, and offer fast run-times [72]. For other applications, such as control algorithm development, a mean value engine model including the air path of the engine may be required [73].

Documentation showing the structure of each component model should be provided to give the user an understanding of the capabilities and limitations of each model. Summarised criteria for a range of powertrain elements, as shown in Figure 9, are described below.

### Parametric Engine Model

Internal combustion engines are the most common source of motive power in automotive vehicles. The engine has a critical influence on vehicle performance, fuel economy, emissions, and vehicle driveability [74]. An accurate engine model is therefore fundamentally important. For some applications, steady-state torque, fuel and emissions maps are appropriate but for other applications, for example in pre-development studies, a parametric model is required [73, 75]. An engine model should incorporate warm-up characteristics, since emissions and fuel economy are worse before the engine has reached its full operating temperature.

### Auxiliaries Defined as Components

Ancillary powertrain components can have a significant impact on the vehicle characteristics under certain operating regimes. Losses due to auxiliary components, such as the alternator, power steering pump, air conditioning pump, fan, oil pump, etc., should be modelled. The exhaust system could be considered as an auxiliary component that can have a considerable effect on vehicle performance, fuel economy and emissions.

### Vehicle Model

The vehicle itself is a relatively simple component to model. Road load must be defined in the model and it should be possible to use either a parametric model representing the aerodynamic and other losses, or use a coefficient based road load curve. Tyre slip and weight transfer modelling is required to define limiting accelerating and braking conditions.

### Electric/Hybrid Vehicle Components

While internal combustion engines are currently the most common form of motive power for road vehicles, in the near future, electric and hybrid vehicles will become far more common. Some manufacturers already have such vehicles on the market. Electric and hybrid powertrain components are therefore required to form a complete powertrain library. Examples would be models of electric motors and generators, batteries and Integrated Starter and Generator (ISG) systems.

### Transmission Models

Models for a range of transmission types should be available, including manual, automatic and continuously variable (CVT) transmissions. In the case of automatic transmissions and CVTs, some representation is required of the dynamics of the transmission during ratio changes. An ideal transmission controller is required to trigger ratio changes at appropriate times. The transmission model would preferably include a representation of its thermal characteristics so that efficiency can be represented as a function of load and temperature.

### Driver Model

If a forward dynamics powertrain model is used, a representation of the vehicle driver is required. The driver provides the throttle inputs that control the vehicle speed so that it follows the drive cycle profile. A realistic driver model will be pre-emptive and have closed-loop feedback.

### Drive Cycles

Prediction of vehicle fuel economy is undertaken by controlling the vehicle to follow a specified vehicle speed profile, or drive cycle. A set of commonly used drive cycles should be available in a powertrain model library.

### Configuration Flexibility

Constructing models of a variety of vehicle configurations, such as two-wheel or four-wheel drive should be straightforward. Changing the configuration of transfer boxes and differentials in the driveline is an important feature for all terrain vehicles such as Land Rovers. As mentioned above, diversification of powertrain configurations, including increased use of electric and hybrid powertrains, is an anticipated future trend [76, 77]. A powertrain component model library should facilitate configuration flexibility, so that both conventional and unusual powertrain configurations can be modelled.

### Driveline Response Model

Simulation of driveline response requires the modelling of compliant powertrain components, such as driveline half-shafts and engine mounts.

### Basic Controller Models

Library models are required for the creation of basic representative electronic controllers. Models that are necessary for the creation of such controllers include a PID controller that can be parameterised with different gain values for each element. Look-up tables, which are often used in automotive control systems, are necessary, along with a rate limiter and a saturation block. It should be possible to define transfer functions of different orders and types.

### *4.1.6 Additional Capabilities*

In addition to the four sets of criteria defined above, systems modelling and simulation packages are often used for the purpose of control algorithm development. Tools for the purpose of controller design, Hardware-in-the-Loop controller development, and rapid prototyping of controller code are desirable. Basic features that would be required for controller design are as follows.

#### Frequency and Root Locus Plots

The 'Classical' controller design tools of root locus and frequency plots should be available, since they are widely used.

#### System Identification

If a physical system cannot be fully mathematically described, system identification techniques can be applied to obtain a mathematical description of the system behaviour from empirical results. A package that is suitable for controller design should ideally feature system identification tools.

#### Optimisation

Development of control algorithms involves making trade-off decisions in order to optimise the most important characteristics of the system. Optimisation tools such as least-cost algorithms would ideally be available with a systems modelling and simulation package.

Hardware-in-the-Loop (HIL) simulation allows controller hardware to be incorporated into a real-time system simulation. HIL can contribute to reducing the number of prototypes that are required during controller development, providing accurate approximations to a final design solution [78]. Elements in a system that are difficult or impossible to model can be included in a HIL simulation as hardware. Alternatively, if there are critical components in the development process, they can be included as hardware without compromising accuracy by creating a mathematical model of the components. In order to run HIL using a systems modelling and simulation package, real-time running models using a fixed-step integration algorithm and providing real-time input and output of external signals must be possible. Usually, the systems modelling and simulation tool should be capable of generating the model as compiled code, which can be run using dedicated HIL equipment.

Rapid prototyping of electronic controllers by automatic code generation is an area of rapid growth for systems modelling and simulation tools [79]. When a controller model is available, rapid prototyping allows the generation of controller code, which can then be used either directly in its target environment, or as part of an HIL set-up.

Important criteria that systems modelling and simulation packages should meet in order to support HIL and rapid prototyping include the following.

Ease of HIL Facility

It should be possible to change parameters in the compiled controller model without having to recompile the controller model.

Automatic Production of Efficient Target Code

There should be an automatic process for compiling and linking models, creating the target controller code, and downloading the code to its intended target. The code that is produced should be the minimal length in order to save memory space in the target environment, but where source code is produced, it should be sufficiently commented to make it easily readable. Handling of functions that were utilised during the model-based design of controller algorithms should be efficiently reconstructed in the target code.

Target Hardware Flexibility

Code should be generated that can support a variety of targets. For instance, C-code may be required for dedicated HIL equipment, or machine code may be required if a control algorithm is to be loaded directly onto controller hardware.

## 4.2 Assessment of Systems Modelling and Simulation Packages

The merits and weaknesses of three selected systems modelling and simulation packages, EASY5/PDSL/EDSL, MATLAB/Simulink/Stateflow and Dynasim Dymola, are compared here. A systematic assessment of each package, based on the appraisal criteria presented in the preceding subsection has been undertaken in Engineering Doctorate Portfolio Submission Four. Key findings and a discussion on the appropriateness of each package to powertrain applications are the focus in this subsection.

Hands-on experience was gained with each of the simulation packages. With the objective of making a fair comparison of the approach and capabilities of each tool, a simple system incorporating a clutch was modelled as a benchmark problem. The clutch is a device that allows separation of the power source from the vehicle. It is essential for ratio changes with manual gearboxes. Introducing a clutch creates a discontinuity in the power flow, which tests the abilities of the packages to handle changes of state – a common feature in powertrain systems.

### *4.2.1 EASY5/PDSL/EDSL*

EASY5 is designed for mechanical, hydraulic and control systems modelling and simulation. It was developed from the outset specifically for modelling time-dependent, non-linear systems, and is based on the 1967 CSSL continuous systems simulation standard [80]. The CSSL standard, however, is not founded on modern object oriented computer programming techniques, which could cause limitations in the package. A significant advantage of EASY5 is the availability of the 'Powertrain Dynamic Systems Library' (PDSL) and 'Engine Dynamic Systems Library' (EDSL), two component libraries. Ideally, these should reduce the effort required to develop powertrain systems models. Some comments that can be made about the component libraries:

#### Limitations in Library Model Scope

It is evident from published work that the primary focus of PDSL/EDSL is dynamic studies in off-highway vehicle applications [40, 81]. This emphasis influences the models contained in the libraries, with the result that common road vehicle powertrain components are not readily available or require further development. For instance, the map-based engine model has no idle speed control. The orientation of the package towards dynamic analysis makes it well suited to driveability, component development and research and development studies. However, lower fidelity component models that are suitable when parametric data is limited are not available.

#### Modification of Library Models Not Possible

The PDSL/EDSL libraries have been created as EASY5 macros, precluding their modification by users. This approach guarantees model integrity, but prevents modification of unsatisfactory components. The Users Manuals give a good explanation of the structure and operation of each component.

#### Detailed Parameterisation Data is Required

Most of the library components are defined parametrically, which offers greater model accuracy and flexibility and makes the tool useful for conducting design optimisation parametric studies. The level of data required to parameterise PDSL/EDSL components can, however, be problematic and make parameterisation tedious.

Its CSSL computing basis means that EASY5 is designed for non-linear dynamic systems and handles changes of state with ease. It is a causal, assignment-based modelling language, but

PDSL/EDSL components have been constructed so that it is not possible to connect them together incorrectly. The necessity to consider first principles and rearrange governing equations has thereby been eliminated, which makes the construction of models a simpler task.

The EASY5 GUI is relatively easy to use and allows intuitive, speedy model construction with icons that allow identification of each component. However, the EASY5 operating system is Unix, which means that the package can only run on a PC via an X-Windows Unix emulator, such as Hummingbird Exceed. Variable names are cryptic and component names are a maximum of two characters in length. Input text files that require a specific format, and output text files that are awkward to manipulate complicate data handling. HIL capability is provided by the Real-Time Toolkit, which generates C or FORTRAN code.

Bespoke GUI creation is not possible in EASY5. In addition, EASY5 models cannot be exported to other packages as compiled code. Each user would, therefore, be required to use EASY5 itself for whatever task he was seeking to perform. For many applications in powertrain, for instance performance prediction or calibration, it is inappropriate for engineers to use the basic modelling environment.

In summary, EASY5/PDSL/EDSL is optimised for dynamic powertrain studies on off-highway vehicles. Despite this, it seems to be competent and useful for all applications listed in the introduction, but with some disadvantages. Firstly, there are significant shortfalls in library models that are available, and they cannot be modified. Secondly, simulation models have to be run in the base model creation environment.

### *4.2.2 MATLAB®/Simulink®*

MATLAB/Simulink has several strengths in its approach to systems modelling and simulation. The Simulink model editor is simple and intuitive to use, and MATLAB offers a powerful data handling and post-processing environment. In powertrain simulation this is particularly important because large volumes of data are generated by, for example, obtaining time series results from a standard drive cycle. Simulink provides a variety of integration algorithms, including stiff and variable-step algorithms. Since powertrain systems are stiff and discontinuous, the availability of robust algorithms is important. Simulink can simulate hybrid systems where continuous and discrete systems are integrated, a situation that occurs when an electronic controller operates on physical plant. An additional element of Simulink is Stateflow, a finite state machine.

The MATLAB 'Handle Graphics' toolbox allows for the creation of an object-oriented Graphical User Interface. Handle Graphics offers a high level of functionality and flexibility and is a clear advantage of MATLAB. Specific user interfaces could be developed for each user of a library of powertrain models, tailored specifically to their needs. A tool used in performance prediction could be made to appear to be very different to one used for transmission calibration, whilst drawing on the same underlying powertrain models.

Simulink is well designed for control algorithm development. The causal approach to model construction suits controller design and the optimisation routines available in the additional MATLAB Nonlinear Control System Design and Optimisation Toolboxes assist in control algorithm development. The Real-Time Workshop facilitates the generation of compiled C Code that can be used in HIL studies. MATLAB/Simulink proves to be useful where plant and controller models are required in tandem, as is exemplified in the engine model created by Weeks and Moskwa [73].

MATLAB/Simulink has an extensive user base and its efficient data handling capabilities has encouraged the developers of over one hundred third party packages to create interfaces between their packages and MATLAB. Powertrain examples include incorporation of high-fidelity engines models through co-simulation with the Ricardo WAVE 1-D Gas Dynamics package, and incorporating high-fidelity driveline models through co-simulation with the ADAMS multi-body simulation package.

MATLAB/Simulink has weaknesses in four main areas.

### Poor Handling of State Events and Discontinuities

Switching between states is a limitation of Simulink. 'Enabled Subsystems' is a feature that enables switching between states, but switching between open and slipping states in a clutch model proved to be a clumsy solution. In particular, re-initialising the output speed of the clutch system after a change of state proved to be difficult. 'Stateflow', an additional tool in the MATLAB portfolio [82], can simplify defining the conditions under which a change of state should occur, but a problem remains with initialisation when switching between discrete sets of differential equations.

### Simulink Modelling Environment is Sub-Optimal

The method used to connect Simulink blocks has weaknesses. Connections are merely 'wires' that carry an undefined signal, allowing unconstrained connections of ports. Thus, there is no implicit protection against modelling errors. Additionally, Simulink provides no assistance in resolving issues of causality. Rubin et al [83] discuss an approach to introduce causality into Simulink modelling using modular component and subsystem models. The visual appearance of large models can be confusing due to an array of connectors carrying signals between blocks.

Simulink Models are Interpreted and not Compiled

Interpreted models have the advantage of quickly and easily modification without the need of re-compilation. Simulation runtimes will be slower than those of a compiled model, however, especially when iterative algorithms are specified, since they are executed on a line-by-line basis.

No Library of Powertrain Models is Available

The vendors of MATLAB/Simulink do not offer a comprehensive set of powertrain systems models. All models that are required must be modified or developed from scratch using basic Simulink Blocksets.

MATLAB/Simulink has an excellent level of functionality but the approach that must be taken to modelling continuous, physical powertrain systems is undesirable.

### *4.2.3 Dymola*

Dymola is a systems modelling and simulation tool that uses the Modelica Unified Modelling Language. Recognition that the CSSL language used outdated computing methods motivated the development of Modelica [84]. A number of academics and industrialists formed a working party to define the specification of the Modelica language [85]. Key objectives in the development of Modelica were to provide a language suitable for the modelling and simulation of large, multi-domain systems, and to capitalise on modern computing methods [86].

Modelica requires a translator, a compiler and a numerical engine for the execution of models. Dymola is a tool that performs these and additional functions. This assessment, therefore, is of the package Dymola, which inherently benefits from the features of its underlying language, Modelica.

Dymola adopts a concept to systems modelling and simulation that is distinct from either block diagram or assignment statement approaches. Cornerstones of the Dymola approach are: object-orientation, which allows inheritance of model properties; non-causal modelling, which allows modelling that is more representative of the true physical plant typology; and equation orientation, which eliminates the need to rearrange system governing equations into assignment statement form.

Object orientation means that, firstly, model classes can be defined so that each component knows which variables are associated with it. For example an electrical component will only expect inputs in the form of voltage and current, a rotational mechanical component will accept torque and speed inputs, etc. This facilitates in-built consistency checking. Secondly, models use a hierarchical structure, which means that when a new class is created based on an underlying class, the new class inherits all the properties of the underlying class. This object-oriented approach means that Modelica lends itself to model re-use and the building up of libraries [87]. Models can be created, compiled and distributed without revealing the model structure itself. They can be saved in either Simulink S-function form as self-contained Dymola blocks and re-used as sub-models in other models. This feature is extremely useful where powertrain models are to be used in a number of different applications.

Equation orientation allows models to be created using governing equations of the system in differential algebraic equation form, without rearrangement into block-diagram or assignment statement form. An automatic symbolic solver rearranges the equations into a suitable form for numerical integration on translation of the model. This feature simplifies the creation of models and hence reduces model development time.

Non-causal modelling means that, while being aware of issues surrounding cause and effect relationships within models, the modeller using Dymola does not need to concern himself with causality when connecting sub-models together. The limitation on the connection of sub-models is simply that any two 'cuts' that are joined together must carry the same variables. Incorrectly connected components will generate an error when the model is compiled. Advantages of non-causal modelling are that model robustness is improved, and that time should be saved during model creation since the modeller does not have to resolve causality issues.

On a practical level, the Dymola user interface is relatively intuitive and logical after initiation. For the novice, however, the modelling concepts upon which Dymola is founded can be difficult to grasp, especially for those familiar with the block-diagram approach used by Simulink [87]. The basic Dymola libraries contain relatively few powertrain components, although an optional Modelica Powertrain Library has been developed since the original assessment.

Dymola bridges the gap between lumped and distributed parameter modelling tools by allowing the definition of a co-ordinate system. Multi-Body Systems (MBS) models can be created, which could be used for enhanced vehicle driveability prediction.

Dymola is not appropriate for controller development. The non-causal approach to modelling means that the package attempts to interpret direct connections that the user makes. A causal approach has been introduced subsequently to this assessment, but it is not reviewed here. There are no controller design or optimisation tools in the package. It is possible to compile Dymola models into MATLAB executable (MEX) file format, and embed and run them in a Simulink model. This facilitates the use of MATLAB/Simulink controller design tools in combination with Dymola models. Another alternative is to produce Dymola simulation output in MATLAB binary format and capitalise on the data processing power of MATLAB.

In summary, Dymola offers a sophisticated approach to continuous systems modelling and simulation with the additional feature of MBS capability. It does not compare with MATLAB/Simulink in the breadth of its functionality, but Dymola models can be integrated into Simulink to combine the power of the two approaches.

### 4.3 An Architecture for Powertrain Systems Modelling and Simulation

From the assessment described in the previous subsection, it is evident that Dymola is the package that has, fundamentally, the most advanced structure for the majority of physical modelling applications. Modern computer methods are used to good effect in the package. EASY5 is also very competent as a systems modelling and simulation tool, but the underlying language is outdated. MATLAB/Simulink has excellent functionality, especially for controller design, with a wide range of toolboxes. However, its block-diagram approach to systems modelling and simulation has weaknesses.

None of the packages that were appraised meet all the criteria. Therefore, a modelling architecture was devised by the author together with colleagues, which combines the capabilities of a number of the packages by causing them to run in a unified manner, or in co-simulation. This architecture is illustrated in Figure 10. The core package is MATLAB/Simulink. Simulink is a modelling environment that allows the inclusion of models of different types using 'S-functions', blocks that can run compiled code. The same approach can be used for co-simulation where Simulink acts as the master and other packages can be included as slaves.

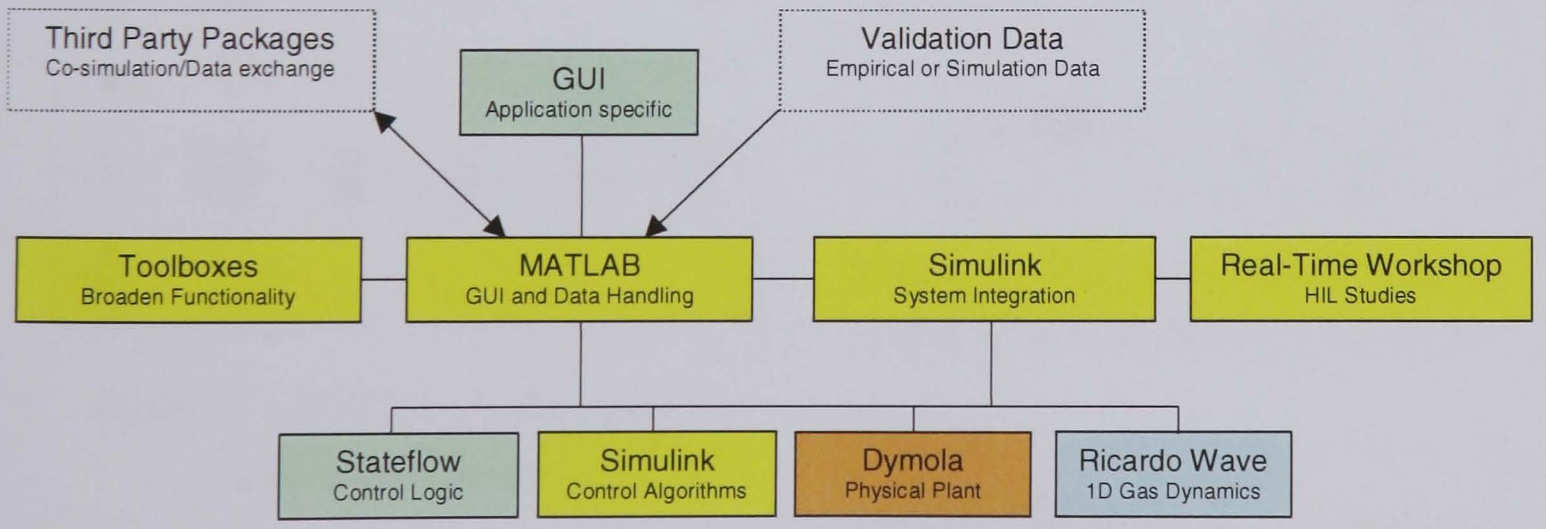

*Figure 10 – Proposed Architecture of Systems Modelling and Simulation Tool*

From Figure 10, it is evident that the architecture can be extended beyond the scope of the packages that were assessed in Section 4.2. 1-D Gas Dynamics can be integrated through a package such as Ricardo Wave or GT-Power. The architecture has Real-Time modelling capability through the Real-Time Workshop and access to the array of MATLAB toolboxes. Dymola and Stateflow are complied code included in Simulink as S-functions, and Wave co-simulates with Simulink. Simulink performs the integration on the compiled elements, whereas the co-simulation approach requires that, at every integration step, the Wave model is invoked and completes the corresponding simulation time-step using its own integrators.

On the basis of the assessment described in Section 4.2, the architecture in Figure 10 was devised. Having established a suitable architecture, a team was able to build a library of models in Dymola, Simulink and Stateflow, known as the 'PTIV Library', for application to the current and future powertrain requirements (Section 4.1). The Dymola aspects of the library consists of basic components, for example inertias and clutches, subsystem models, for example transmission and driveline models, and whole vehicle models, for example automatic and manual vehicles. Subsystem and whole vehicle components were constructed in varying levels of fidelity depending on the application of the model. Illustrations of the libraries are given in Figure 11 to Figure 13. The Simulink library consisted of drive cycle data, driver, engine control unit and transmission control unit models. In addition, a vehicle model was created that consists of a simple S-function containing a Dymola model with parameters, input and output variables formatted appropriately.

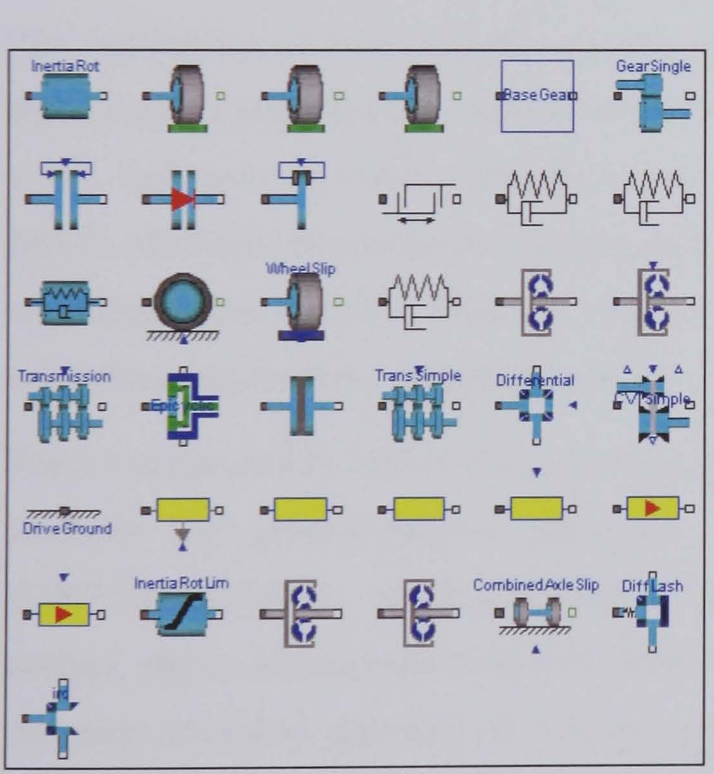

*Figure 11 – PTIV Dymola Rotational Components Library*

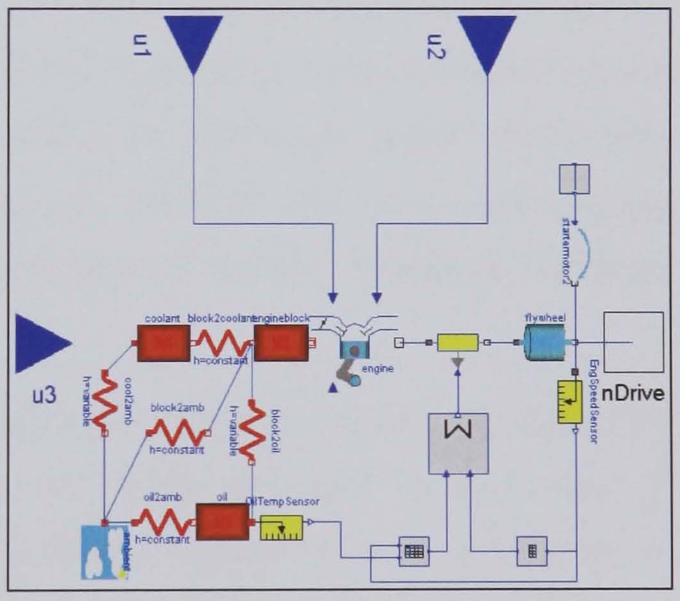

*Figure 12 – PTIV Dymola Basic Mapped Engine Model with Warm-Up Capability*

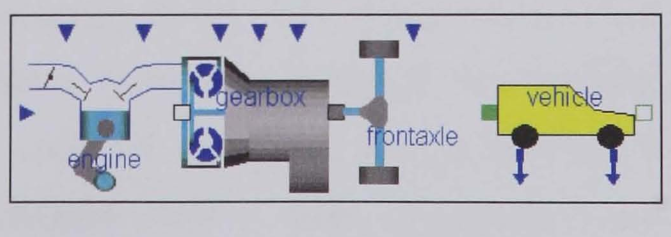

*Figure 13 – PTIV Dymola Whole Vehicle Model*

## 4.4 Conclusion

Taking a coherent approach to powertrain systems modelling and simulation maximises the benefits of modelling work that is undertaken. A range of powertrain design and development problems would benefit from the application of systems modelling and simulation. In order to tackle these areas of application in a coherent manner, ensuring that the particular requirements of each application are properly met, appropriate systems modelling and simulation packages are required.

In this section, a set of criteria for selecting a suitable systems modelling and simulation package were proposed. Seven categories of criteria were established, which addressed different aspects of package capabilities. The criteria were tailored to powertrain applications, but elements of these criteria might also apply to other automotive applications, such as chassis simulation. The more general criteria, such as 'mathematical basis', 'computational basis', 'data handling' and 'user interface' could even apply to non-automotive applications. Whilst these criteria are not completely comprehensive, they provide a standard by which systems modelling and simulation packages can be assessed for powertrain applications. This is believed to be new. Previously, packages had been selected using far less defined criteria.

The capabilities of three systems modelling and simulation packages were assessed against the criteria. Boeing EASY5 with Ricardo PDSL/EDSL represented a package based on the CSSL language convention with the benefit of a library of powertrain models. Mathworks MATLAB/Simulink represented an interpreted language simulation tool with a block diagram modelling environment. Dynasim Dymola represented a unified modelling language capitalising on modern computing techniques.

Three fundamentally different architectural approaches to systems modelling and simulation underpin the general-purpose packages. The 1967 CSSL Standard is the basis of EASY5/PDSL/EDSL. MATLAB/Simulink applies Matrix Algebra Tools to simulation. A unified, object-oriented approach that features non-causal modelling is used in Dymola, and is the most advanced approach. It is most appropriate to modern-day systems modelling and simulation requirements, including powertrain.

While Dymola offers the most advanced mathematical architecture, MATLAB/Simulink offers the greatest range of functionality. Examples include sophisticated data handling capabilities; GUI creation functions; a wide range of toolboxes; the possibility of incorporating compiled code in models; co-simulation with a range of packages; and advanced Real-Time functionality.

A conceptual architecture for systems modelling and simulation has been developed, which offers flexibility in its application. It capitalises on the advantages of Dymola, MATLAB/Simulink and other types of simulation software (e.g. 1-D Gas Dynamics) and allows them to work in an integrated manner. Naturally, the structure is continuously under review so that it can be updated and adjusted to keep track of current business requirements, but it is the basis of a robust, coherent and flexible approach for the future.

A library of powertrain models, called the 'PTIV Library' was created using the architecture defined in this section. The library models have been successfully used for a number of different powertrain applications to reduce the duplication of modelling effort. In Sections 5 and 6, two such applications of the models are reported.

# 5. Applying Systems Modelling and Simulation to Continuously Variable Transmission Calibration

The Continuously Variable Transmission (CVT) is an automotive powertrain component that is growing in importance in passenger cars [88]. The CVT is a proven alternative to manual or discrete ratio automatic transmissions. CVTs allow the selection of any gear ratio within a continuous range, potentially enabling the engine to maintain a near optimal operating condition whilst meeting the varying torque demand of the driver [89] .

A number of CVT variants are available on the market, as described in Engineering Doctorate Portfolio Submission Five. It is common for automotive manufacturers to purchase CVT units as a complete system from a supplier. The supplier is responsible for the design and development of the CVT unit itself, and the manufacturer is responsible for the integration of the system into vehicles. Calibration of the electronic controller is an important aspect of integrating electro-mechanical push-belt CVTs into a vehicle, but it is a process that is very reliant on physical prototypes.

This section reports on the third Engineering Doctorate Portfolio work package, the aim of which was to demonstrate the benefit of applying systems modelling and simulation to improving the calibration of CVTs. Particular benefit could be gained through the development of a simulation model that is capable of predicting the effect of CVT calibration changes on the vehicle response to specific driver inputs. Application of the simulation model should reduce dependence on physical prototypes and improve the calibration engineers' understanding of the system. This is the first example of applying the PTIV Library models that were described in Section 4, and contributes to the overall Engineering Doctorate Portfolio aim of demonstrating the benefit of applying systems modelling and simulation in a modified powertrain product development process

Current CVT technology is summarised in this section, as background information, including a description of push-belt CVT operation. The typical approach to CVT calibration is described and it is identified that applying systems modelling and simulation is a means by which CVT calibration can be enhanced. A systems model of a push-belt CVT is presented and some examples are given of how the model might be applied.

## 5.1 Current CVT Technology

In contrast to conventional, fixed gear transmissions, CVTs allow the setting of any ratio between a maximum and a minimum value. Using CVTs, it is possible to control the engine to run at its most efficient point, whilst providing the torque demanded by the driver. Hence, fuel economy improvements are possible over conventional discrete ratio automatic transmissions. CVTs are also lighter and less complex than their discrete ratio automatic counterparts. If they are well calibrated, they give very smooth progress without the discrete shifts of conventional automatics. For a general review of CVTs and their applications see Hendriks [90] or Chana [91].

### *5.1.1 Basic CVT Concepts*

At the heart of a CVT is its variator, which determines the transmission ratio. In addition to the variator, CVTs have a number of periphery systems: the hydraulic or electrical actuation system, an electronic control system, a lubrication/cooling oil system, and a start from rest clutch. A number of different types of CVT variator exist. Push-belt, chain-drive and traction-drive variators are three types that have automotive applications. Push-belt CVTs are described in most detail here, since this is the type of transmission used in this study.

Push-Belt CVTs

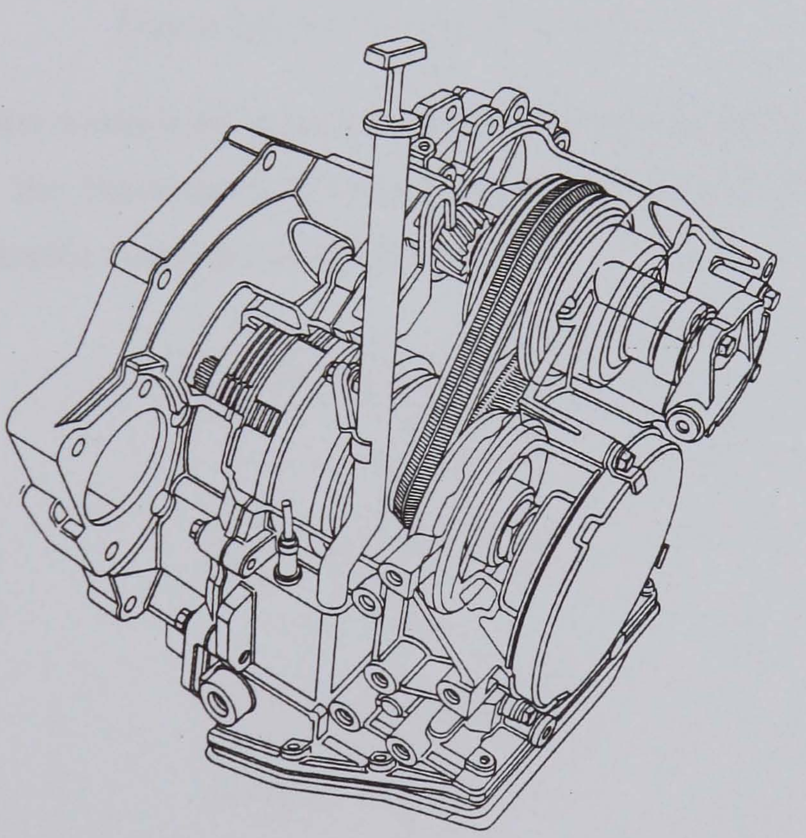

*Figure 14 – Cutaway Drawing of a Push-Belt CVT*

Push-belt CVTs transfer torque by means of a metal belt that runs between a primary and a secondary pulley. A push-belt CVT can be divided into four major components: the variator; the hydraulic unit; forward and reverse epicyclic gears and their clutches; and the electronic controller. The first three subsystems are mounted into a single casing, as shown in Figure 15 [92]. The movement of the sheaves is result of the balance of forces acing on them. On the back face of each moveable sheaf, a hydraulic cylinder applies a pressure, hence a force. When the force acting on the primary sheaf exceeds that acting on the secondary sheaf, the movable primary sheaf will slide towards its static counterpart, forcing the belt outwards Concurrently, the belt will be pulled deeper into the secondary pulley. The overall effect is that the input/output speed ratio will reduce, producing a shift in the ratio towards overdrive. Hendriks et al [90] give a more complete description of the functioning and application of a push-belt CVT variator.

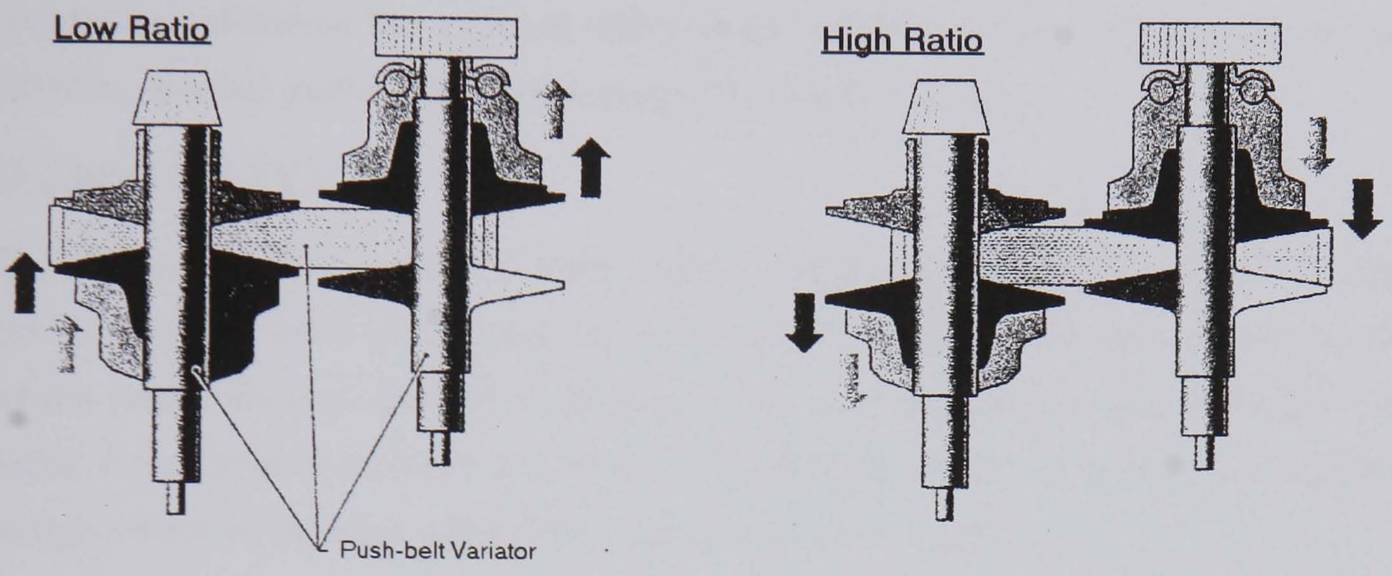

*Figure 15 – CVT Variator Operation*

The hydraulic controller controls the pressure acting on the primary and secondary sheaves. A brief explanation of the functioning of the hydraulic controller is given along with the description of the hydraulic controller model below.

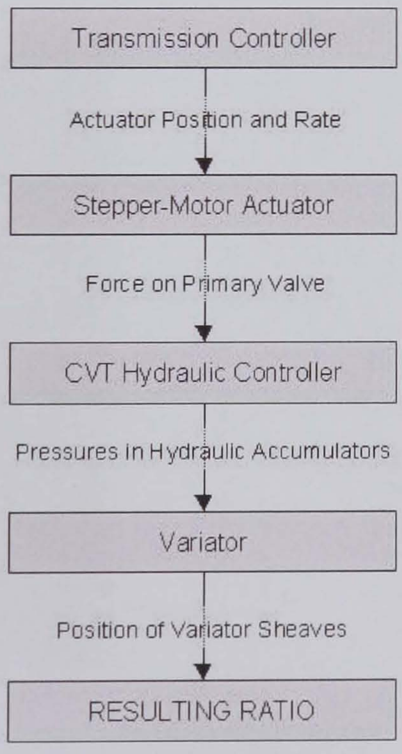

*Figure 16 – CVT Ratio-Setting Causality*

Electro-hydraulic control is a feature of the specific CVT that is the subject of this modelling exercise. An electronic closed-loop controller determines a target engine speed and implements a control action by means of a stepper motor. The stepper motor position defines a desired engine speed, and the transmission hydraulics cause the ratio to vary dynamically so that the desired ratio is produced. The causality of the CVT operation is illustrated in Figure 16.

The CVT calibration determines, firstly, the desired engine speed under any vehicle speed/load condition, and secondly, the rate of change in engine speed. Therefore, transmission calibration has a critical effect on the vehicle attributes of fuel economy and emissions, absolute performance, performance feel, and driveability.

PIV Chain Drive CVTs

PIV Chain Drive CVT operation is fundamentally similar to that of Push-Belt CVTs. A chain runs between moveable pulleys and the radius of the chain in the pulleys determines the variator ratio. Likewise, the pulley actuation system and electronic control system is very similar to that used in push-belt CVTs. The important difference is that drive is transmitted through tension in the chain rather than compression in a push-belt.

The construction of a chain drive belt illustrates the reason for this difference. The chain is made up of links that are joined together by pins, using the same principle as a bicycle chain. Therefore, it cannot support compressive loads but is designed to operate in tension. Figure 17 [92] and Figure 18 [93] illustrate the appearance of the chain and its construction respectively.

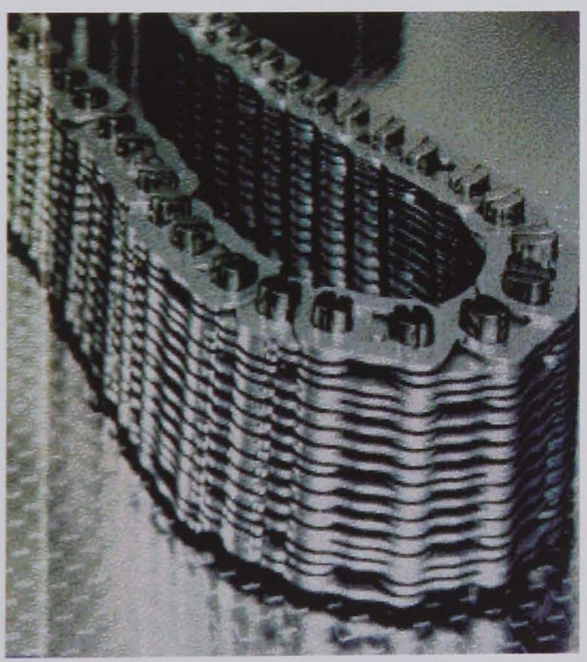

*Figure 17 –Chain Portion*

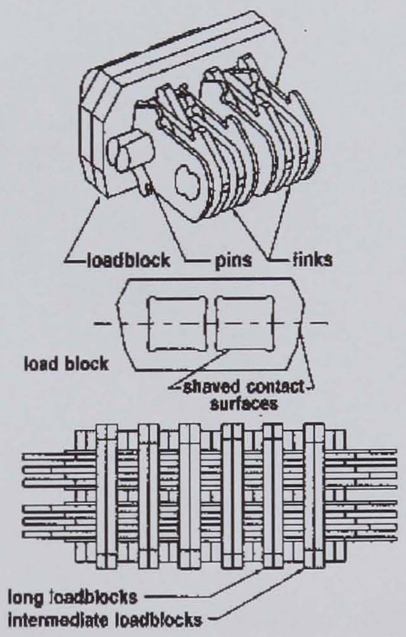

*Figure 18 – Chain Components*

Drive is transmitted from the pulleys to the chain by means of contact at both ends of the pins. Approximately fourteen links join each pair of pins. At any one time, in the LUK variator used in the Audi A6, only nine pins are in contact with the pulley halves at any moment in time [92]. This gives rise to very high contact pressures and minimal slip. A ratio range of approximately 6.0 can be achieved with a chain-drive variator. Compared with push-belt variators, it is claimed that chain drives have a higher torque capacity in an equivalent installation space [92]. However, chain drive variators produce more noise than push-belt variators since the contact between the chain and pulleys is less continuous than that between the push-belt and pulleys. Compared with push-belts, there is less experience of applying chain-drive CVTs in automotive applications.

Toroidal (Traction Drive) CVTs

Traction Drives are the most basic form of transmitting power. A rubber wheel turning on tarmac driving a motor car is an elementary form of traction drive. This simple system does not, however, have any form of ratio adjustment. The most basic form of CVT is a traction drive, where one disk is perpendicular to another. The driving disk can move in and out from the centre of the driven disk thereby varying the speed ratio.

Traction drive is used in Toroidal CVT variators, which are named after the toroidal cavities in which steel rollers run to drive the transmission. The mechanism of power transmission is through the elastohydrodynamic fluid film established between hardened, metallic rolling bodies. Thus, a traction drive is distinct from both Push-Belt CVTs and PIV Chain Drive CVTs, since the mechanism in these transmissions uses static rather than rolling contact.

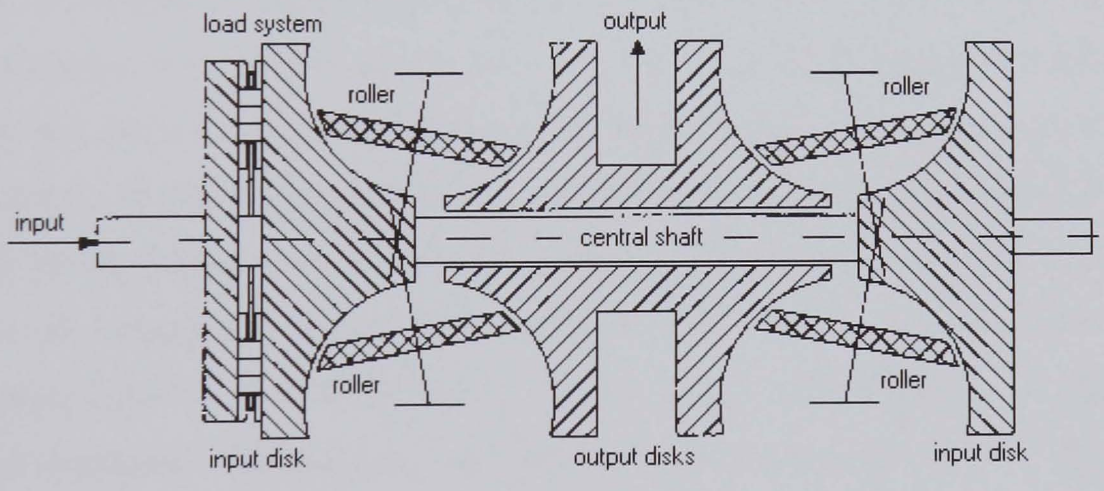

*Figure 19 – Design of a Toroidal Traction Variator*

A double toric variator is shown in cross section in Figure 19 [94]. Taking a single toric element, there are three rollers spaced at $120^{o}$ within the toroidal cavity. Each roller turns about its own axis. The diameter of the rollers is the same as the transverse diameter of the torus, and their centres are located at the pitch centre of the torus (in a full toroidal transmission). The ratio of the transmission is defined by the ratio of the radii between the central shaft centre line and the contact points of the roller on the input and output sides of the toroidal cavity. Therefore, adjusting the angle of the rollers changes the radii and hence the ratio of the transmission. The rollers are 'steered' during ratio changes, following a spiral course around the toroid. This allows smooth, rapid and efficient ratio changes and low power control inputs are required.

The torque capacity of the variator is defined by the clamping load exerted by the load system, multiplied by the contact friction coefficient between the roller and the toroid. Toroidal transmissions offer a large ratio range up to a value of approximately 9.0.

When compared with belt and pulley sheaf CVTs, or even conventional transmissions, toroidal transmissions offer significant advantages in many areas [95]. Most significantly, the large ratio range, high transmission efficiency and rapid ratio change rates. Rolling contact generates low noise emissions. Manufacturing operations are turning and grinding as opposed to gear cutting or manufacture and assembly of small elements. However, there are also some serious limitations associated with toroidal transmissions. Achieving very tight manufacturing tolerances for the components is difficult. Synchronising roller position is vital for efficient operation and accurate ratio control. This too is very difficult to achieve. If the friction contact moves from rolling to slipping, catastrophic failure can result. The limitations of toroidal drives have prevented them ever being successful in volume production for automotive applications.

### *5.1.2 Challenges in the Application of CVTs*

There are a number of theoretical benefits associated with using CVTs. Firstly, a CVT decouples engine and vehicle speeds allowing any valid combination of torque and engine speed that will deliver the required power at the wheels. Thus, the engine can be controlled to run at its most efficient operating point. As a result, vehicles equipped with a CVT should be capable of giving improved fuel economy over equivalent stepped ratio transmission vehicles. Secondly, ratio changes are undertaken seamlessly, which should improve vehicle driveability and passenger comfort. Thirdly, CVTs are simpler, lighter and require fewer components than equivalent automatic transmissions, and therefore the manufacturing cost should be lower. Unfortunately, these potential benefits have not yet been fully realised due to a number of limiting factors that are confronted when implementing CVTs in a vehicle.

Fuel economy proves to be, in general, slightly better than a standard automatic transmission but 5-10% worse than a manual transmission [88]. There are two main reasons why this is the case. Firstly, controlling a CVT so that the engine runs at its most efficient point tends to compromise emissions performance. Greatest efficiency is generally obtained when the engine operates at low engine speeds and high loads, but emissions, especially Nitrous Oxide ($NO_x$), tend to be poor under this condition. Therefore, a trade-off is required between optimising fuel economy and emissions, which results in sub-optimal vehicle fuel economy.

Secondly, torque losses in a CVT are much higher than in an equivalent manual transmission, which is the main cause of the CVT fuel economy penalty. Primary sources of torque loss are the oil pump, the variator, drag in the input shaft bearing and seal, oil churning in the wet-plate clutch, and inefficiencies in the final drive. Of these losses, oil pump losses and belt slip losses are the most significant in a push-belt CVT. Torque losses have the greatest effect under low load and low lubricant temperature conditions.

CVTs offer a smooth, stepless driving experience. However, a complaint of many drivers is that the response of the vehicle and the engine to a step change in throttle demand is unusual. Objectively, the vehicle performance may be equivalent to a discrete ratio automatic or a manual vehicle, but subjectively, the vehicle performance feels poor. The reason for this is that, to optimise fuel economy, the CVT adopts a high ratio when in cruise or overrun conditions. When the driver tips-in to accelerate, there may be insufficient surplus engine torque to provide the desired acceleration [96]. A ratio change is required, incurring an acceleration response delay time and giving the sensation of poor performance. The engine sound during an acceleration manoeuvre is also unusual. As the transmission ratio changes, the engine speed will rise relatively rapidly. However, this engine speed rise will not, initially, be associated with the expected level of acceleration. This can be disconcerting for drivers who are used to discrete ratio transmissions. Providing a smooth launch from rest is another weakness in those CVT vehicles that use automated clutches. At the point of engagement, the clutch may experience stick-slip that produces a high frequency judder. After engagement, torsional vibrations in the driveline can produce an acceleration spike or longitudinal oscillations. These effects are all highly unpleasant for the driver.

The cost of a CVT is higher than the cost of an equivalent conventional automatic transmission, mainly due to the economies of scale enjoyed by automatic transmissions. Torque capacity limitations of push-belt CVTs have mean that they have only been installed in cars with lower engine capacity (below 2 litres). Profit margins are narrower on smaller vehicles, and therefore they are more sensitive to the unit cost of components. It is important for the widespread acceptance of CVTs that they are able to match the cost of an equivalent automatic transmission.

### *5.1.3 Developments in CVT Technology*

In order to overcome the challenges in the application of CVTs that were described in the preceding paragraphs, various technologies are being employed by transmission suppliers as described in Engineering Doctorate Portfolio Submission Five. Developments are taking place in the areas of base transmission design, electronic control, CVT ratio range, launch from rest clutch control, belt technology, hydraulic system loss reduction technology and lubricating oil technology. Table 1 shows how each area of technological development is being used to tackle implementation challenges.

Base transmission design developments are helping to improve fuel economy and torque capacity. Increasing the stiffness of the transmission housing has improved variator and gear alignment and contributed to the reduction in losses, thus improving fuel economy [97]. Power-split CVTs divide the flow of power between a fixed helical gear and a CVT variator [98]. Power flow through the variator is reduced and increased capacity CVTs can be developed without up rating the variator. In addition, since the fixed gear is more efficient than the variator, the losses from the transmission as a whole are reduced.

Increasing the ratio range of a CVT allows a reduction in engine speed in cruising conditions whilst still providing the low ratio necessary for launch from rest gradeability. Lowering engine speed gives improved fuel economy and emissions during cruising. A ratio range increase can be facilitated by a stepped shift in addition to variator ratio control. Two-stage and '$i^2$' are two transmission configurations that can provide a ratio shift. Two-stage transmissions give a discernable shift between the two ranges [99]. The requirement for a change in variator ratio at the mode change point is avoided when using $i^2$ transmissions, and they offer slightly better fuel economy than two-stage transmissions at the price of greater bulkiness and cost [100].

Launch from rest driveability is being improved by using closed loop electronic clutch control [101]. With this system, clutch pressure is modulated to ensure that predetermined engine and transmission characteristics are followed. An additional benefit is that the clutch pressure can be modulated to reduce hydraulic losses when in light load conditions.

The variator drive belt is a critical component in the CVT. Improved belt technologies can help to improve fuel economy and system torque capacity [102]. CVTs with larger torque capacities can be fitted to larger vehicles with higher specification engines, in which the unit cost of the transmission is less significant.

A number of new technologies are being applied to improve CVT efficiency. A novel push-belt design being used by Japanese manufacturers eliminates the standard metal bands and uses a hybrid band of rubber and fibre construction [103]. Although the belt has a very low torque capacity, it is more than 95% efficient across most of its operating range, and is ideal for application in Japanese micro cars. More important efficiency savings can be obtained through improvements in CVT hydraulic control [104]. The clamping pressure on the variator belt can be reduced in some circumstances, reducing hydraulic losses. Variable flow hydraulic pumps have been introduced that enable a pressure loss reduction when lower flow rates are demanded by the transmission.

*Table 1 – Applying Technology to Tackle Push-Belt CVT Implementation Issues*

| | **Fuel Economy and Emissions** | **Driveability** | **Torque Capacity** | **Cost** |
|---|---|---|---|---|
| **Base Transmission Design** | Efficiency improved through transmission housing design changes | | Power-split CVTs allow larger torque capacity | |
| **Increased Ratio Range** | Allows lower engine speed at cruise conditions | | | |
| **Improved Clutch Control** | | Launch from rest smoothness | | |
| **Improved Belt Technologies** | Reduced cone angle allows reduced clamping loads hence lower losses | | Adjusting belt band volume and cone angle increases torque capacity | Higher torque capacity CVTs can be fitted to larger vehicles. Cost is less significant. |
| **Secondary Pressure Control** | Reduced losses under most operating conditions | | | |
| **Oil Pump Loss Reduction** | Variable flow rate pump reduces losses | | | |
| **Lubrication Oils** | Higher friction coefficient allows clamp force to be reduced | Improved clutch friction characteristic gives better launch from rest smoothness | Increased friction coefficient improves torque capacity | |
| **Electronic Control** | Integrated powertrain control used to optimise engine/transmission operating point | Driver features offered.<br>Response of powertrain can be controlled for driveability | | Features allows greater sales premium to be charged with minimal additional cost |

The lubricant is a critical component in a CVT [105]. There is generally a trade-off when designing a lubricant between obtaining optimal launch-from-rest clutch slip characteristics and minimal variator belt slip. Improvements in lubrication oil formulation have allowed the trade-off to be reduced so that both friction characteristics are enhanced. By increasing the friction coefficient between the sheaves and the belt in a variator, the torque capacity can be increased or the clamp loads reduced. Reducing clamp loads improves fuel economy. Thus, tribology developments are helping to address fuel economy, driveability and torque capacity issues in push-belt and chain-drive CVTs.

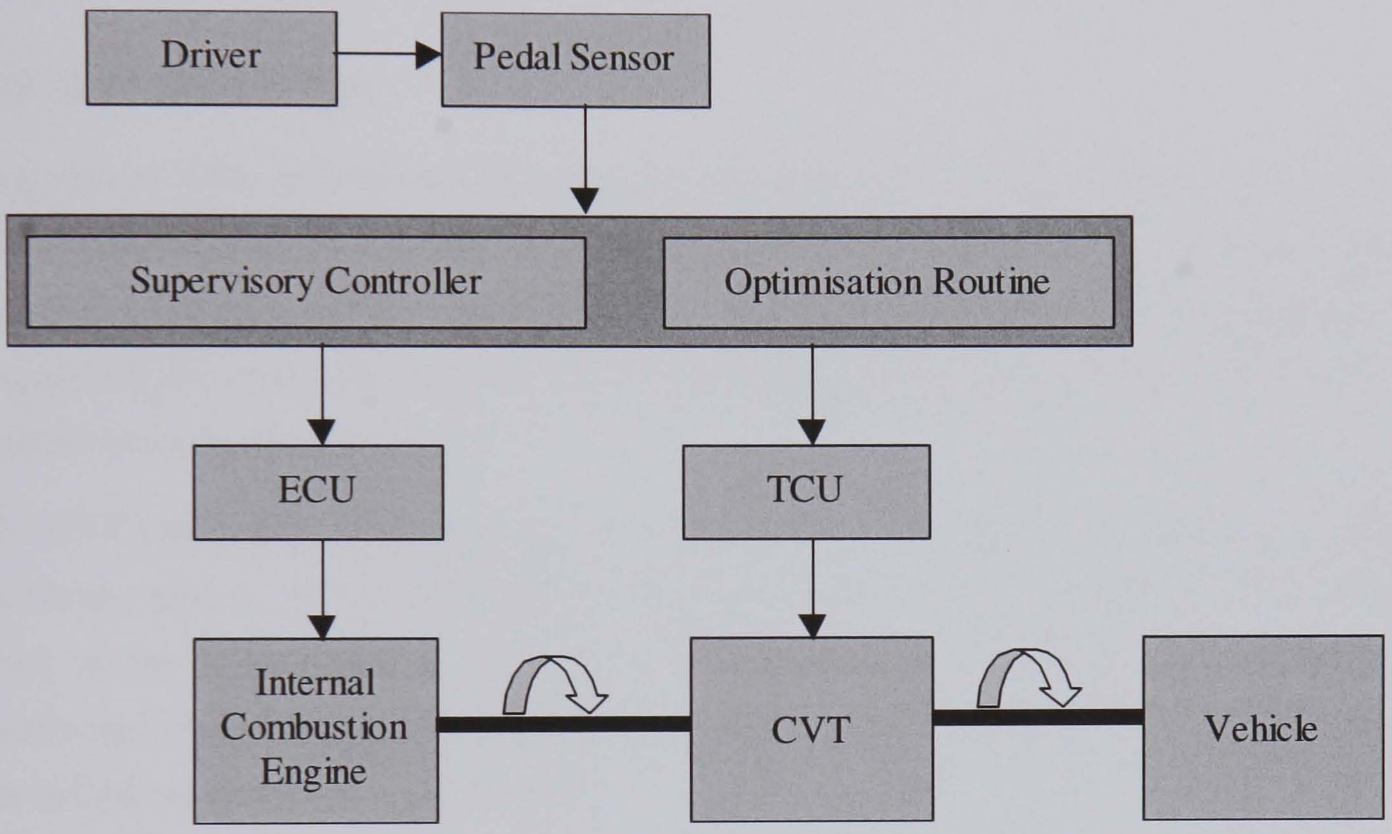

*Figure 20 – Basic Concept of Supervisory Controller*

Enhanced electronic control of CVTs can help to improve fuel economy [104], emissions and driveability. Torque losses can be reduced through more precise control of hydraulic clamping elements, and higher levels of functionality can be offered. There are different degrees of development in electronic CVT control. The push-belt electro-mechanical CVT that is used here employs a basic form of control. An electrical solenoid replaces a mechanical actuator to dictate desired engine speed. More sophisticated electronic control can be used to modulate belt and clutch clamping pressure when the transmission is under low load. Integrated powertrain control is a complete solution, which can be used to ensure that the engine and transmission operation is optimised for efficiency in real time whilst delivering the vehicle response that is desired by the driver. An integrated powertrain controller controls high-level engine and transmission functions as a single entity rather than two independent units. A feasible approach to implementing integrated powertrain control is to use a supervisory controller that has authority over the existing Engine Control Unit (ECU) and Transmission Control Unit (TCU). Figure 20 shows a schematic of an integrated powertrain controller [106]. The figure illustrates how the supervisory controller that includes an optimisation routine interprets the driver demand and translates it into specific instructions for the system controllers. All electronic controllers must be calibrated effectively in order to reap the benefit from their application.

In conclusion, improvements are taking place in a number of aspects of CVT technology. The outcome of these developments will be CVTs that are able to assist in improving vehicle fuel economy whilst offering pleasing driveability. Transmission torque capacity will increase, enabling CVTs to be fitted to a wider range of vehicles and reducing their cost sensitivity.

## *5.2 CVT Calibration*

One area of CVT technological development that offers the greatest potential for resolving limitations in the application of CVTs is electronic control and calibration. The transmission supplier undertakes control algorithm development, but the vehicle manufacturer is responsible for optimising the controller calibration, which determines the benefit that is realised from electronic control.

The CVT system that is the subject of this work, however, is equipped with relatively simple electronic control. As described above, in this system an electrical stepper motor exerts a force on the primary control valve in the hydraulic actuator, and its position determines steady-state engine speed. The movements of the electrical stepper motor are determined by the electro-mechanical CVT calibration.

### *5.2.1 A Typical Approach to CVT Calibration*

The most basic task during CVT calibration is setting steady state engine speed as a function of vehicle speed and throttle position. There are a number of modifiers that operate on the basic target engine speed. Each of these must also be calibrated. Examples of modifiers are a positive offset on engine speed if the vehicle senses that it is accelerating downhill, and minimum engine speeds when in sport mode. Setting engine speed ramp rate is the second important task in defining a transmission calibration, since it affects vehicle response. The third calibration task is to set gain values for a PI controller that compares target engine speed with actual engine speed and modifies the stepper motor position until they match.

A combination of track and chassis dynamometer vehicle testing has historically been the only mechanism for CVT calibration. Best-guess values for the steady-state engine speeds, ramp rate and the PI controller gain were set during an initial desktop exercise. Track and road testing was the mechanism for assessing vehicle behaviour and deciding on modifications to calibration parameters. Although the calibration parameters have a strong influence on vehicle attributes of fuel economy, emissions and driveability, primary emphasis was placed on subjective driveability and the optimisation of these and other vehicle attributes was not thoroughly tackled.

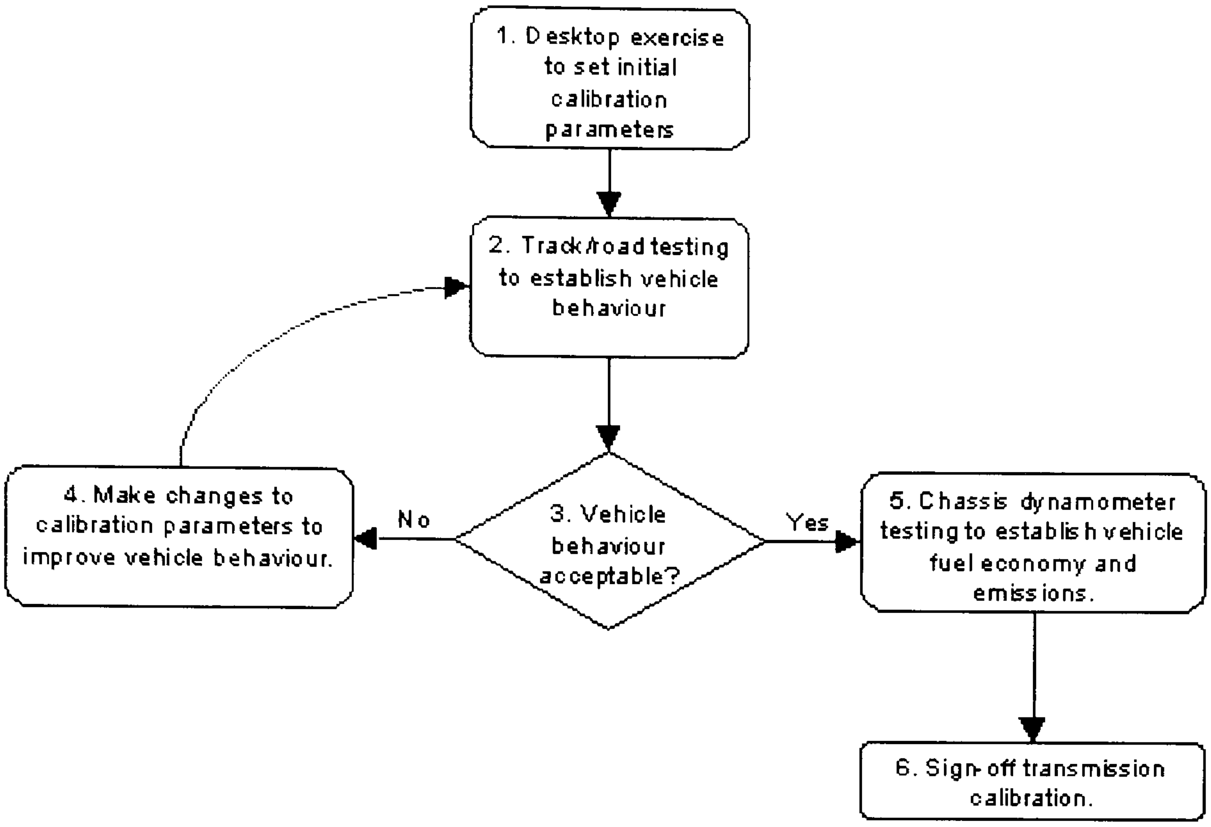

*Figure 21 – Simplified CVT Calibration Process*

Figure 21 shows a diagram of the simplified CVT calibration process. The diagram illustrates that emphasis is given to obtaining a calibration that gives acceptable on-road vehicle behaviour. There is an iterative process of testing and assessing the vehicle behaviour, and making changes to the calibration parameters (Steps 2-4). Once acceptable vehicle behaviour has been established, fuel economy testing is undertaken as a validation exercise before final calibration sign-off (Steps 5-6).

This typical approach to CVT calibration has clear weaknesses. Firstly, the experience of the calibration engineers is the only basis for setting initial calibration parameters (Step 1). This means a high reliance is placed on vehicle testing for optimisation of the calibration, an expensive and time-consuming approach. Secondly, a very detailed understanding of the system is required to make changes to calibration parameters that will improve specific aspects of vehicle behaviour (Step 4). This level of understanding only comes with experience of both the vehicle and the transmission calibration. Thirdly, when changes are made to calibration parameters, fuel economy tests are not generally performed alongside vehicle behaviour tests. To do so would add an unacceptable time delay in the assessment of calibration parameter changes. An alternative approach is required that will bring greater insight of the system, and enable the effect of changes in calibration parameters to be understood without requiring extensive vehicle testing.

### 5.2.2 *Enhancing CVT Calibration*

The following weaknesses were identified in the typical approach to CVT calibration:

(i) a lack of insight into the system behaviour when calibration parameters are initially set;

(ii) a limited understanding of the effect on the vehicle behaviour of specific changes to calibration parameters;

(iii) a dependence on vehicle prototypes throughout the process;

(iv) and no means by which to quickly identify the effect of changes in calibration parameters on vehicle fuel economy.

Powertrain controller calibration is an aspect of the vehicle development process that is generally on the critical path for product delivery. In Section 3, the potential for development time and cost reductions, and product quality improvement, through implementing CAE in the product development process was discussed. In Section 4, it was stated that powertrain calibration is an area in which one CAE technique, systems modelling and simulation, can be applied. Applying systems modelling and simulation to transmission calibration could, therefore, improve the efficiency of the CVT calibration process especially through improving system understanding and reducing dependence on vehicle prototypes.

A simulation model is required that represents these vehicle attributes, and that can be used by CVT calibration engineers at appropriate stages in the CVT calibration process. The scope of the model is that it must represent the entire vehicle system and especially the behaviour of the CVT in response to control inputs. Representation of higher frequency effects such as the detailed behaviour of the CVT hydraulic system, or the dynamics of the variator, are outside the model scope. It should be possible for calibration engineers to adjust the control parameters with ease, run simulations, and post-process the results for analysis.

Figure 22 shows how a simulation model with the scope defined in the previous paragraph may be implemented in the CVT calibration process. The grey boxes in this figure represent activities that depend on a simulation model. The initial calibration would be set using a simulation exercise before simulating the vehicle behaviour and fuel economy. A decision about the suitability of these vehicle attributes would determine whether further development iterations are required, or whether it is reasonable to proceed to vehicle testing. If the vehicle testing validates the simulation model results, the calibration could be signed off, otherwise the model could be recalibrated using experimental data and the process would be repeated.

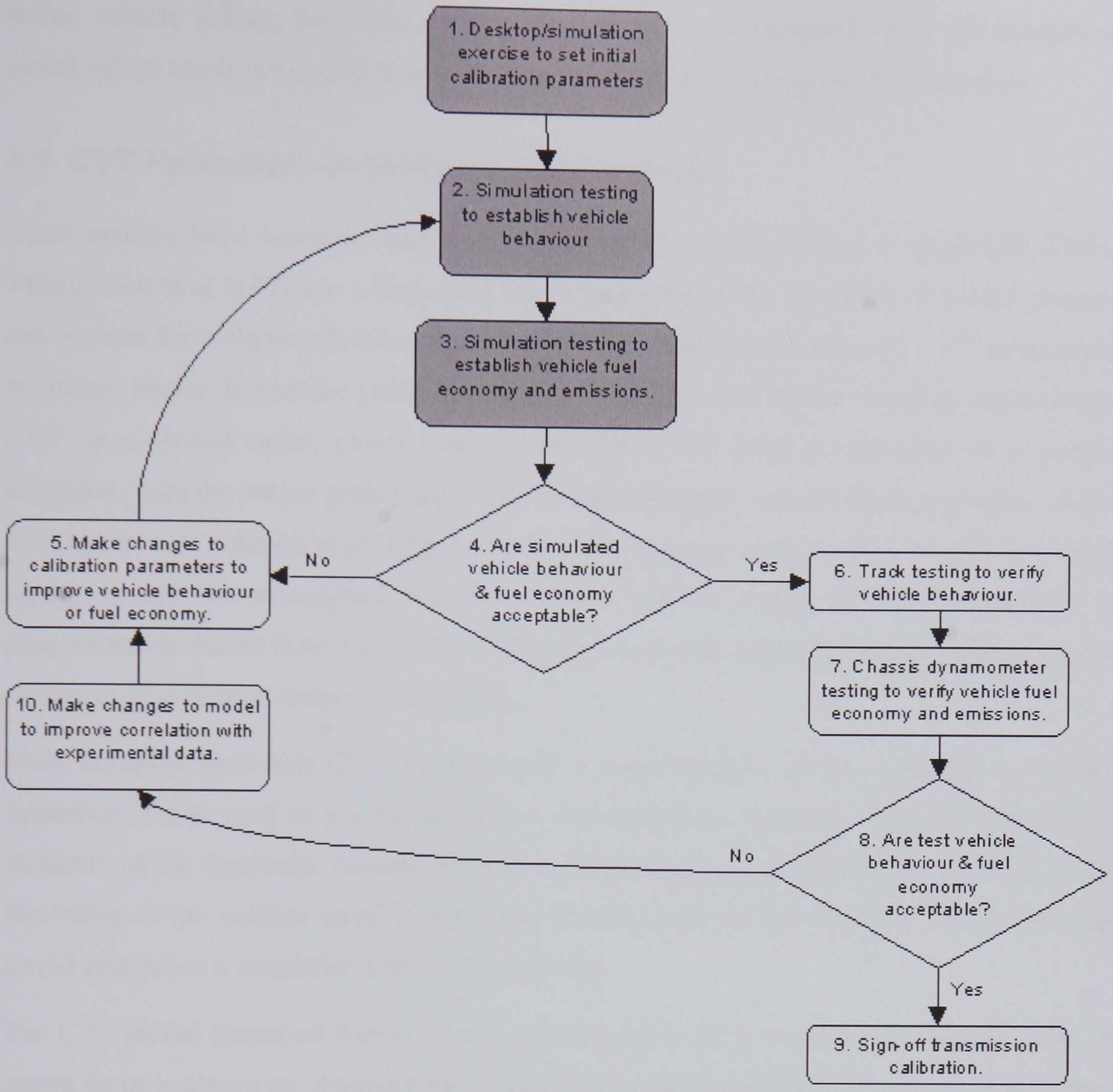

*Figure 22 – Modified CVT Calibration Process*

Comparing Figure 21 and Figure 22, it is evident that a number of changes would be required in the typical approach to CVT calibration to capitalise on the potential of systems modelling and simulation. In Figure 21, iterative loops that are used to refine the calibration parameters are conducted using physical prototype vehicles. In Figure 22, the same tests are conducted using the simulation model. Simulation tests take significantly less time than physical prototype tests, which allows the effect of a calibration change on vehicle response or drive cycle fuel economy to be assessed during the iterative process, rather than as a confirmation check. Trade-off decisions between fuel economy and vehicle behaviour can thus be intelligently made. In addition, a more detailed understanding of vehicle system behaviour can be derived from the simulation results than from equivalent experimental test results. Vehicle testing becomes oriented towards verification, which reduces the level of physical testing that is required. When further changes to the calibration parameters are required during vehicle testing, the effect of the changes can be investigated using the simulation model before implementing them in a prototype vehicle, thus saving physical test time.

### 5.3 CVT Powertrain-in-Vehicle Systems Model

Other authors have taken a variety of approaches to the modelling of push-belt CVTs. Vahabzedeh et al [107] use a first-order lag to approximate the dynamics of a ratio change, and account for a slight reduction in steady state ratio that occurs when the CVT load torque increases. Mayer & Shröder [108] describe the dynamics of a hybrid driveline containing a CVT as a second order, closed-loop system. The CVT itself is described as a simple integrator, with the output giving ratio. Rate of ratio change is implied by the dynamics of the driveline model. Schmidt et al [109] do not attempt to model the hydraulics of a CVT, instead opting to use the assumption that the relative rate of change of the transmission is proportional to the oil flow into the CVT chamber. A control signal defines the relative rate of change to give desired torque at the wheels.

More complex push-belt CVT models have a representation of the hydraulic controller dynamics. These tend to use mass-balance and continuity equations between the various elements of the hydraulic circuits but use a simplistic variator model [110], [111], [112]. Modelling of the variator itself is tackled by Deacon et al [113] who use a viscous belt slip model coupled to a simplified hydraulics controller.

The CVT model presented here is of a simple form, based on basic system identification. A strong focus is placed on obtaining the correct form of the identified CVT system. Robustness and speed of the plant model are of the essence for its intended application in the CVT calibration.

Figure 23 is a schematic of the complete vehicle powertrain system, including the engine, transmission, driveline and vehicle, and the engine and transmission controllers. These communicate on the same Control Area Network (CAN) Bus. The four mechanical elements – the engine, transmission, driveline and vehicle – could be considered as the 'plant' from a control perspective and are modelled in the Modelica language using Dymola. Components from the Dymola PTIV Library were utilised. Specifically, library models of the engine, vehicle and wheels were combined with new models of the transmission controller and variator. The new models were added into the PTIV Library so that they could be reused for future applications.

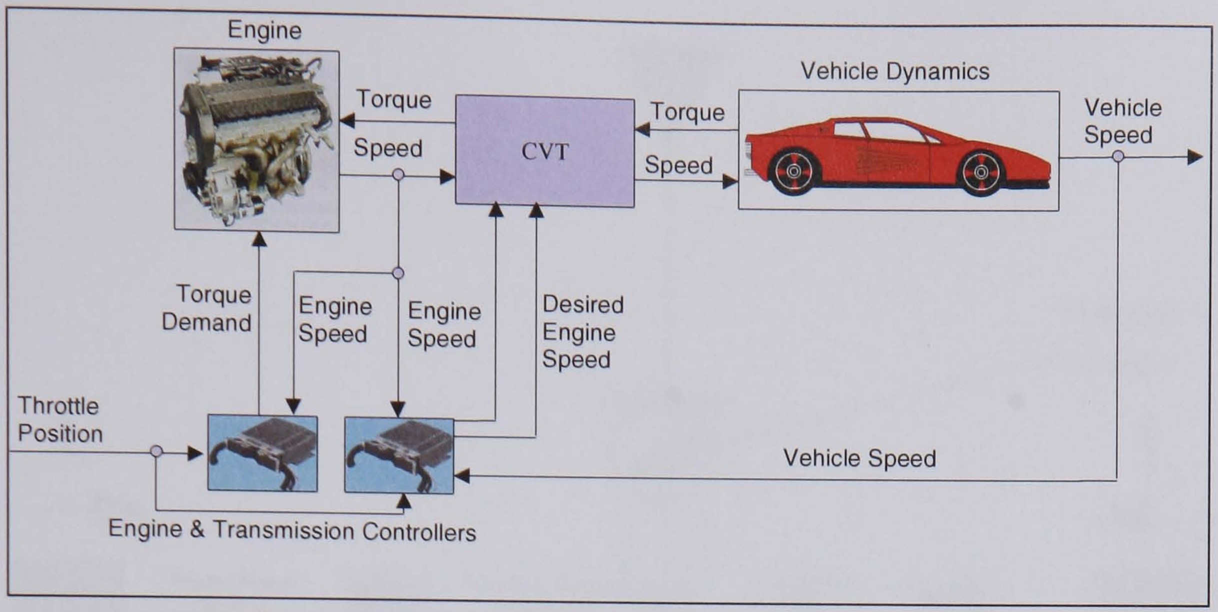

*Figure 23 – Complete Vehicle System*

An illustration of the complete vehicle model in Dymola is given in Figure 24. The controllers are modelled in the Simulink environment. This is in line with the approach to systems modelling and simulation that was outlined earlier.

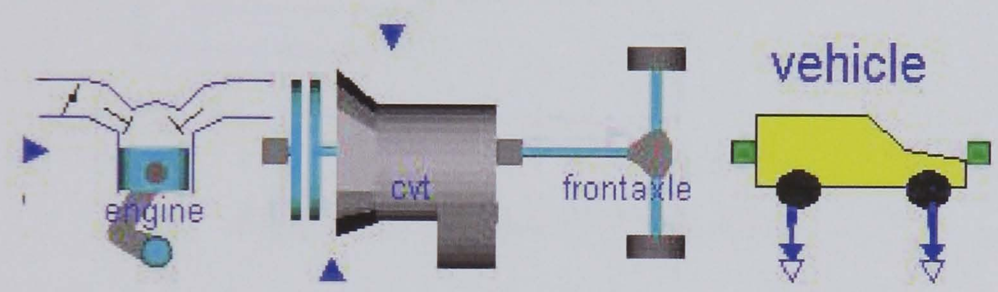

*Figure 24 – Dymola Vehicle Model*

Considering the CVT model in more detail (Figure 25), at either end of the transmission model are mechanical rotational connections. These provide rigid connections to the engine and driveline models respectively. Torque at the connection to the engine is represented in Figure 25 by $t_e$ and the rotational position of the engine is represented by $r_e$. Torque at the connection to the driveline is $t_d$ and position is $r_d$. The variator model is a simple variable ratio, the ratio itself being defined by the hydraulic controller. Upstream of the variator, there is a drive clutch and an inertia representing the input shaft and primary pulley shaft inertia. Power losses from the CVT, as a function of torque, speed and variator ratio, are drawn upstream of the variator. Downstream of the variator lies a final drive ratio, and an inertia representing the secondary pulley, gear and output shaft inertia. Control inputs into this model are, firstly, drive clutch position, and secondly, stepper motor position. The stepper motor position feeds directly into the hydraulic controller.

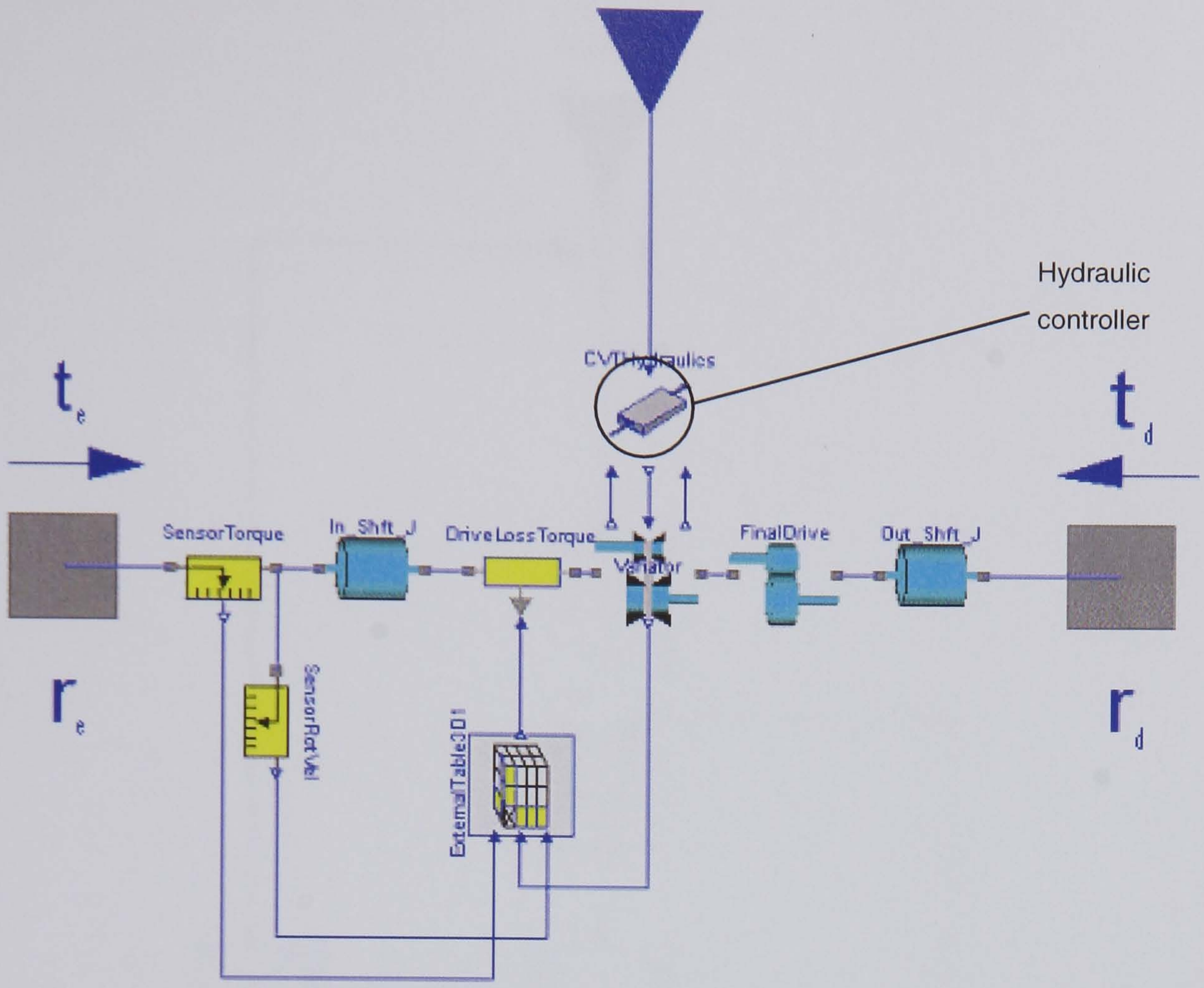

*Figure 25 – Dymola CVT Sub-Model*

As can be seen in Figure 25, the structure of the model reflects almost exactly the physical system that is being modelled. The behaviour of the model elements and their interconnection is highly intuitive, which is an advantage of modelling in Dymola.

The hydraulic controller governs the behaviour of the CVT. Since the operation of the hydraulic controller is complex, it was deemed unnecessary to create a full hydraulic model of the system for the purposes of calibration studies, as long as a good representation of the controller behaviour could be derived. Reasons for taking this approach are as follows. Firstly, it would be very time consuming to construct a full hydraulics model. Secondly, the run-time of a full model would be slower. Thirdly, basic parametric data and other system information that would be required for a full model was not available. Finally, facilities for conducting experimental testing in order to validate the model were unavailable. This reasoning highlights the importance of applying systems modelling and simulation in a way that is targeted to specific needs, and the fidelity of models should be geared to the actual requirements.

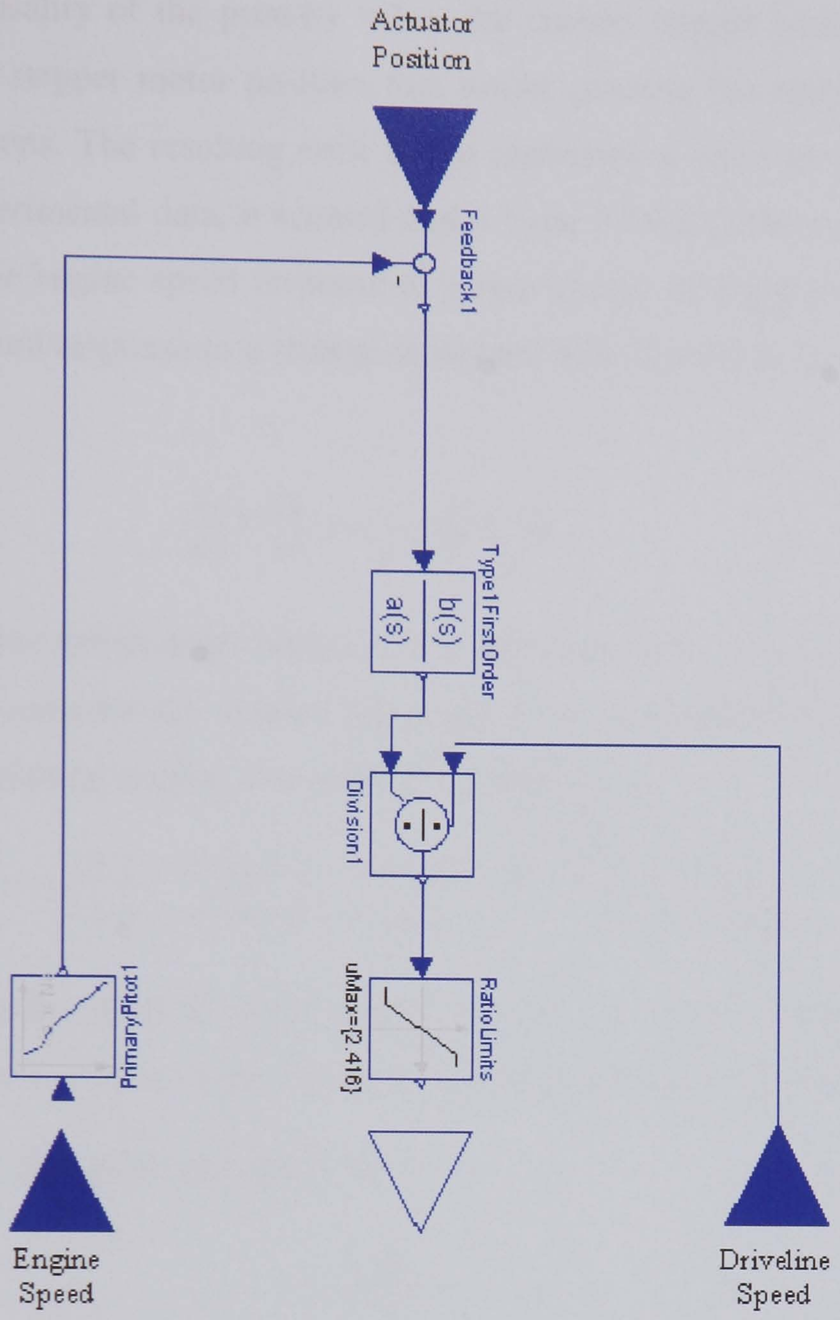

*Figure 26 – Dymola Hydraulic Controller Sub-Model*

A basic system identification exercise was undertaken to gain an improved understanding of the hydraulic controller behaviour. During in-vehicle testing, calibration equipment was used to control the stepper motor position directly, short-circuiting the transmission controller. Step and ramp changes in stepper motor position were performed, and the system response in terms of engine speed and transmission ratio was obtained. The structure of the hydraulic controller model was based on an understanding of the fundamental operation of the system.

A critical element in the hydraulic controller is the primary valve. The primary valve controls the pressures in the hydraulic accumulators, which in turn determines the force on the variator sheaves. On one side of the primary valve, the stepper motor applies a force by means of a spring. A force proportional to the current engine speed acts on the opposing side of the valve. Thus, the position of the primary valve depends on a comparison between stepper motor force and current engine speed.

To recreate the causality of the primary valve, the current stepper motor position must be compared with the stepper motor position that would generate the current engine speed in steady state conditions. The resulting error signal represents a valve position. From detailed analysis of the experimental data, it seemed that a Type 1 First Order response gave a good representation of the engine speed response to a step change in stepper motor position. The resulting engine speed response to a change in stepper motor position away from steady state is given by

$$\frac{d}{dt}\left(T\frac{d\omega_t}{dt}+\omega_t\right)=k\{e(t-\tau)\} \tag{5.1}$$

where $\omega_t$ is the engine speed target (rad/s), $\tau$ is a pure time lag (s), $k$ is a response gain and $T$ is a response time constant (s). Values for $k$ and $T$ are assumed to be constant and were derived from experimental testing. The error, $e$, is given by

$$e(t-\tau)=\begin{cases} X_a(t-\tau)-\{p\omega_e^2(t-\tau)+q\omega_e(t-\tau)+r\} & X_a > 75\,\text{steps} \\ X_a(t-\tau)-\{m\omega_e(t-\tau)+n\} & X_a \leq 75\,\text{steps} \end{cases} \tag{5.2}$$

where $X_a$ is the stepper motor position (steps), and $p$, $q$, $r$, $m$ and $n$ are coefficients of the relationship between $X_a$ and $\omega_e$, which were derived from experimental testing.

The variator ratio, $r_v$ that gives $\omega_t$ is given by

$$r_v=\frac{\omega_t}{\omega_d} \tag{5.3}$$

where $\omega_d$ is the driveline speed (rad/s). Realisation of the basic hydraulics model in Dymola is illustrated in Figure 26. Output from the hydraulic controller, a transmission ratio, forms the input to the variator in the transmission subsystem model.

This model represents pseudo steady-state effects that facilitate the prediction of engine speed and ratio response for basic calibration parameter setting. No driveline dynamic effects, such as driveline compliance or backlash have been included in the model, and the engine model is based on a simple look-up table without engine manifold filling dynamics. Future work could include enhancing the fidelity of the engine model, in order to increase the scope of the model for supporting CVT calibration.

The final aspect of the CVT powertrain-in-vehicle model is the transmission electronic controller model, as shown in Figure 27. All the functionality of the actual controller that is relevant to controlling the stepper motor position is included in the model, including all the parameters that are adjusted by the transmission calibration engineers. This is necessary if the model is to be used as a calibration tool.

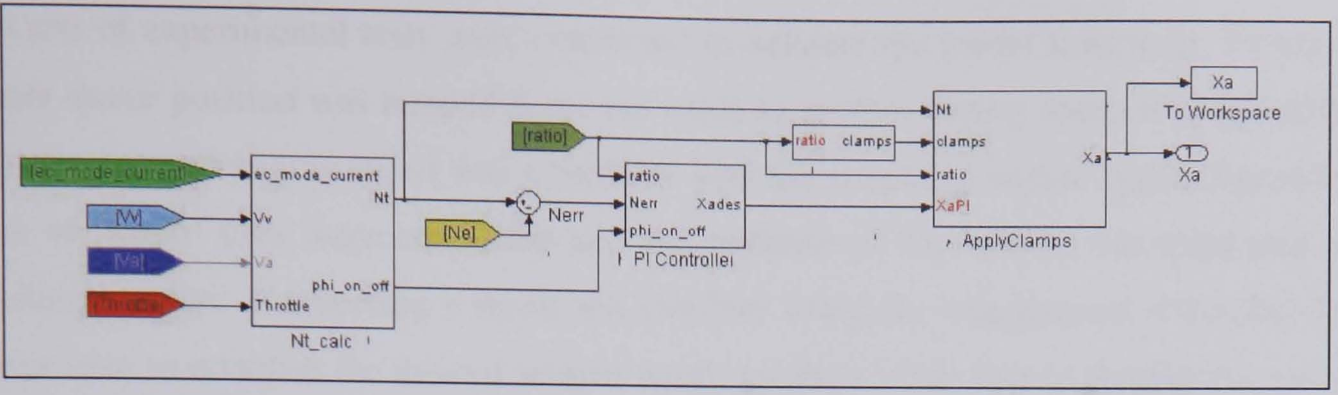

*Figure 27 – Simulink Electronic Transmission Controller Model (Top Level)*

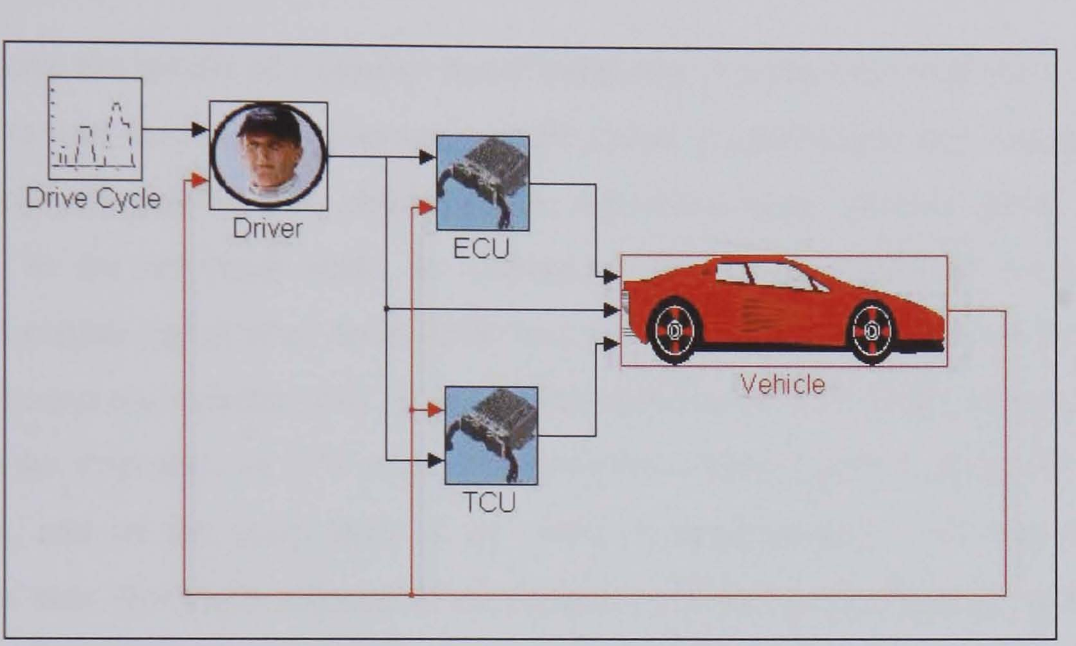

*Figure 28 – Simulink Model Construction*

The highest level Simulink vehicle model structure is illustrated in Figure 28. A desired driving profile or manoeuvre is defined in the 'Drive Cycle' block, which is interpreted by the 'Driver' model as a throttle or brake position. The 'ECU' model replicates idle speed functionality. The TCU model (Figure 27) was developed specifically for this application and replicates the actual transmission controller functionality, allowing the all the adjustment of all important CVT calibration parameters. The vehicle model is an S-function that calls the complied Dymola model.

## 5.4 Application of the CVT Powertrain-in-Vehicle Model

Before the model described in the previous section could be confidently delivered to transmission calibration engineers and applied to real problems, validation of the model function and the correlation of simulation results to experimental results were required.

A development vehicle and calibration tools were available for the purpose of experimental testing. Calibration tools consisted of a laptop computer and a re-programmable transmission control unit. These pieces of equipment could be used to set the position of the stepper motor precisely, or ramp the position at a specified rate between two values. A range of vehicle variables could be logged using the laptop computer.

Two sets of experimental tests were conducted to validate the model behaviour. Firstly, the stepper motor position was ramped from one value to another during constant speed driving. The experimental engine speed was compared with the simulated engine speed. Secondly, a series of 'tip-in' tests were conducted and the response of the vehicle was compared with simulation results. Conducting a tip-in test involves using the transmission controller in its normal state to establish the desired stepper motor position. After approximately two seconds of steady state driving at an initial throttle position, the driver executes step change in throttle position to wide-open throttle.

Figure 29 shows the results of a stepper motor ramp test. A ramp from 100 steps to 175 steps was applied in one second, at a constant vehicle speed. Experimental and simulated stepper motor positions are plotted with respect to the right-hand scale. Engine speeds are plotted with respect to the left-hand scale. In response to a change in stepper motor position, experimental engine speed rises from 2800 rpm to 5050 rpm. The shape of the simulation engine speed response matches that of the experimental result very well, although there is a slight lag in the response. At 175 steps, the predicted engine speed is about 60 rpm higher than the test, and on the ramp there is an offset of approximately 150 rpm or 5%. It is interesting to note that there appears to be some hysteresis in the response of the variator, since the steady speed after the ramp-out is about 50 rpm higher than the speed before the ramp-in.

Despite differences in detail between the experimental and simulation engine speed responses, the overall behaviour matches relatively well. A wide range of comparisons like the one shown in Figure 29 were conducted in order to gain confidence that the model was valid.

Figure 30 shows the engine speed response, and Figure 31 shows CVT ratio response, to a wide-open throttle tip-in test. The engine speed ramps from 2500 rpm to 4200 rpm in response to the manoeuvre. The experimental and simulation engine speeds are practically indistinguishable during the initial response, although there is a slight deviation between experimental and simulation engine speeds as the target speed is approached. While the experimental engine speed meets its target smoothly, the simulation engine speed overshoots by about 3%. Some differences between experimental and simulation response are to be expected, given that there are inherent approximations in the modelling approach. This small deviation, however, should not adversely affect the usefulness of the tool to the calibration engineers. In all cases, the engine speed stays constant until approximately 9 seconds and then starts to gently increase. This is due to the control strategy demanding an increased engine speed as the vehicle accelerates.

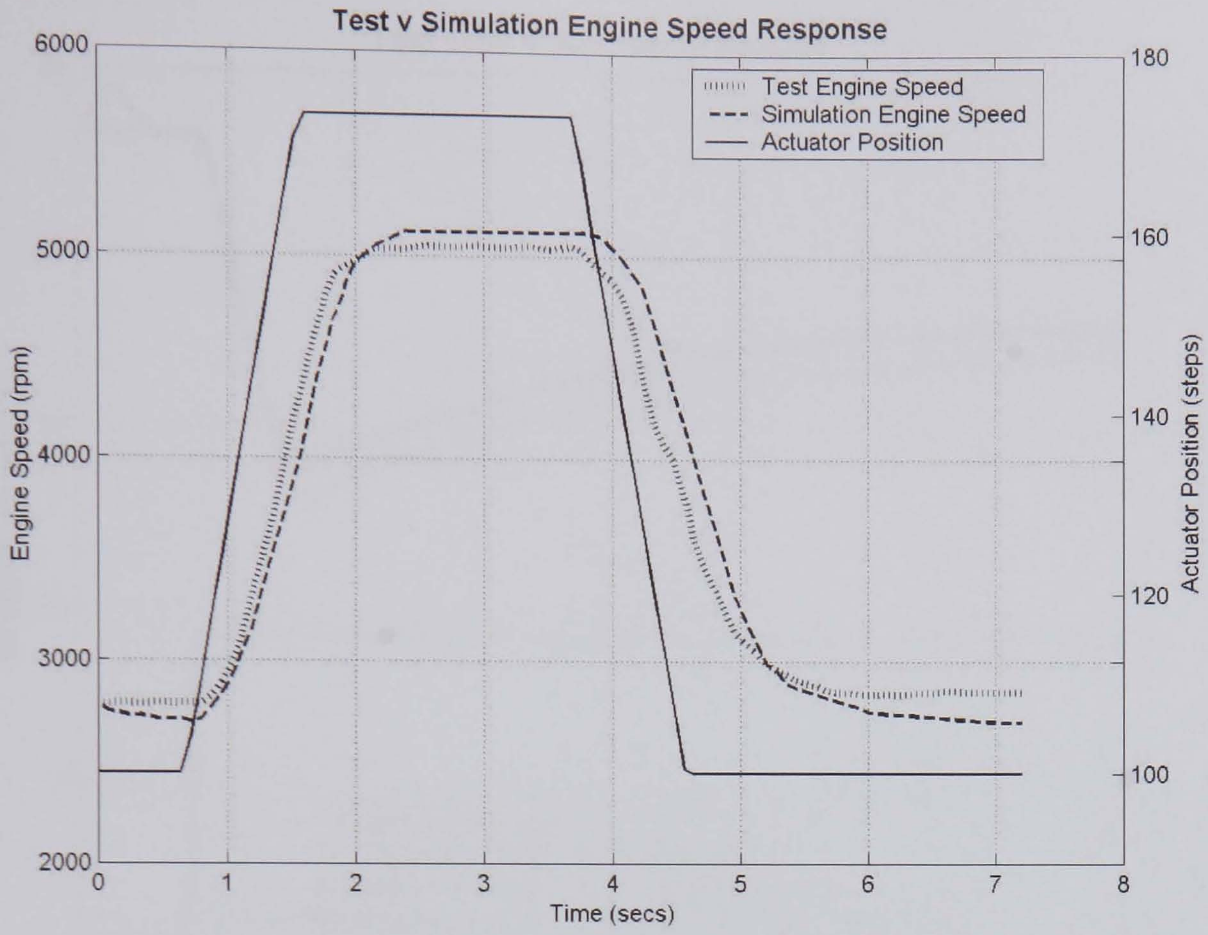

*Figure 29 – Validation of Simulation Results*

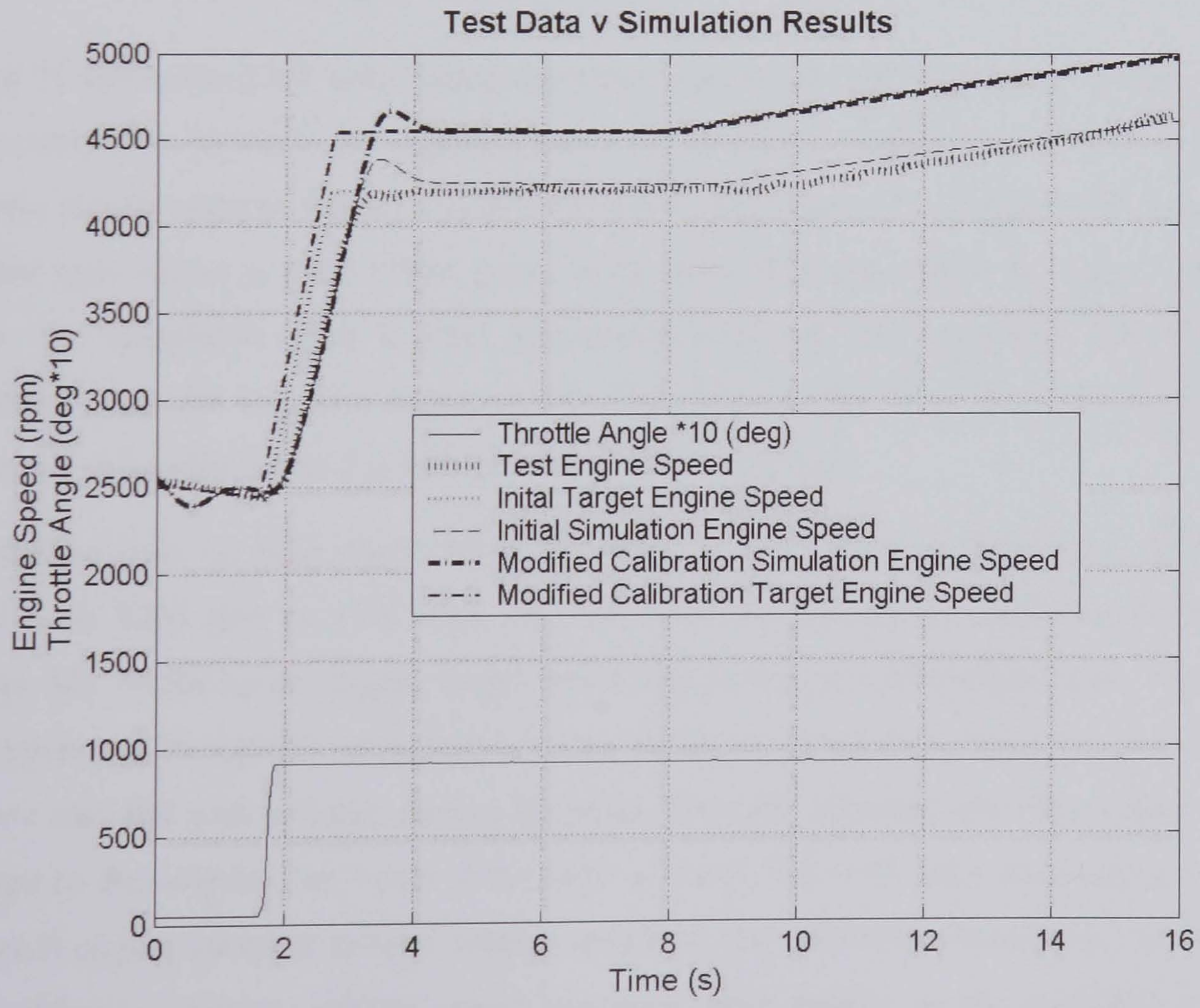

*Figure 30 – Effect of CVT Calibration Changes on Vehicle Speed*

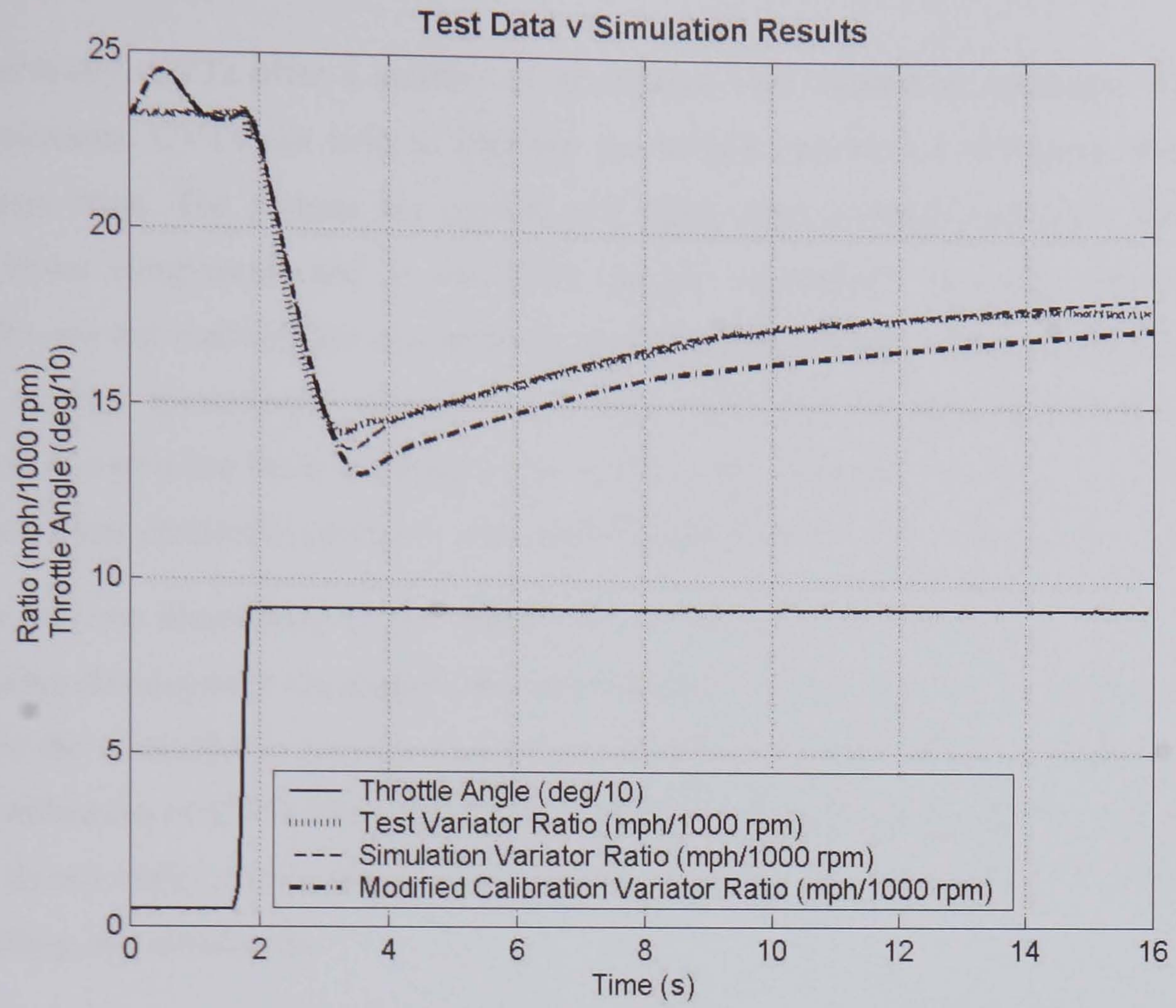

*Figure 31 – Effect of CVT Calibration Changes on Engine Speed*

Figure 31 shows the CVT ratio during the wide-open throttle tip-in test. Once again, there is a close correlation between the experimental and simulation results. In response to the tip-in, the ratio rapidly reduces from 23 mph/1000 rpm to approximately 14 mph/1000 rpm. The test variator ratio shows a clear elbow point at 14 mph/1000 rpm where the ratio starts to rise again. The simulation gives a good representation of the ratio reduction, but has a slight overshoot when the test ratio begins to rise. One second after the elbow, the simulation has recovered and again shows a good correlation to the test ratio.

The dashed lines on both charts show the effect of increasing the maximum target engine speed from 4200 rpm to 4500 rpm. The effect of this change on engine speed is evident (Figure 30). At the tip-in, engine target speed rises to the new maximum value. The shape of the response to the tip in is very similar to the validation simulation, with the same delay time and rise rate, but with a higher maximum value. The ratio response after the change is similar in shape to the original, but value of the ratio is lower. The CVT ratio must adjust to give the increased engine speed at similar vehicle speeds to the validation simulation. As a result of this calibration change, vehicle speed increases more rapidly in the modified calibration simulation than in the validation simulation, give the vehicle a different performance feel. Acceleration time from 100 kph to 125 kph is reduced by one second in the modified calibration.

## 5.5 Conclusion

Theoretically, CVTs offer a number of advantages over manual or automatic discrete ratio transmissions. CVTs can help to improve powertrain operational efficiency and provide a seamless drive. The systems are smaller and lighter than standard automatic transmissions, with fewer components and so should be cheaper to produce. In reality, these theoretical benefits are not realised due to a number of technical challenges in the application of CVTs, such as poor transmission efficiency and high unit cost. Various technologies are being applied to overcome these challenges, one of the most important of which is electronic CVT control. Basic electronic control is used on the push-belt CVT that is used in this work.

There are two dimensions to the application of electronic control systems for CVTs. Base algorithm development determines the functionality of the controller. Calibration is required to tune the controller to give the desired transmission characteristics in a vehicle application. The calibration of CVTs has historically been an iterative, prototype-intensive process. It has been shown in this section that CVT calibration is an area in which there is a need for systems modelling and simulation.

A CVT vehicle simulation model has been developed for calibration purposes. By applying the PTIV approach to the development of the simulation model, only the CVT hydraulics, the CVT variator and the transmission controller had to be modelled from scratch. Experimental test data has been acquired and used to show that the simulation model described in this section is valid in predicting the engine speed, ratio and vehicle speed response to step changes in stepper motor or throttle position. Changes can be made in transmission calibration parameters, and the effect on the vehicle performance and driveability can be predicted using the simulation model. Some simple modifications to the engine and engine controller models would enable the prediction of fuel economy and emissions.

Since transmission calibration engineers assisted with the experimental testing in support of simulation model development, and helped specify its capabilities, there is a good level of confidence that the tool can be effectively applied. Effective application of the tool should enable a reduction in the level of vehicle testing and hence a time and cost saving. Additional understanding of the system dynamics through using the tool provides the possibility of an improved optimisation of the CVT calibration. Using simulation-based techniques for CVT calibration will demand an increased level of analysis and a quantification of the desired outcome, which should result in a calibration of improved quality.

Further work on the CVT-in-vehicle simulation model should be focused on implementation of the simulation model in the CVT transmission calibration process. This may include developing a tool in which to wrap the simulation model. Systems should be devised for data storage, data editing, results storage and results post-processing. The impact of the simulation model and tool on the CVT calibration process should be measured. Possible measures may include the time saved during the process or the reduction of development cost through the application of the tool. If a wider range of parametric and operational data for the electro-mechanical CVT unit could be obtained, a higher fidelity model could be created. This would facilitate the simulation of higher order transmission responses, such as ratio fluctuation as a function of the rate of change in stepper motor position. More accurate calibration of the vehicle transient response to varying stepper motor rates of change would then be feasible.

In this work package, the application of the PTIV approach and library models to systems modelling and simulation in CVT calibration has been demonstrated. Now that CVT models have been added to the PTIV library, they could be used for other CVT design and development applications. For instance, with minor modifications the models that are now available could be used to study the effect of CVT torque losses on drive cycle fuel economy. This demonstrates the usefulness of the approach to systems modelling and simulation that was proposed in Section 4.3.

# 6. Applying Systems Modelling and Simulation to Discrete Ratio Automatic Transmission Calibration

Modern discrete ratio automatic transmissions are electronically controlled. Typically, automotive manufacturers purchase transmission units from a supplier, with the responsibility for integration of the transmission into the total vehicle system resting with the automotive manufacturer. This involves calibrating the transmission electronic controller. Setting the transmission calibration is an aspect of the product development process that can have a significant impact on the quality, profitability and time to market of new vehicles. Vehicle performance, fuel economy, responsiveness and smoothness are all affected by the transmission calibration.

Like CVT calibration, discrete ratio automatic transmission calibration has historically been highly dependent on vehicle testing. The main focus of the calibration task has been to produce a shift schedule with good driveability quality[1] within the operating limits of the engine and transmission. Other vehicle attributes, such as fuel economy, were considered to be of secondary importance, and were often assessed as an after thought to the bulk of the transmission calibration activity. Competitive pressures demand an improved approach, with increased levels of analysis.

This section reports on the fourth Engineering Doctorate portfolio work package, the aim of which was to develop a transmission calibration simulation tool capable of predicting the effect of shift schedule calibration changes on vehicle fuel economy, performance and driveability, and to demonstrate implementation of the tool in the transmission calibration development process. This work package builds on the third work package, in which an application of the PTIV approach to systems modelling and simulation was demonstrated.

The following subsections give an introduction to the operation of discrete ratio automatic transmissions, discuss the transmission calibration process, and the review the approaches of other authors to the problem of modelling automatic transmissions. A transmission calibration simulation tool that has been developed is presented and validated. In support of the transmission calibration simulation tool, a method for objectively assessing shift schedule driveability quality is described. A comparison of experimental and simulation-based approaches to transmission calibration is given and conclusions are drawn.

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[1] 'Shift schedule driveability quality' is used in this portfolio to describe those aspects of driveability that are affected by the shift schedule. These are the willingness of the transmission to downshift and the consistency of upshifts during acceleration manoeuvres.

## 6.1 Discrete Ratio Automatic Transmission Operation

Automotive discrete ratio automatic transmissions are complex power transmission systems comprised of four major subsystems of different types [114]. Firstly, at the heart of the system is a mechanical gear train, which is usually comprised of an epicyclic gear set. Alternative ratios are selected by engaging and disengaging wet plate and band clutches [115]. Secondly, a hydraulic controller activates the clutches. Thirdly, electronic controllers are calibrated to optimise clutch pressures (pressure schedule) and shift points (shift schedule). In modern transmissions, electronic control is vital for meeting the shift quality and flexibility demanded by customers [116]. Fourthly, fluid torque converters have historically been used as the launch-from-rest device and are an integral part of the transmission system. Figure 32 shows a typical modern automatic transmission [117].

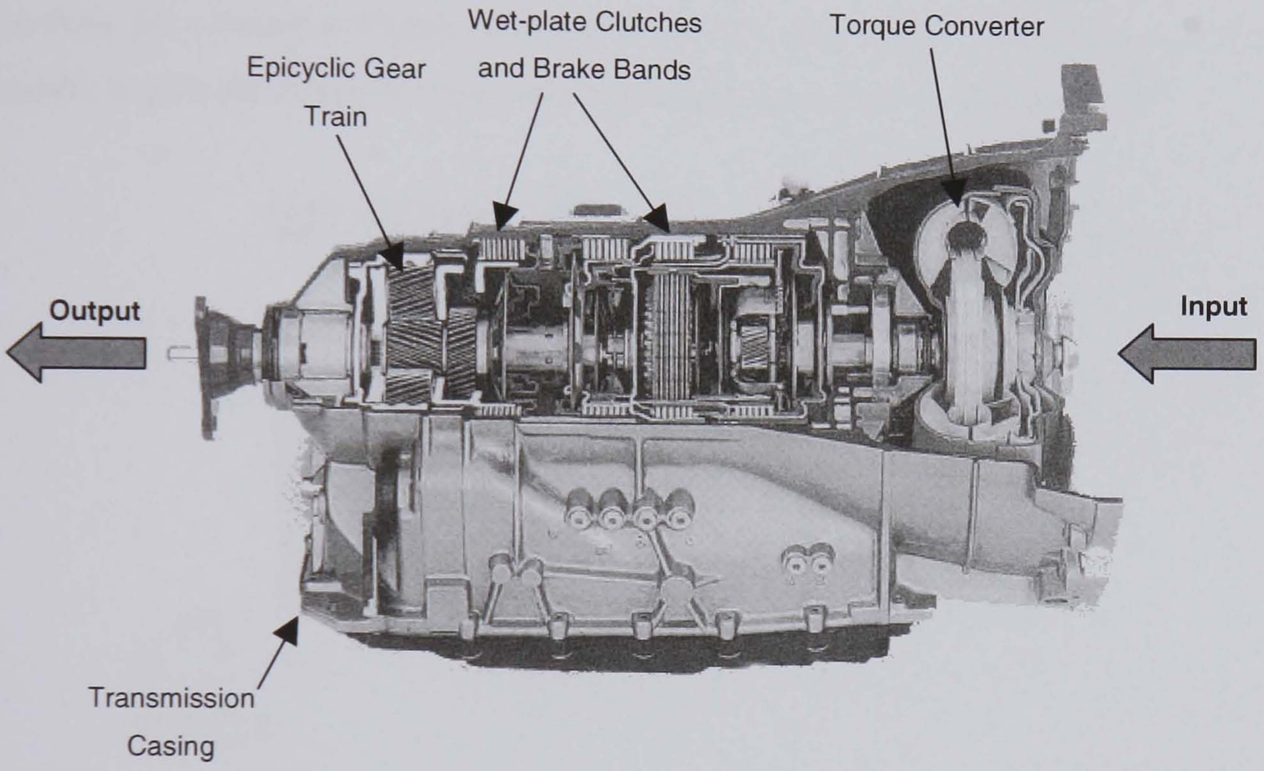

*Figure 32 – Cutaway Photograph of ZF myTronic$^6$ Transmission*

The principles of epicyclic gear train operation are illustrated in Figure 33. Epicyclic gear trains are constructed from three elements: the sun gear in the centre; the planets; and the annulus that forms an outer ring. Any one of the elements can act as the input, and any can act as the output. If all elements are unconstrained, the epicyclic transmits no drive. By constraining different elements, different gears can be selected. In the example of a simple (Simpson) epicyclic in Figure 33 [118], the sun gear is the input and the planets form the output. A brake ring can clamp the annulus to provide drive.

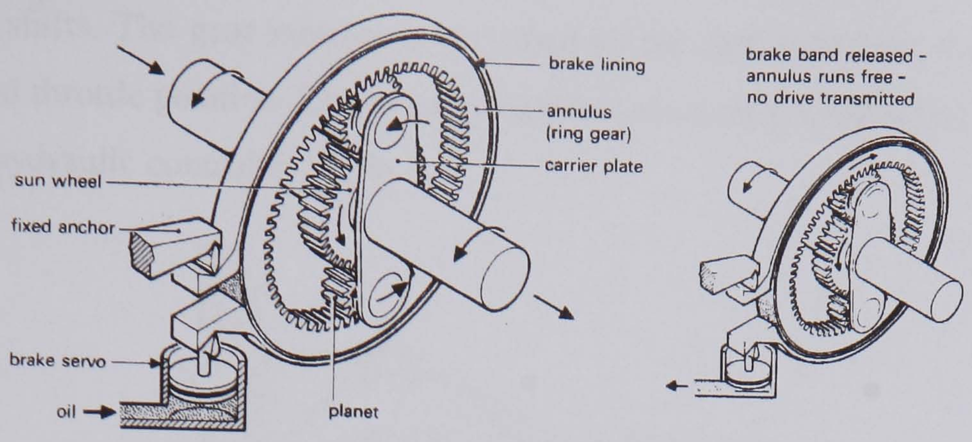

*Figure 33 – Basic Epicyclic Gear Train Operation*

A simple epicyclic can be configured to provide up to six different forwards and reverse ratios. Automatic transmissions capitalise on this property, providing up to six forward ratios from a compound epicyclic [117]. Figure 34 shows how this can be achieved [118]. Extending the concept in Figure 33, brakes and wet-plate clutches can be applied to different elements to provide different torque paths through the automatic transmission.

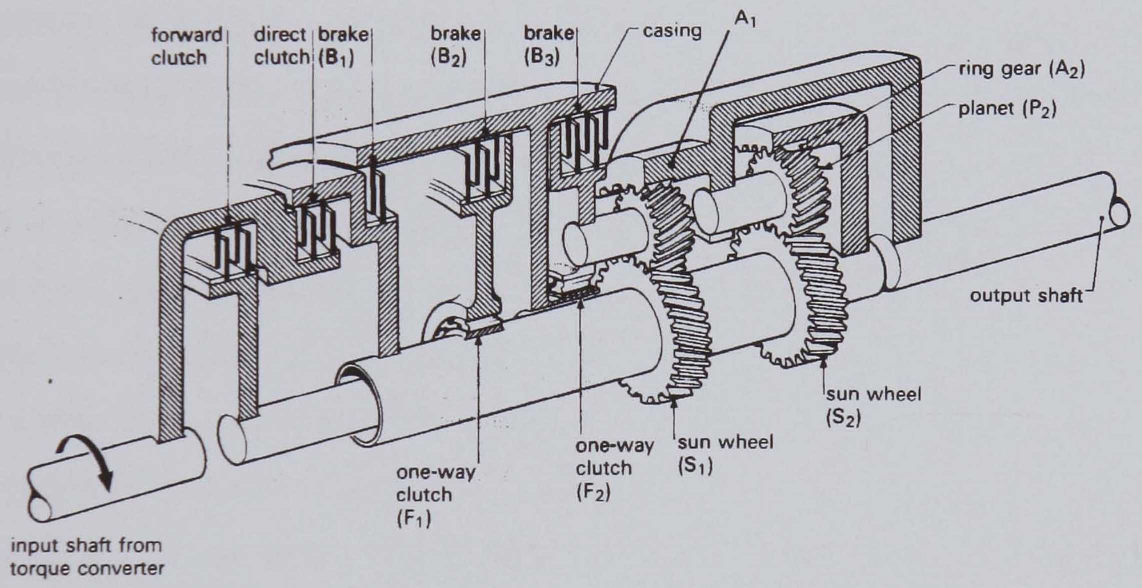

*Figure 34 – Principles of Drive Train Operation*

The clutches and brakes are hydraulically actuated. A hydraulic control unit contains a series of valves, one for each clutch and brake element. Hydraulic system pressure is maintained by a positive displacement pump, usually driven from the engine crankshaft, and controlled by regulator valves. When 'Drive' is selected using the selector lever, a manual valve is operated which pressurises the hydraulic system and selects first gear. Historically, a pressure proportional to vehicle speed acted on one side of the element valves, which was opposed by valve spring force and a pressure proportional to throttle pedal position. The timing of the shifts depends on the physical design of the system, in particular the strength of the valve springs [118]. Modern transmissions are electronically controlled, and solenoids that act directly on the clutch and brake valves trigger shifts. Transmission pressure schedule calibration is concerned with setting the precise time-based motion of the solenoid valves to provide smooth shifts. The gear number is specified by the shift schedule, based on sensed vehicle speed and throttle position. This set-up combines electronic intelligence with the rapid response of the hydraulic controller [119].

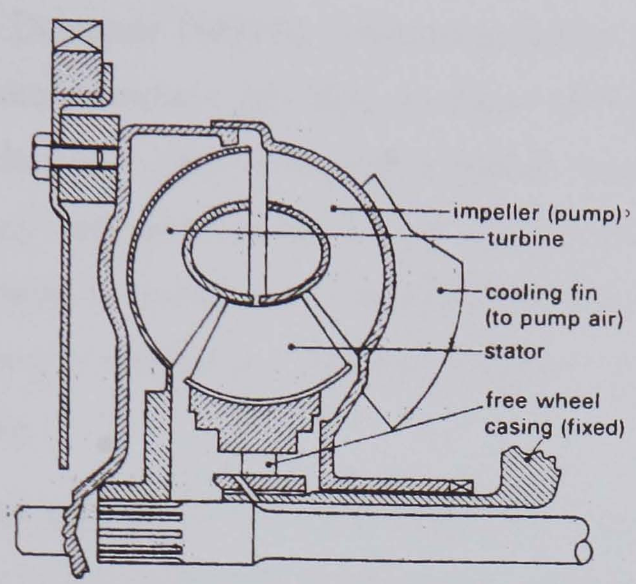

*Figure 35 – Torque Converter Construction*

The construction of a torque converter is shown in Figure 35 [118]. A torque converter is usually used to separate the engine rotation from transmission rotation. The torque converter is a hydrokinetic device consisting of three or more elements filled with a fluid, which are configured in a hollow toroid. The impeller, or pump, is driven rotationally by the engine. Centrifugal force pushes the fluid it contains towards the widest diameter of the impeller, from where it is directed into the turbine. The resulting change in direction of the fluid movement exerts forces on vanes in the turbine, and the turbine accelerates until it reaches nearly the same speed as the impeller. The stator, or reactor, redirects fluid flow between the exit of the turbine and the entry of the impeller, allowing a torque multiplication effect. When a critical speed ratio is reached, called the coupling point, the stator moves with the turbine and impeller and the capacity to multiply torque is lost. Drag losses in the torque converter mean that the speed ratio will never reach unity while the impeller is driving the turbine. Most modern transmissions are equipped with an electronically controlled torque converter lock-up clutch, which physically couples the impeller to the turbine, reducing losses. Defining the behaviour of the lock-up clutch is an integral aspect of the transmission calibration task.

## 6.2 Discrete Ratio Automatic Transmission Calibration

There are two aspects to discrete ratio automatic transmission calibration. Firstly, the pressure schedule determines the pressure time profile for the actuation of the various clutches and brake bands in the transmission, and affects its shift quality and durability. Secondly, the shift schedule determines the required gear and torque converter lock-up clutch state for a given set of vehicle operating conditions. Typically, the shift schedule[2] calibration is conducted in-house, and while the transmission suppliers develop the pressure schedule.

Specific objectives or desired outcomes from the transmission calibration process are described in Engineering Doctorate Portfolio Submission Seven. They are: meeting vehicle performance and fuel economy targets; providing excellent shift quality; giving appropriate vehicle response and performance feel; giving indiscernible acceleration discontinuity over shifts; ensuring consistency and predictability in shift points; minimising the level of shift busyness; ensuring that there is smooth switching between modes; and validating that the vehicle cooling performance is satisfactory. The shift schedule affects all of these objectives directly, except shift quality.

In addition to ensuring that the vehicle behaviour meets the objectives listed in the previous paragraph on final release of the transmission calibration, prototype vehicles require interim release transmission calibrations for their proper operation. The first prototype vehicles that become available in a vehicle programme are generally buck vehicles fitted with a design intent powertrain. An initial shift schedule must be provided to run these vehicles. By the time the first full design intent prototype vehicles are available, the normal mode schedule should be fully developed. Selective and adaptive shift modes will be developed using this prototype level vehicle. At the close of the full design intent prototype stage, all modes should be fully developed and validated.

### *6.2.1 A Typical Approach to Discrete Ratio Automatic Transmission Calibration*

The high-level powertrain development process is shown in Figure 36, along with an overlay of the corresponding transmission calibration activities. According to this process, by the conclusion of the Concept Development phase (Gateway 3), the initial ‘normal’ mode shift schedule must be defined and ready for implementation in simulator vehicles. The normal mode acts as the base schedule for later development of additional modes. In fact, the duration of the transmission calibration process can be highly dependent on the quality of the initial normal mode. Design of the initial normal mode is an analytical, desktop operation since no prototype vehicles are available at this stage. Upshift and coastdown downshift shift

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[2] ‘Shift schedule’ in this document also includes the torque converter lock-up clutch schedule unless it is referred to separately.

points are defined based on vehicle physical constraints, and then the shift schedule is completed to give acceptable fuel economy and driveability quality[3].

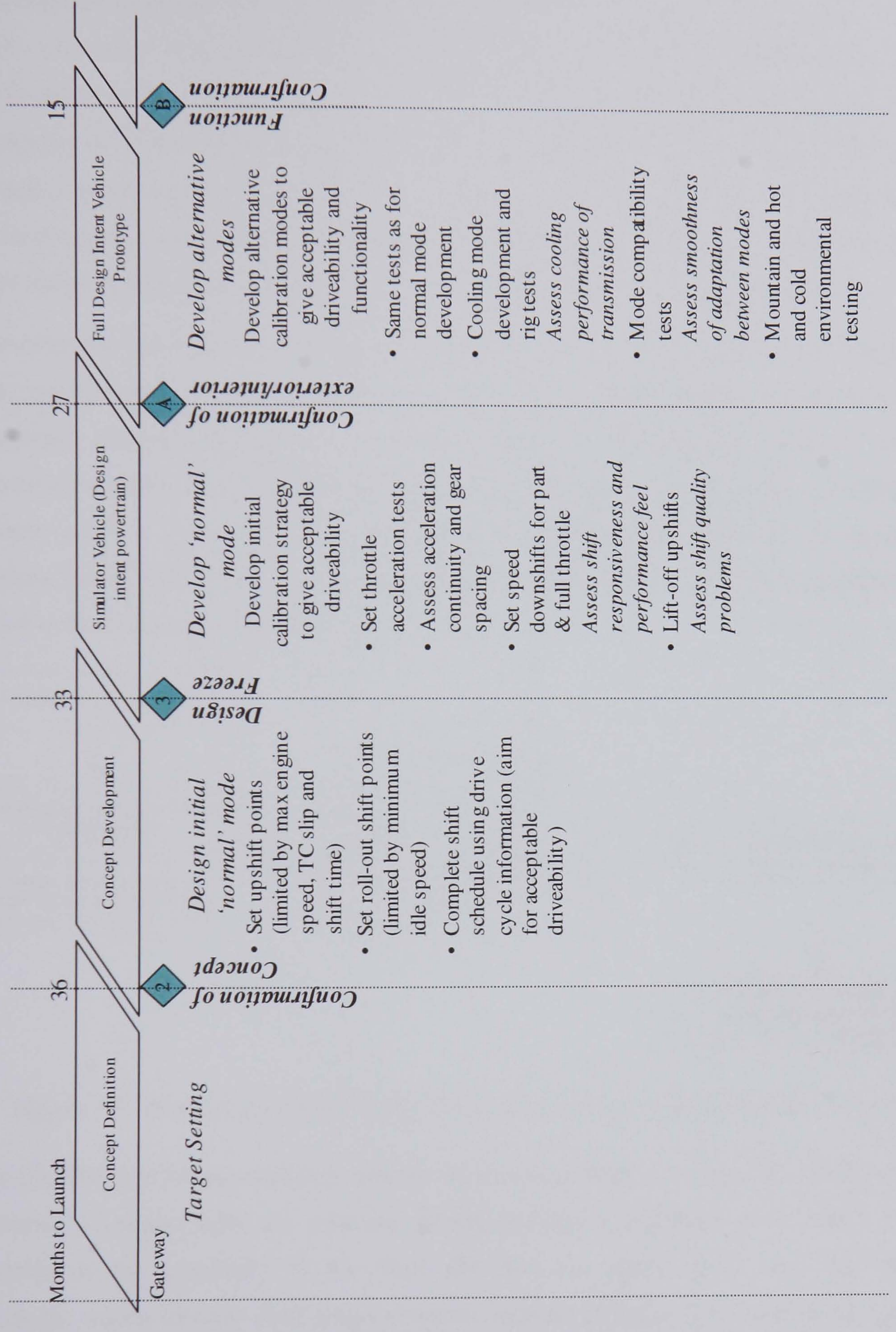

*Figure 36 – Stages of the Transmission Calibration Process*

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[3] 'Shift schedule driveability quality' is used in this submission to describe those aspects of driveability that are affected by the shift schedule. These are the willingness of the transmission to downshift and the consistency of upshifts during acceleration manoeuvres.

In the Simulator Vehicle phase, which commences at Gateway '3', a design intent powertrain is fitted to a donor vehicle that may not be fully representative in order to allow prototype powertrain development. The transmission calibration can be developed on the simulator vehicle to a stage where the normal mode is confirmed at the close of the phase. Further modifications to the normal mode at a later stage should be limited to compensation actions for changes in other elements of the powertrain. During the Design Intent Vehicle phase, alternative modes are developed from the normal base mode. Both selective modes, such as sport and cruise control modes, and adaptive modes such as mountain, downhill and cooling modes must be developed. The calibration is frozen at the conclusion of this stage.

The process by which an initial normal mode shift schedule is designed is shown in Figure 37. Initial vehicle targets provide guidance for desktop calculations, which are used to estimate appropriate transmission ratios and torque converter characteristic (Steps 2 and 3). Transmission hardware definitions are required as the basis for designing an initial shift schedule, again a desktop exercise. Experience in transmission calibration is required to complete Step 4 effectively, and no optimisation is applied to the shift schedule before it is applied in the Powertrain Simulator vehicle (Step 5).

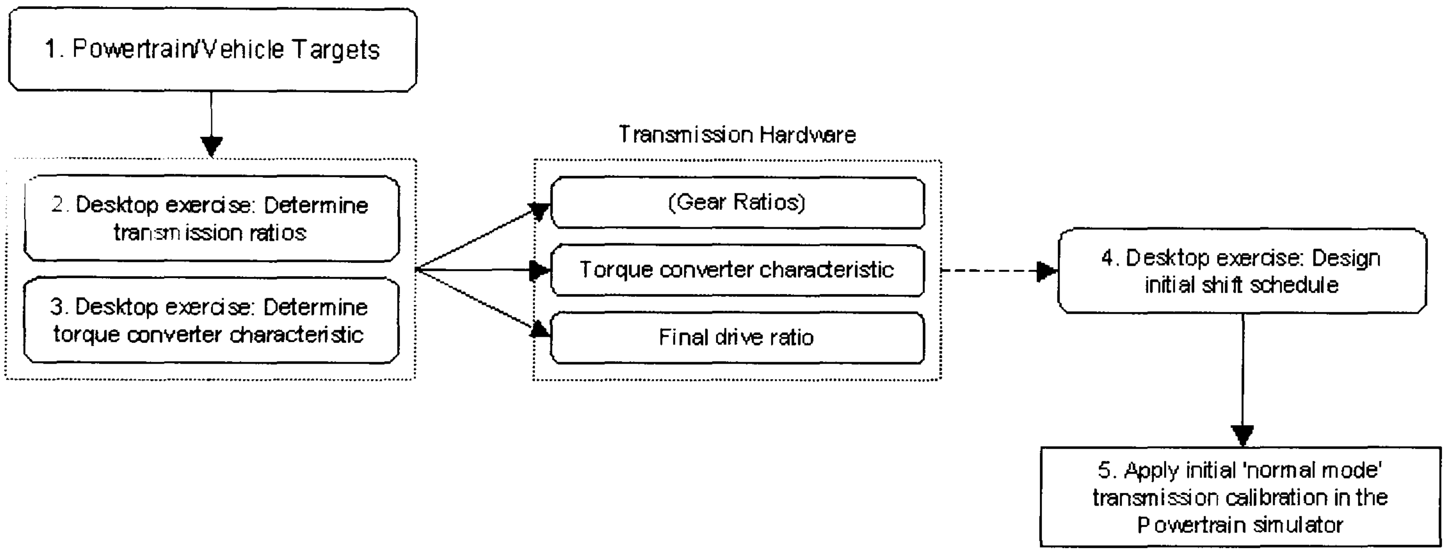


*Figure 37 – Historical Discrete Ratio Transmission Normal Mode Design Process*

When the first powertrain simulator vehicles become available, development vehicle tests can commence. Common tests are: constant throttle position acceleration tests, which give an indication of the continuity of the shift schedule; set speed tip-in tests that produce downshifts, which identify shift responsiveness and performance feel; and lift-off upshifts, which can identify shift quality problems. Refinements to the shift schedule during this phase are based on driveability considerations. Using the integrated prototype vehicle, the normal mode is verified and selective and adaptive modes are developed.

The process by which the normal mode is developed is shown in Figure 38. Normal mode development would generally be conducted on a powertrain simulator vehicle. Experimental testing would be used to assess and improve shift schedule driveability quality. Once this has reached a satisfactory level, vehicle fuel economy testing can be conducted using a chassis dynamometer. A difficulty at this stage is that the road load from the actual vehicle is not yet available and must be estimated. This compromises the robustness of the fuel economy measurements. An experimentally-based iterative process is used to achieve acceptable fuel economy and driveability. The verified normal mode is applied in the integrated vehicle simulator vehicle (Gateway 'A').

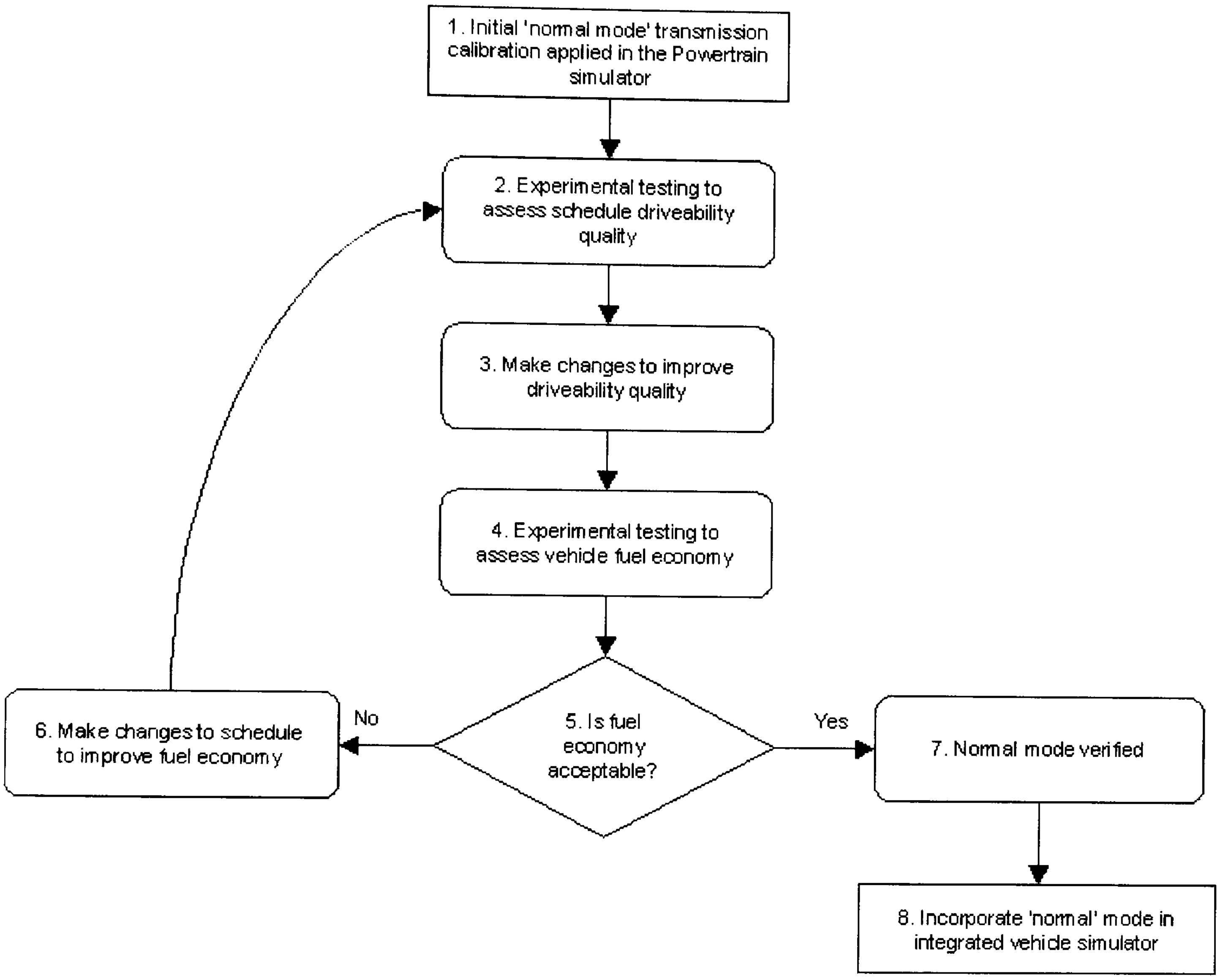


*Figure 38 – Historical Discrete Ratio Transmission Normal Mode Development Process*

A range of information is required to successfully design and develop the normal mode shift schedule. Difficulties arise when that information is not available at the time when it is required for decisions. A full review of the required information and its level of availability can be found in Engineering Doctorate Portfolio Submission Seven. Items of required information that can be difficult to obtain include transmission shift time, a static engine torque map and engine fuel economy data. It is particularly difficult to identify the interaction between the shift schedule and the entire vehicle system during these early stages, even when using powertrain simulators. Therefore, it can be difficult to establish vehicle objective performance; vehicle fuel economy; vehicle performance feel; the correlation between throttle position and vehicle acceleration; the change in vehicle acceleration as a result of a shift; and the level of shift busyness. Even more complex system interactions must be understood to identify the effect of a shift on the engine and transmission cooling, Noise Vibration and Harshness (NVH) of the vehicle, and drive-by-noise.

Designing and developing shift schedules involves making a series of trade-off decisions. Where one vehicle attribute may benefit from a specific change, another may suffer. The information deficits described in the previous paragraph imply that calibration engineers must base trade-off decisions on assumptions.

Drive cycle fuel economy is a good example of a piece of information that is often unavailable during shift schedule design and development, leading to decisions that are based on assumptions. Pressure to improve vehicle fuel economy is being exerted by factors both outside and inside the automotive manufacturers. For instance, Ford company policy is to improve the fuel economy of Sports Utility Vehicles by 25% by 2005 [120]. Shift schedules that are designed to optimise fuel economy can contribute to meeting this target. Analytical methods are required for tackling this problem. Historically, fuel economy optimisation has been undertaken using chassis dynamometer testing during the development phase of the calibration process. In an iterative development process, each change in the shift schedule requires a number of tests to establish confidence in the fuel economy results, and only one test can be performed each day. Changes that improve fuel economy may have a detrimental effect on driveability quality, so track testing is required for each iteration, adding more time and cost to the process. This approach to transmission calibration is insufficient for current and future demands. An alternative is required that increases the level of analysis giving improved understanding of the system, and reduced time and cost in the process.

### *6.2.2 Enhancing Discrete Ratio Automatic Transmission Calibration*

The key weaknesses that have been identified in the traditional approach to discrete ratio transmission calibration are that the process is very reliant on physical prototypes, and that a number of items of information that are required during transmission calibration are generally unavailable.

Systems modelling and simulation could provide an understanding of the behaviour of the system, and provide some of the deficit information, without requiring prototype hardware. In the case of transmission calibration, simulation could provide an early understanding of the interaction between the shift schedule and the entire vehicle system. It should be possible to predict a number of vehicle attributes that are dependent on overall system behaviour.

Two specific tasks would benefit particularly from the application of systems modelling and simulation.

(i) Designing an initial normal mode shift schedule.

(ii) Quantifying the effect on fuel economy of changes in the normal mode shift schedule during development.

A critical trade-off decision between vehicle fuel economy, performance and shift schedule driveability quality must be made during the development of the initial normal mode schedule. Shift schedules that have been optimised for fuel economy tend to give unacceptable driveability quality, and vice-versa. In order to assess this trade-off using simulation results, a quantitative measure of shift schedule driveability quality is required.

A simulation model that could be used 'in-vehicle' would enable calibration engineers to assess the effect of changes in the schedule on fuel economy during normal mode development field-testing. This is especially important when environmental testing is being undertaken, and it is impossible to assess the effect on fuel economy of schedule changes using the conventional chassis dynamometer tests.

As with CVT calibration, the way in which simulation models are integrated into the calibration process is a critical issue. They must be effective in reducing in-vehicle testing and improving the quality of the calibration. Competitive advantage can be gained when an organisation is able to coherently integrate software, hardware and 'humanware' in an effective system [121].

The typical process for developing a shift schedule was described in the preceding subsection. A view of an enhanced process, featuring the application of systems modelling and simulation is illustrated in Figure 39 and Figure 40.

Figure 39 illustrates the normal mode pre-prototype vehicle design process. During design, simulation is used to specify transmission hardware. Although this is outside the scope of this study, it has a critical effect on the shift schedule design process. Hardware specifications are required to parameterise a simulation model, which can be used by the calibration engineers to derive an initial normal mode shift schedule (Step 4) and then engage in an iterative trade-off exercise (Steps 5 & 6). Once an acceptable solution has been obtained, the normal mode can be applied in the Powertrain Simulator prototype vehicle for vehicle testing.

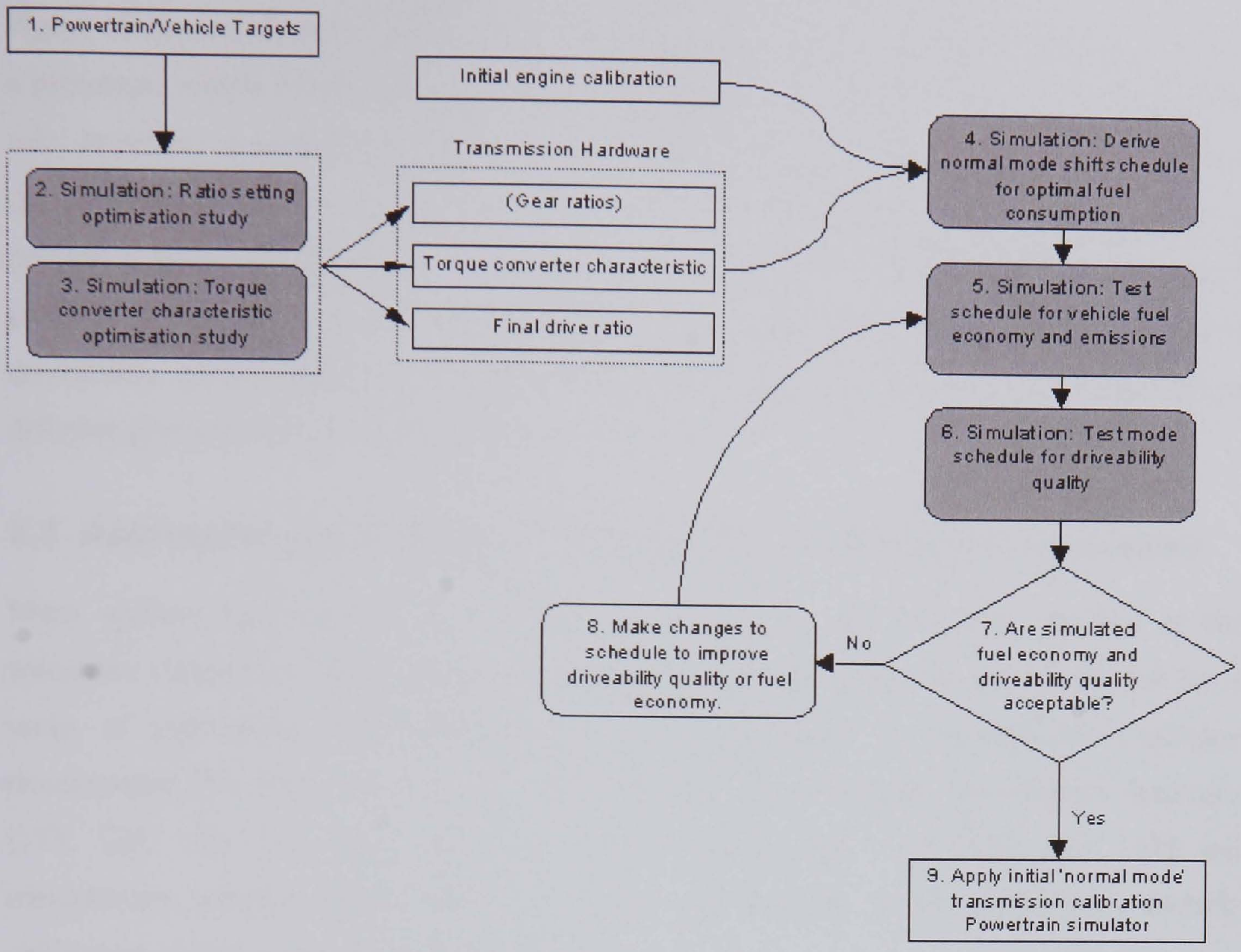


*Figure 39 – Modified Discrete Ratio Transmission Normal Mode Design Process*

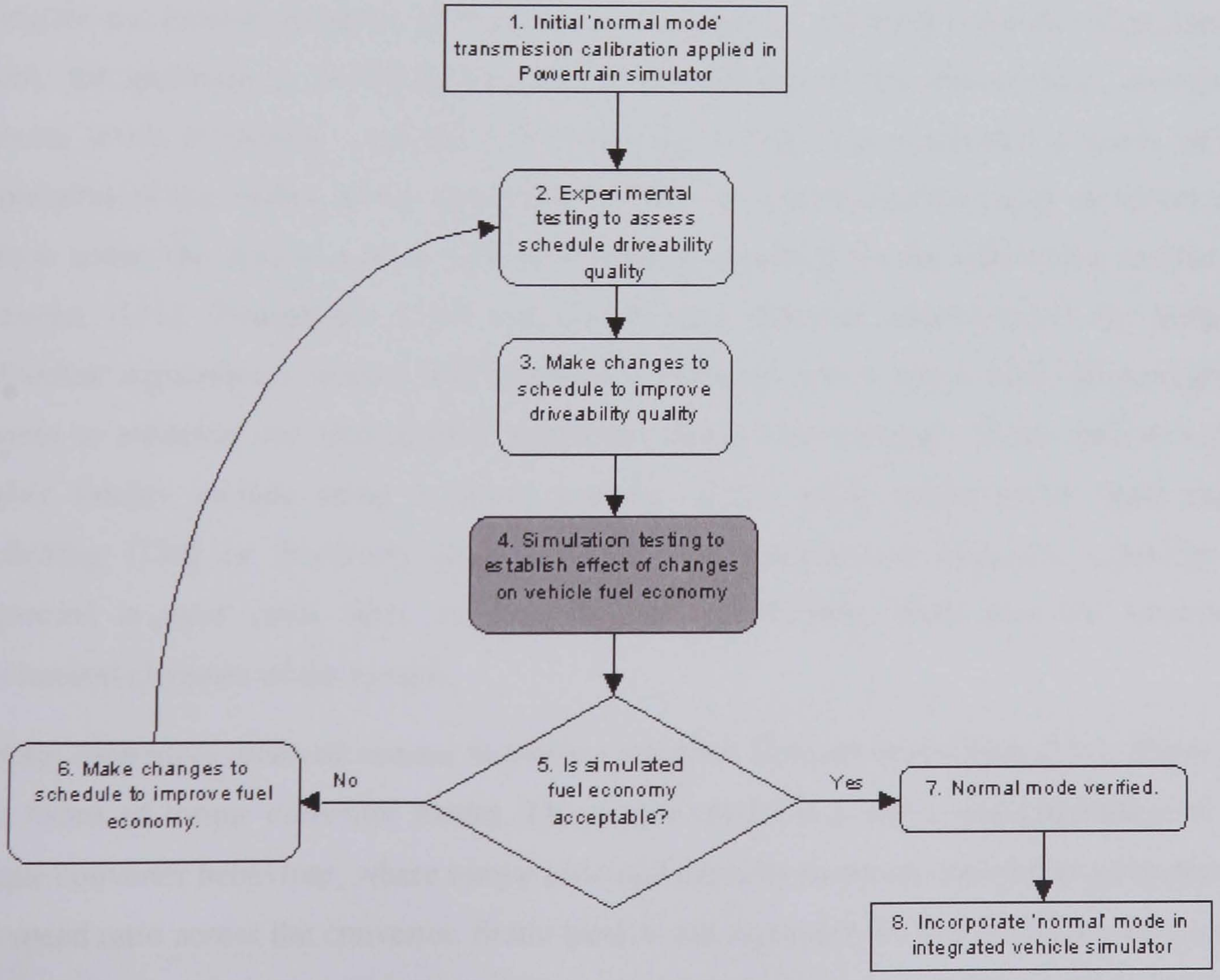


*Figure 40 – Modified Discrete Ratio Transmission Normal Mode Development Process*

Figure 40 illustrates the normal mode shift schedule development process, which is primarily a prototype vehicle-based verification exercise. A simulation model could play an important role, however, in establishing the effect of changes in the shift schedule on other vehicle attributes that cannot be readily tested. In particular, vehicle fuel economy can be simulated to prevent it being unwittingly adversely affected by changes to improve driveability quality (step 4). This represents an important improvement over the historical process, in which driveability quality and fuel economy shift schedule development had to be conducted in different physical test environments (Figure 38).

## 6.3 Approaches to Automatic Transmission Modelling and Simulation

Many authors have tackled the modelling of automatic transmissions. Models of the automatic transmission itself are usually integrated with powertrain and vehicle models for a range of applications. Four main categories of application are transmission controller development [39, 122, 123, 124, 125, 126, 127, 128], studying general powertrain dynamics [115, 129, 130, 131, 132, 133], shift quality analysis, [37, 134, 135, 136, 137] and transmission concept studies [138]. Controller development model applications include calibration of shift and lockup clutch schedules.

An automatic transmission model can be broken down into its constituent elements, those being the mechanical elements, the torque converter and the electronic controller. Considering firstly the approach to modelling the mechanical elements of the transmission, models of varying levels of fidelity could be developed. The fidelity that is selected depends on the application of the model. At the most basic level, a ratio multiplication factor on speeds and torque across the system gave a sufficient dynamic response for the application tackled by Freeman [131]. Tsangarides [130] introduced more dynamic characteristics by lumping individual transmission inertias and compliance elements into a single mass-spring-damper system to represent the transmission dynamics, along with backlash. Some authors tackle higher fidelity models using a ‘lever analogy’ [134], while others prefer bond graph modelling [139] or free-body analysis [140]. The transmission hydraulic controller is neglected in most cases since its dynamics are significantly faster than the associated mechanical elements of the system.

Torque converters received serious modelling attention from the mid-1960s [141]. There are two forms of torque converter model. The simple model is a static characterisation of the torque converter behaviour, where torque ratio and capacity factor are defined as a function of the speed ratio across the converter. Static models can represent the low-frequency behaviour of the torque converter, when there is less than one perturbation for every two impeller revolutions [129, 140]. For higher fidelity vehicle or powertrain models, for instance to simulate a launch-from-rest manoeuvre, dynamic torque converter models are required [142, 143].

Electronic controller models can be tailored to represent the functions that are required for a specific simulation task. These could be as simple as representing shift and lock-up schedules to provide an output gear number to the transmission, and as complex as a full controller model including On-Board Diagnostics (OBD) capability. More usually, simulation models are used to assist in the development of transmission controller. Example applications are developing control of the shift dynamics [122, 123, 124, 125, 126, 127], and adapting the characteristics of the shift schedule to suit the driver's style [144, 145, 146, 147, 148, 149].

This review has illustrated that most automatic transmission models, or powertrain models that incorporate an automatic transmission, are designed to assist in solving specific problems or for use in early electronic controller development. Analysing and improving transmission shift quality, for instance, is the focus of considerable modelling effort. With the exception of a few papers by authors from Japanese motor manufacturers, and one by Jauch [62] in which he applied automatic transmission vehicle models in developing an appropriate control of the torque converter lock-up clutch, little has been published about the use of simulation models to support the transmission task of designing and optimising basic transmission shift schedules. Creating an automatic transmission-in-vehicle simulation model that is suitable for these calibration tasks would assist transmission calibration engineers to determine the effect of shift schedule changes on the attributes of the vehicle.

The majority of the publications reviewed in this section were written by academics or by engineers in the research sections of their companies. As such, the emphasis of their modelling efforts is on the functionality rather than the usability of the simulation models. It is vital, if systems modelling and simulation is to make a significant impact on the product development process, that the engineers responsible for making product decisions use the simulation model themselves. Generally, engineers in product development roles have little or no modelling and simulation expertise. Presenting a simulation model to engineers in a user-friendly form is, therefore, vital for their effective implementation. Little has been published about the appropriate means by which to deliver models to engineers. An important criterion for the simulation models that are developed for use engineers who are not systems modelling and simulation experts is that, beyond their functional suitability, they are presented in such a way that their use is extremely intuitive. This is especially true if the users of the models are calibration engineers, who typically work to very tight timing plans and have little time to learn modelling techniques.

In light of the gaps that have been identified in the published literature, a vehicle model, incorporating a basic automatic transmission vehicle model is required for the purposes of transmission calibration. It could be used to investigate the effect of the shift and torque converter lock-up schedules on vehicle attributes. Development engineers should use the simulation model themselves as an integral part of the transmission calibration process. The model should, therefore, be encapsulated in a simulation tool to assist the calibration engineers to define and run tests, to handle data, and to process results.

## *6.4 Discrete Ratio Automatic Transmission Calibration Simulation Tool (TCST)*

It has been identified in the previous subsection that a simulation model of an automatic transmission vehicle is required for transmission calibration. Prediction of vehicle fuel economy, performance and shift schedule driveability quality should be possible using the model. Simulation of these tests should provide data for improved levels of analysis of the transmission and vehicle response, and the ability to assess the effect of changes in the transmission calibration quickly and with a high level of repeatability. Additionally, the model should be encapsulated in a user environment in order to ensure that calibration engineers with little or no experience of simulation can use it intuitively.

In this subsection, an appropriate simulation model is presented and validated, and a user environment is described.

### *6.4.1 The TCST Automatic Transmission Vehicle Model*

A number of requirements for a TCST simulation model have been identified thus far. In simple terms, it should be able to predict absent information and provide a platform from which calibration engineers can confidently make engineering decisions. This means that the level of fidelity in the simulation model should be appropriate, and that the results must have proven validity. Calibration engineers should use, but not modify, the underlying models.

#### Specification of the Physical System

The specification of the vehicle selected for this modelling exercise specification is presented in Table 2.

*Table 2 – Vehicle Specification*

| | |
|---|---|
| Engine configuration | V6, 2.5 litre capacity |
| Engine torque | 240Nm @ 4000 rpm |
| Engine power | 130kW @ 6250 rpm |
| Engine idle speed | 750 rpm |
| Transmission | 5-speed automatic with integral lock-up torque converter and final drive. |
| Transmission ratios | 1st: 3.474, 2nd: 1.948, 3rd: 1.247, 4th: 0.854 and 5th: 0.685 |
| Final drive ratio | 3.66 |
| Driveline configuration | Four-wheel drive with an 'Intermediate Reduction Drive' (IRD) splitting drive between the front and rear wheels, and a viscous coupling in the propeller shaft |
| IRD ratio | 1.4 |
| Wheels & tyres | 16" diameter wheels, giving a tyre rolling radius of 0.355 m |
| Vehicle weight | 1600 kg unladen |

### Aim and Scope of Simulation Model

The aim of the simulation model described here is to predict the effect of changes in the transmission shift schedule and torque converter lock-up clutch calibrations on key vehicle attributes. Specific attributes of interest are fuel economy, performance and the effect of the shift schedule on vehicle response. Transmission calibration engineers should be able to use the model to assist them in developing shift and lock-up schedules. The model should therefore capture the powertrain and vehicle dynamics that are likely to affect that decision. Additionally, the model should be packaged such that that it is intuitive for use by non-modellers.

The simulation model presented here is concerned with predicting mean, rather than transient driveline torque. Throttle pedal position and vehicle road speed, which are inputs to the shift schedule, must be accurately predicted so that the model will select the correct gear. For this purpose, a pseudo steady-state model is sufficient. Capturing the behaviour of the clutches and brakes in the transmission is, therefore, not necessary. Compliance in the driveline need not be modelled. Accurate prediction of vehicle speed relies on robust engine torque output, torque converter, transmission ratio and driveline efficiency models.

A Description of the Simulation Model

The total vehicle system model is made up of driver, controller and vehicle elements (Figure 41). Each element is represented as an individual subsystem in the model architecture.

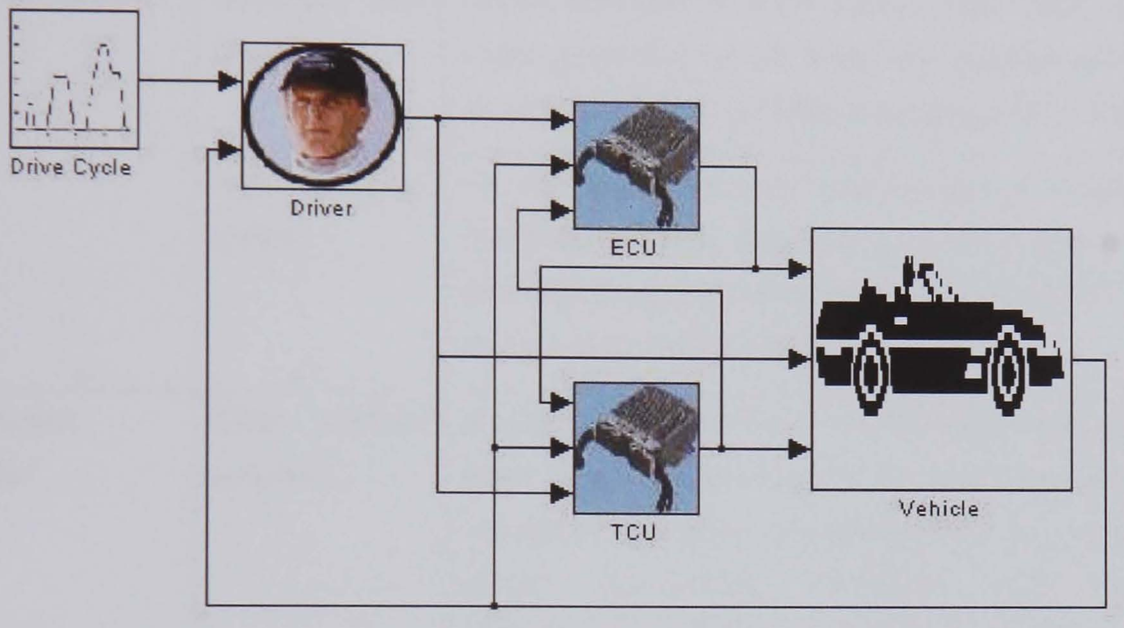


*Figure 41 – Total Vehicle System Model*

A number of the components required for this model are available in the PTIV model library. Table 3 outlines the availability of models, and where development of models was required. It demonstrates the benefit of the PTIV approach t powertrain modelling and simulation described in Section 4.3. The modelling effort that was required to obtain a simulation model of the required fidelity and function was greatly reduced since a library of models was available from which to build.

Figure 42 shows an operational schematic of the vehicle subsystem.

*Table 3 – Model Development Required for Vehicle Simulation Model*

| **Subsystem** | **Component** | **Status** |
|---|---|---|
| Vehicle | Engine | Model available in PTIV Library was used |
| | Transmission | Model available in PTIV Library was used as a base. Introduced a three-element transmission loss model |
| | Driveline | Model available in PTIV Library was used. |
| | Vehicle body | Model available in PTIV Library was used. |
| Engine Controller | Over-run fuel cut-off | Model available in PTIV Library was used as a base. Logic governing cut-off times and duration was changed in accordance with updated data acquired for this engine. |
| | Idle speed control | An idle speed controller was introduced, incorporating a Stateflow model to determine the conditions for activation and deactivation of idle speed control, and PI control of the idle speed once active. |
| Transmission Controller | Gear position selection | Model available in PTIV Library was used as a base. Basic gear position Stateflow model was developed to include an estimation of gearshift time, and a capability to control torque-down. Conditions were applied to engagement and disengagement of the torque converter lock-up clutch. |
| Driver | | Model available in PTIV Library was used. |

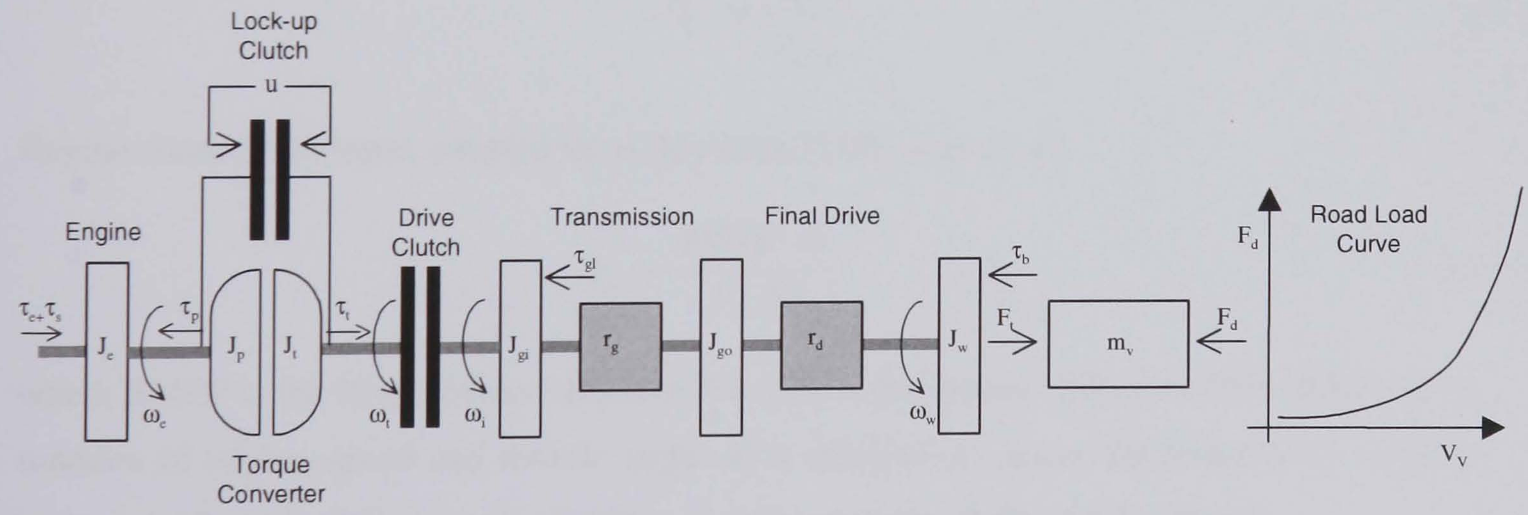


*Figure 42 – Schematic of Vehicle Model*

In Figure 42, $\tau_e$ is the engine crankshaft torque, $\tau_s$ is the torque produced by the starter motor, $\tau_p$ is the torque converter pump torque, and $\tau_t$ is the torque converter turbine torque, all in Nm. The tractive effort produced by the driveline, $F_t$ (N) is found by dividing the wheel torque by the tyre rolling radius, $R_R$ (m). Road load force $F_d$, (N) is a function of vehicle speed $V_V$ (m/s).

Inertias in the system are in units of kg m$^2$. $J_e$ is engine inertia, $J_p$ is torque converter pump inertia, $J_t$ is torque converter turbine inertia, $J_{gi}$ and $J_{go}$ are transmission input and output shaft inertias respectively. Wheel inertia is $J_w$ and vehicle mass is $m_v$. Gearbox ratio is $r_g$ and the combined IRD and final drive ratio is $r_d$. Angular speeds through the system are in rad/s, where $\omega_e$ is the engine and torque converter pump speed, $\omega_t$ is the turbine speed, $\omega_i$ is the transmission input shaft speed and $\omega_w$ is the wheel speed.

When the drive clutch is engaged and the torque converter clutch is disengaged, two differential equations describe the system behaviour. On the engine side of the torque converter

$$\dot{\omega}_e = \dot{\omega}_p = \frac{1}{J_e + J_p}\left(\tau_s + \tau_e - \tau_p\right) \qquad [6.1]$$

which gives the engine flywheel and torque converter pump rotational speeds. On the vehicle side of the torque converter

$$\dot{\omega}_t = \frac{1}{J_t + J_{gi} + r_g^2 J_{go} + \left(r_g^2 r_d^2\right)\left(J_w + m_v R_R^2\right)}\left(\tau_t + u\tau_{\max} - \tau_{gl} - \tau_b - \frac{F_d R_R}{r_g r_d}\right) \qquad [6.2]$$

where $\tau_{max}$ is the torque capacity of the clutch when fully clamped and $u$ is the clutch activation signal (a value between 0 for disengaged and 1 for fully engaged). Vehicle velocity is directly proportional to transmission turbine speed when a fixed gear ratio is selected, hence

$$V_v = \frac{\omega_t R_R}{r_g r_d} \qquad [6.3]$$

Engine crankshaft torque, adapted from Heywood [150], is given by

$$\tau_e = \frac{BMEP \cdot V_s}{12.57} \qquad [6.4]$$

where BMEP is the Brake Mean Effective Pressure in the engine cylinders (kPa). BMEP is a function of engine speed and throttle angle. It is obtained by linear interpolation of a static look-up table derived from engine testing. $V_s$ is the capacity of the engine (litres).

The flywheel is initially accelerated from rest by a 'starter' torque, $\tau_s$ (Nm), applied directly to the flywheel.

$$\tau_s = \begin{cases} \tau_s & t < t_s \\ 0 & t \geq t_s \end{cases} \qquad [6.5]$$

where $t_s$ is the duration of the starter motor activity (sec).

Gas dynamics in the engine, combustion and cyclical torque production dynamics are not modelled.

A static torque converter model is utilised in the simulation model. The torque converter impeller torque and turbine torque are given by

$$\tau_t = TR\,\tau_p \qquad [6.6]$$

$$\tau_p = C\omega_p^2 \qquad [6.7]$$

where the capacity factor, $C$ (Nm/(rad/s)$^2$), and torque ratio, $TR$ are functions of the speed ratio across the transmission, given by

$$C = f\left(\frac{\omega_p}{\omega_t}\right) \text{ and } TR = f\left(\frac{\omega_p}{\omega_t}\right) \qquad [6.8]$$

The automatic transmission gear ratio, $r_g$, is a piecewise constant dependent on the gear number. Transmission torque losses are given by

$$\tau_{gl} = \tau_{gp} + \tau_{gs} + \tau_{gt} \qquad [6.9]$$

$$\tau_{tp} = f(\omega_e) \qquad \tau_{ts} = f(\omega_{gi}, n) \qquad \tau_{tt} = f(\omega_{gi}, \tau_{gi}, n) \qquad [6.10]$$

where $\tau_{gp}$ are oil pump losses, $\tau_{gs}$ are spin losses and $\tau_{gt}$ are torque related losses (all in Nm). Transmission losses are derived experimentally and are included in the model in the form of look-up tables.

Braking torque, $\tau_b$ (Nm) is given by

$$\tau_b = u_b T_{b\max} \qquad [6.11]$$

where $u_b$ is the brake signal (from 0 for brakes off to 1 for brakes fully engaged) and $T_{b\max}$ is the maximum braking torque (Nm).

Vehicle drag force as a function of velocity is given by

$$F_d = aV_v^2 + bV_v + c \qquad [6.12]$$

where $a$, $b$ and $c$ are empirically derived coefficients.

The vehicle subsystem model was constructed in the Modelica unified modelling language, using Dymola as the model editor and compiler. The Dymola model was compiled and linked into the Simulink S-function form, allowing it to run as an integral element of a Simulink model.

The vehicle subsystem model requires a number of control inputs to run. In the simulation model, the control inputs are produced by subsystem models representing the driver, the Engine Control Unit (ECU) and the Transmission Control Unit (TCU), reflecting the physical structure of the system. All the controller elements were modelled in Simulink.

The driver model contains a PI controller which determines the acceleration and brake postions in response to the error between the drive cycle speed profile and the actual speed.

Two functions are controlled by the ECU. Firstly, the throttle angle is modulated to maintain a set point idle speed when conditions for idle are met. Secondly, engine fuel flow is calculated, based on a steady-state fuel flow map derived from engine testing.

The TCU model applies the shift schedule (Figure 43) to determine the gear number and torque converter lock-up clutch state. A change in gear number is implemented when an upshift or downshift line is crossed. The lock-up clutch is activated in exactly the same way as gear shifts. Gear number and clutch position outputs from the TCU are inputs into the vehicle subsystem.

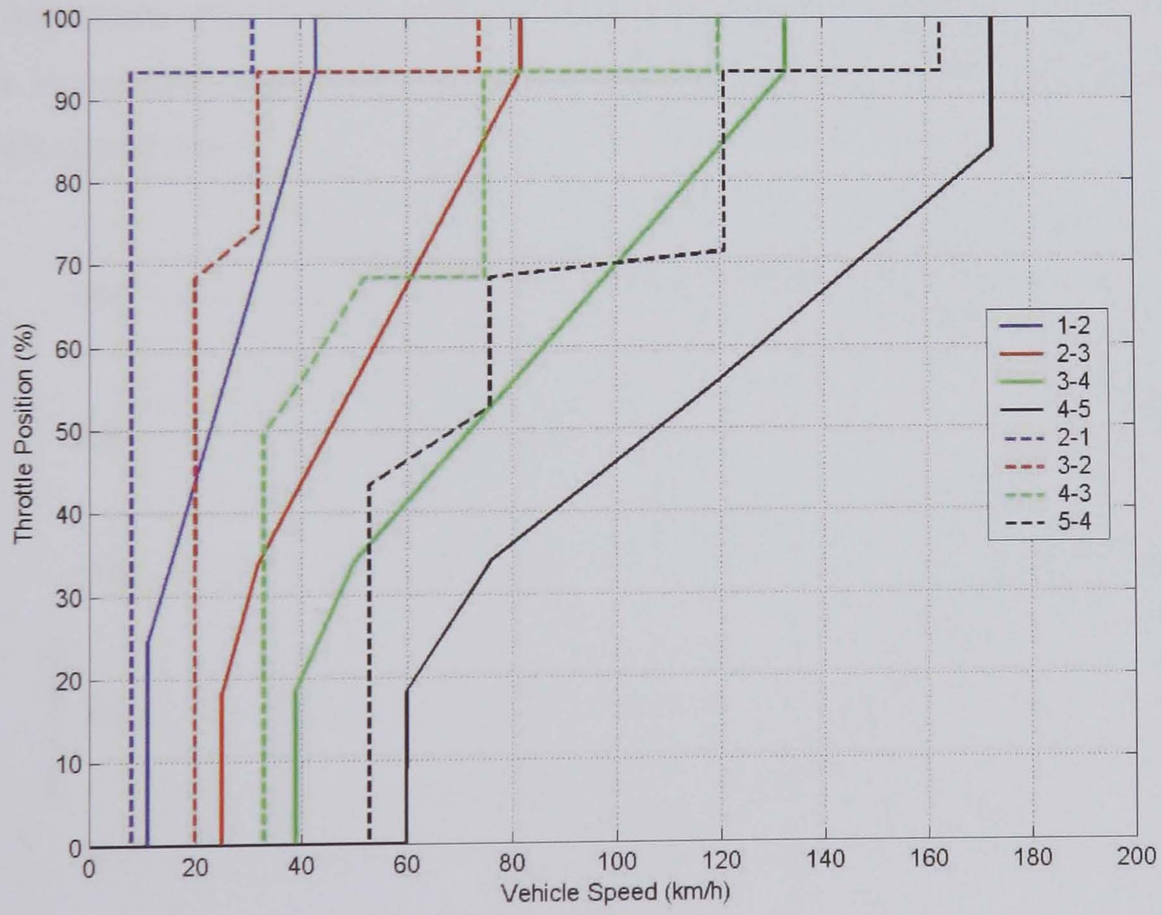


*Figure 43 – Example Transmission Shift Schedule*

### 6.4.2 *Parameterisation of the Simulation Model*

Obtaining and interpreting data with which to parameterise system models can be a challenging aspect of model development. Test results and other information about the operation of the vehicle have been used to derive model input data and to define the normal operating regions of the model.

Deriving Road Load Coefficients

The vehicle road load characteristic was calculated from archived coastdown tests, conducted under certification conditions, and results from coastdown testing conducted in direct support of model development.

A force against velocity curve for the vehicle was derived from the coastdown velocity against time profile. By Newton's second law, force is directly proportional to acceleration

$$F_v = m_v a_v \qquad [6.13]$$

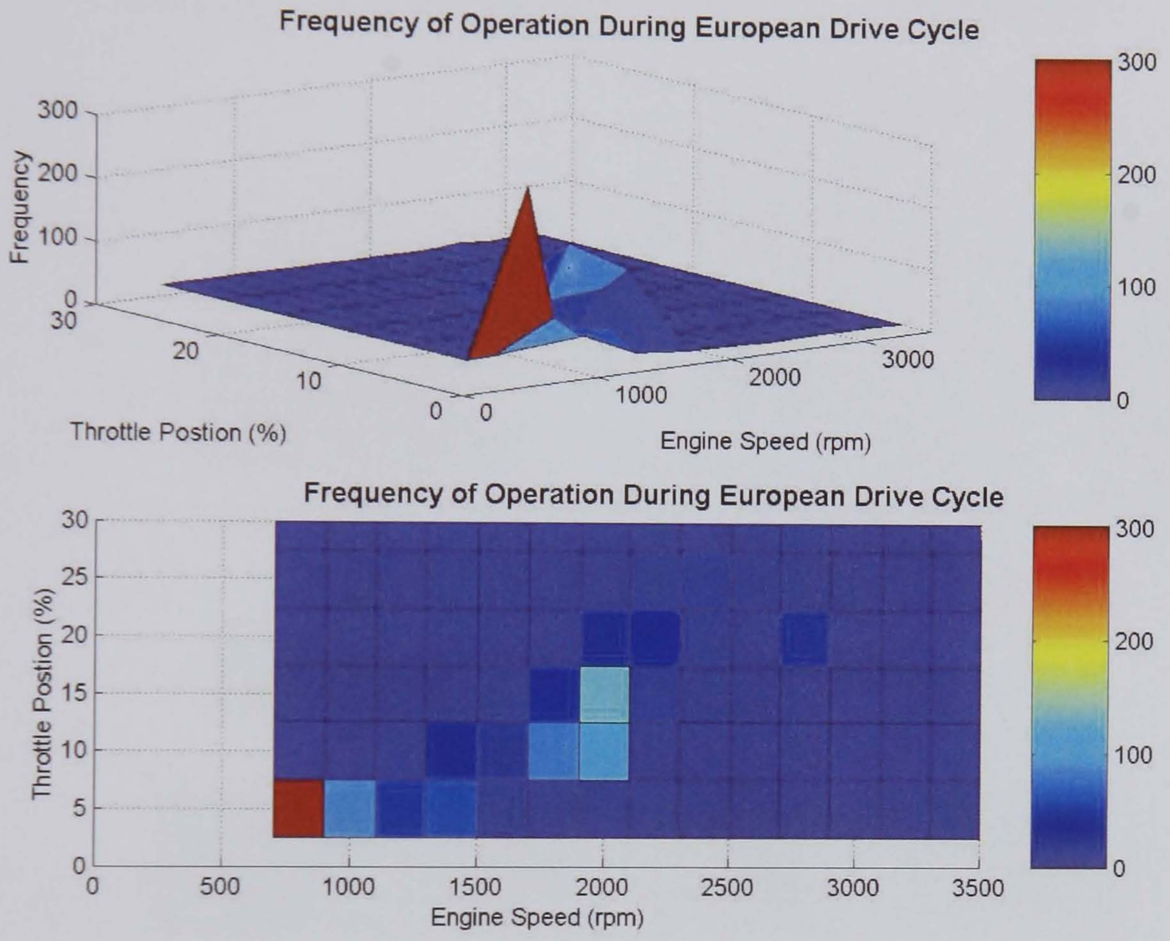
where $a_v$ is vehicle acceleration (m/s). Since the mass of the vehicle is known, force can be calculated by differentiating the velocity-time profile and multiplying by vehicle mass.

As shown in Equation 6.12, drag force is a quadratic function of velocity. The values of *a, b* and *c* are drag coefficients. Aerodynamic drag is the highest order effect, and is a function of the square of velocity. Drag force can be plotted against vehicle velocity and second order linear regression used to derive the *a*, *b* and *c* drag force coefficients (Figure 44). For the vehicle in question, road load coefficients *a*=0.48, *b*=6, and *c*=255 were derived from the track test coastdown.

*Figure 44 – Example Road Load Curve*

#### Drive Cycle Operating Region

Obtaining parametric data for models can be a challenge, and efforts can be concentrated if the model only operates in certain, known regions. For the TCST, legislative drive cycles are an important test routine. Therefore, in Figure 45, typical engine operating regions during the New European Driving Cycle (NEDC) are plotted. The engine operating region is divided into elements of 5% throttle angle by 200 rpm engine speed. Engine speed and throttle position are sampled each second. Cumulative frequency is calculated by summing engine speed and throttle position occurrences in each element.


Frequency of Operation During European Drive Cycle

Frequency of Operation During European Drive Cycle

*Figure 45 – Frequency of Visiting Different Engine Operating Regions During the NEDC*

Figure 45 shows that more than double the time is spent in the idle condition (0-5% throttle, 700-900 rpm), than at any other single operating point. Thus, the idle condition is dominant during the NEDC. It is vital that the simulation gives accurate values of BMEP and fuel flow at low throttle positions and engine speeds.

### 6.4.3 The TCST User Environment

There are three main elements to the structure of the TCST user environment (Figure 46).

(i) Parameterising data files (yellow, blue and grey blocks)

(ii) Defining and running a selected simulation test routine (green blocks)

(iii) Post-processing and viewing simulation test results (orange block)

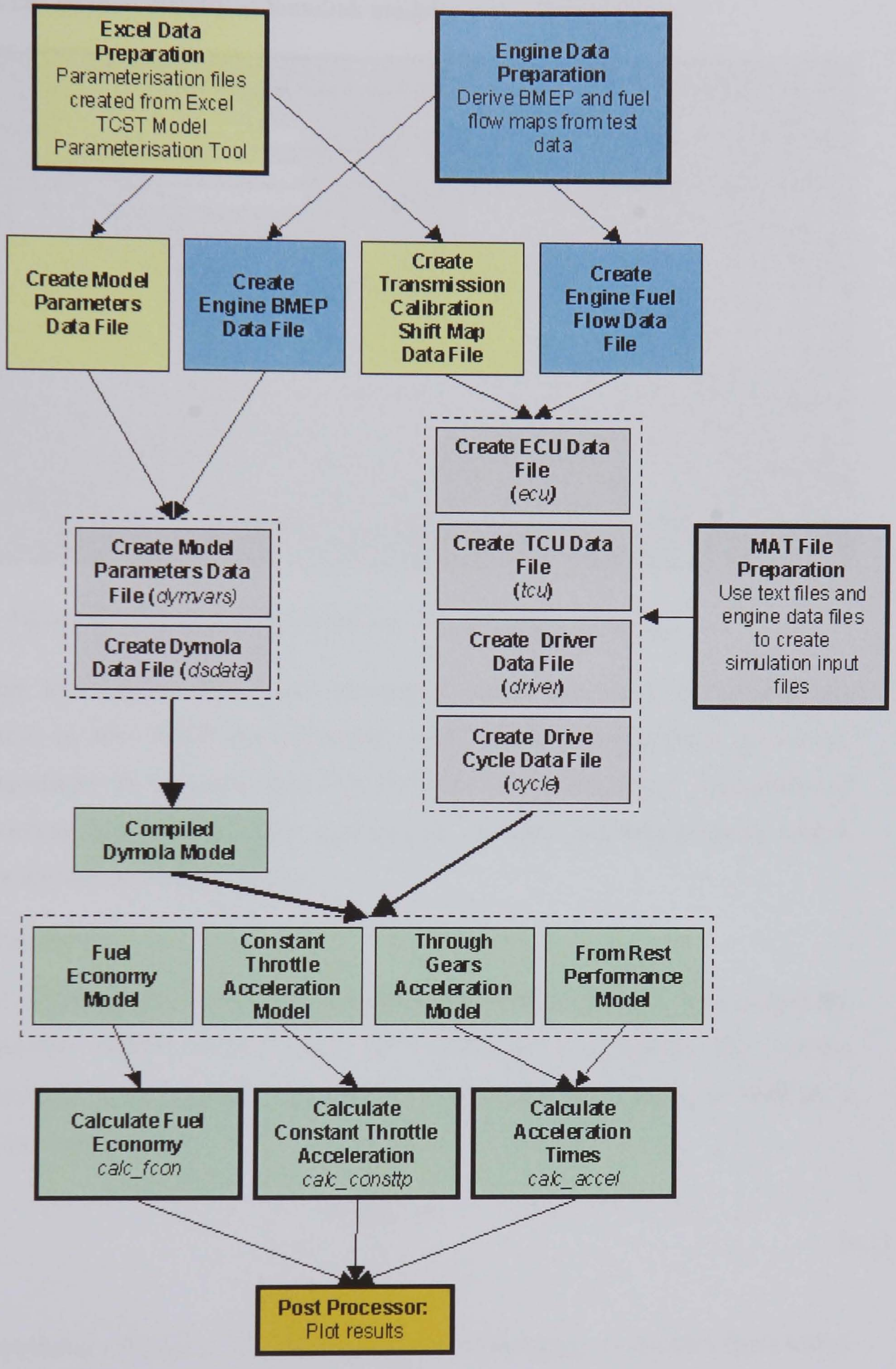
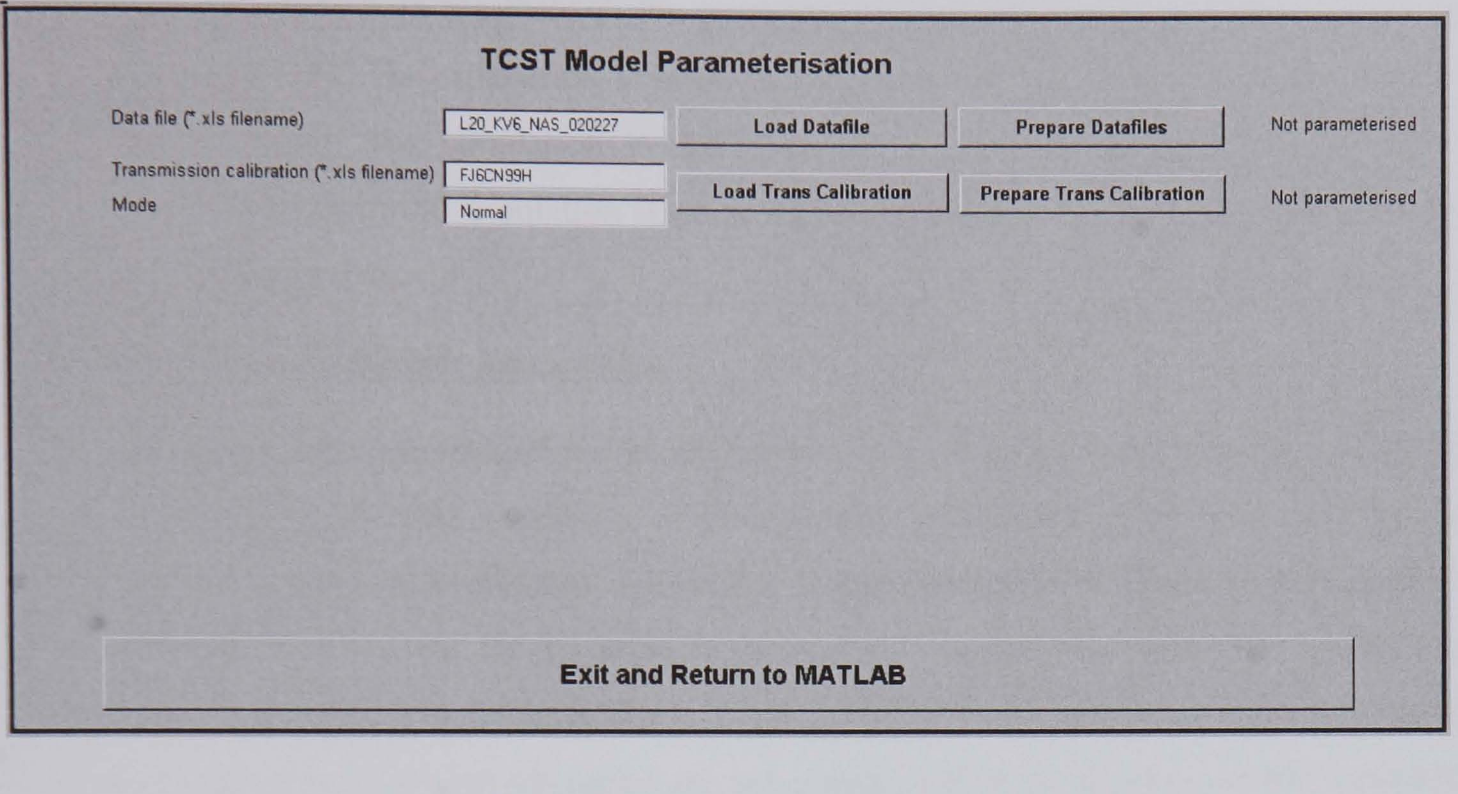


*Figure 46 – TCST Program Structure*

Editing the simulation parametric data is undertaken in two Microsoft Excel spreadsheets, an environment with which the calibration engineers are familiar. Visual Basic macros called from a basic Graphical User Interface (Figure 47) extract the data from the spreadsheets and save it as a set of text files. In a separate stage, the text files are translated into MATLAB binary files that can be used directly in Simulink models.



Data file (*.xls filename): L20_KV6_NAS_020227

Transmission calibration (*.xls filename): FJ6CN99H

Mode: Normal

Not parameterised

Not parameterised

*Figure 47 – TCST Parameterisation Graphical User Interface*

Three simulation test routines have been developed, which are called by clicking the appropriate button in the TCST user interface. Each routine parameterises the model, automatically translating the parameter text files into MATLAB binary files. The function of the three test routines is to calculate fuel economy, to calculate acceleration times, and to conduct constant throttle acceleration tests.

Calculate Fuel Economy

This test routine simulates driving a vehicle around a specified drive cycle, for example the NEDC or American FTP75 cycles. Once the simulation is complete, this routine automatically calculates fuel economy for each section of the drive cycle, as well as a combined economy value using

$$\kappa = \frac{100 \int \dot{m}_f \, dt}{s \rho_f} \qquad [6.1]$$

where $\kappa$ is fuel economy (l/100km), $\dot{m}_f$ is fuel mass flow rate (g/s), $s$ is distance (km) and $\rho_f$ is fuel density (g/l).

Calculate Acceleration Times

Two acceleration tests are conducted using the acceleration time routine. Launch-from-rest and through-gears acceleration times are calculated. In the launch from rest acceleration test, the user is prompted to enter the desired final velocity. The simulation is initialised so that the model is running in an 'idle' condition. At a specified time, Wide Open Throttle (WOT) acceleration commences. Once the final velocity has been reached, simulation is automatically stopped. In the through the gears acceleration test, initial and final speeds are defined by the user. The simulation is initialised at the initial speed and WOT acceleration commences. Again, the simulation is automatically stopped when the final velocity is achieved. Output from the simulation is an acceleration time for each test, and the times are displayed on the screen.

Calculate Constant Throttle Acceleration

The constant throttle acceleration test is relatively simple. After the model has been initialised and is running in an 'idle' condition, a tip-in throttle manoeuvre is executed to a throttle position that is specified by the user. A constant throttle position is maintained throughout the test. Once the test has run for 80 seconds or once the highest gear has been reached, the simulation is stopped. The simulation results are post-processed to produce values of engine speed at each shift. Full shift dynamics are not represented in the model, but the simulation results can be used to give an indication of the continuity of the shift schedule.

### *6.4.4 Validation of the Transmission Calibration Simulation Tool*

In order to support TCST development through validation, a set of experimental, vehicle-based tests were conducted and the tests were replicated using the TCST. By comparing the two sets of results, a level of confidence can be established in the validity of the TCST. In this subsection, the experimental methods are described first, and then a comparison between the experimental and simulation results is presented.

Experimental Testing

A vehicle of the type and specification represented in the simulation model, was used for the experimental testing. The only non-standard element of the vehicle specification was a developmental, re-programmable, transmission control unit. A laptop computer equipped with data acquisition software was connected to the transmission control unit via a break-out box. Any control signal present in the Transmission Control Unit (TCU) could be acquired at a predetermined rate using this experimental setup, and the data log stored on the laptop computer.

Four categories of test were undertaken, and these are explained in Table 4. The speed profile of the New European Drive Cycle (NEDC), as used in Test 4 (Table 4) is shown in Figure 48.

*Table 4 – TCST Validation Tests*

| **Test** | **1. Coastdown Testing** | **2. Tip-in Testing** | **3. Tip-out Testing** | **4. Fuel Economy Drive Cycle Testing** |
|---|---|---|---|---|
| **Purpose** | Correlate the road load of the simulation model to the real world. | Identify the behaviour of the vehicle in response to a step change in the throttle pedal angle. | Identify the behaviour of the vehicle during a transition from positive drive to an overrun condition. | Identify the behaviour of the driver, vehicle and transmission during a standard fuel economy drive cycle. |
| **Experimental methodology** | This test is conducted on a level piece of test track.<br>1. Accelerate vehicle to a pre-determined road speed (120 km/h).<br>2. Select neutral gear.<br>3. Allow the vehicle to coast to a lower speed (50 km/h). | This test is conducted on a test-track.<br>1. Select 'Steptronic' transmission mode and the desired gear.<br>2. Establish steady-state vehicle operating condition at a set engine speed, and commence data logging<br>3. Move throttle pedal rapidly to the desired final throttle position.<br>4. Stop logging once the engine speed reaches its limit.<br>Use initial engine speeds in the range from 1000 to 4000 rpm and final tip-in throttle positions of 25%, 50% and 100%. Use first, third and fourth gears. | This test is conducted on a test-track.<br>1. Select the desired gear<br>2. Establish an initial steady-state engine speed<br>3. Driver swiftly removes his foot from the throttle pedal<br>4. Stop logging once a minimum engine speed was reached<br>Use initial engine speeds of 2000, 4000 and 6000 rpm. Conduct tip-out tests in first, second, third and fourth gears. | This test is conducted on a chassis dynamometer.<br>1. Warm up the vehicle to achieve target engine coolant and transmission oil temperatures (approx. 90°C in both cases)<br>2. Set up the experimental test according to the legal requirements for the European Drive Cycle (Figure 48).<br>3. Set up a fuel mass flow meter to measure fuel flow into the engine on a second-by-second basis.<br>4. Conduct the test. |
| **Simulation representation** | Simulation model is initialised with a vehicle speed that replicates test conditions. Zero throttle pedal position is defined to allow vehicle to coastdown. Compared predicted and actual vehicle speed traces. | Throttle position and torque-converter lock-up clutch signals acquired during the experimental testing form simulation input signals. Compare predicted and actual response. |  | Compare simulated and actual vehicle speed, throttle pedal position, gear number and fuel flow. |

A data acquisition rate of 25 Hz was selected. All but the highest frequency driveline vibrations can be captured at this frequency, and the predictive capability of the simulation model does not reach 25 Hz. In all the tests, a range of signals were acquired, including engine speed, torque converter turbine speed, and gear number, torque converter lock-up clutch duty, and vehicle speed.

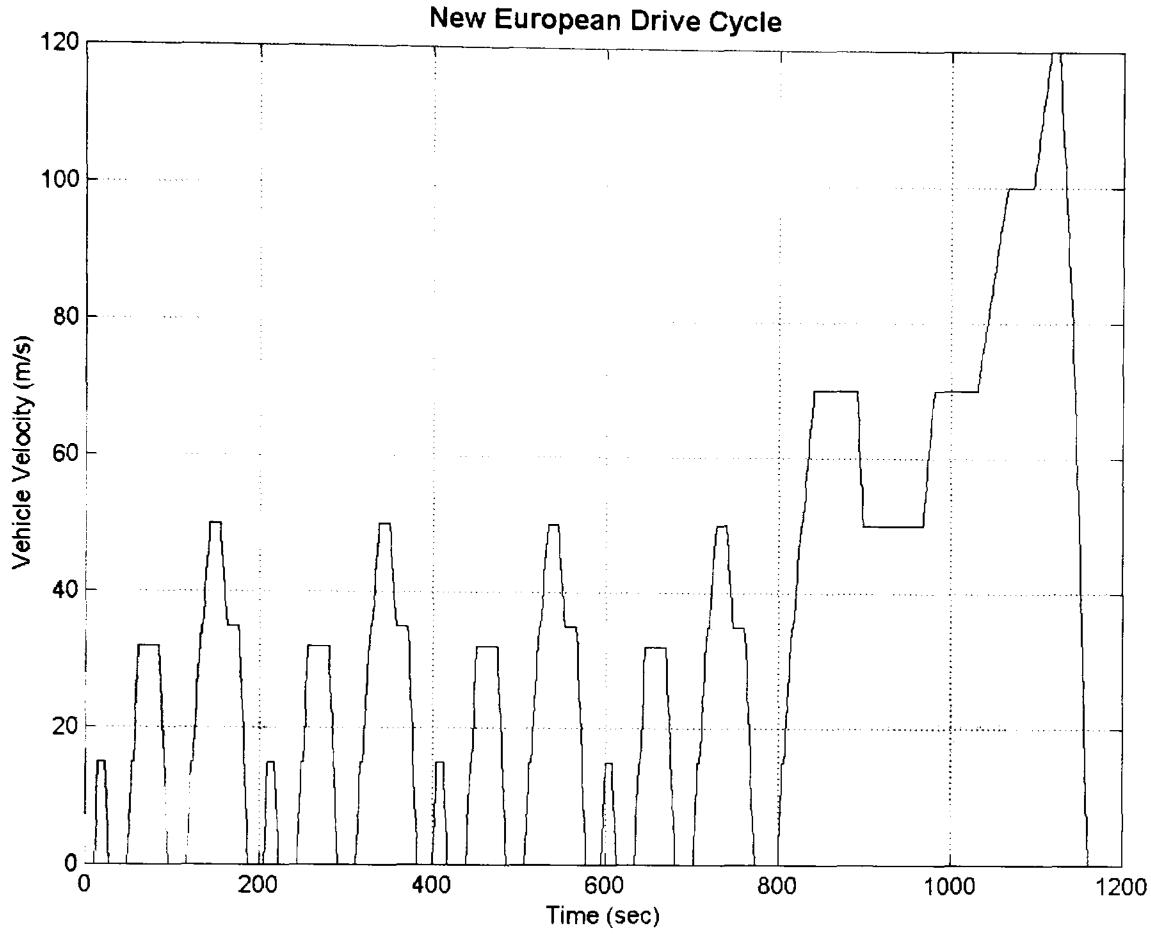


*Figure 48 – New European Drive Cycle Speed Profile*

Comparison of Simulation and Experimental Test Results

The simulation model was parameterised, using the TCST, to match the vehicle that was used for the experimental testing and simulation runs to replicate each test were conducted Experimental test logged data was used as the input to the simulation model, which enables a direct comparison between the experimental and simulation results.

*Coastdown Testing*

An accurate representation of the vehicle road load is an important factor in a simulation model. Vehicle response is a function of the engine output, the vehicle mass and the losses in the system. Aerodynamic losses, rolling losses and transmission losses are major contributors, and these are represented in the coastdown velocity profile.

Figure 49 shows four different measures of experimental vehicle coastdown, compared with the simulation coastdown. The simulation coastdown curve is very similar to the '26 psi' and 'Test' curves. A maximum error of 4.8% occurs between simulation and experimental results for the time taken to coast from 125 to 115 kph, corresponding to an absolute error of 0.22 seconds. This level of error is deemed to give sufficiently accurate simulation results.

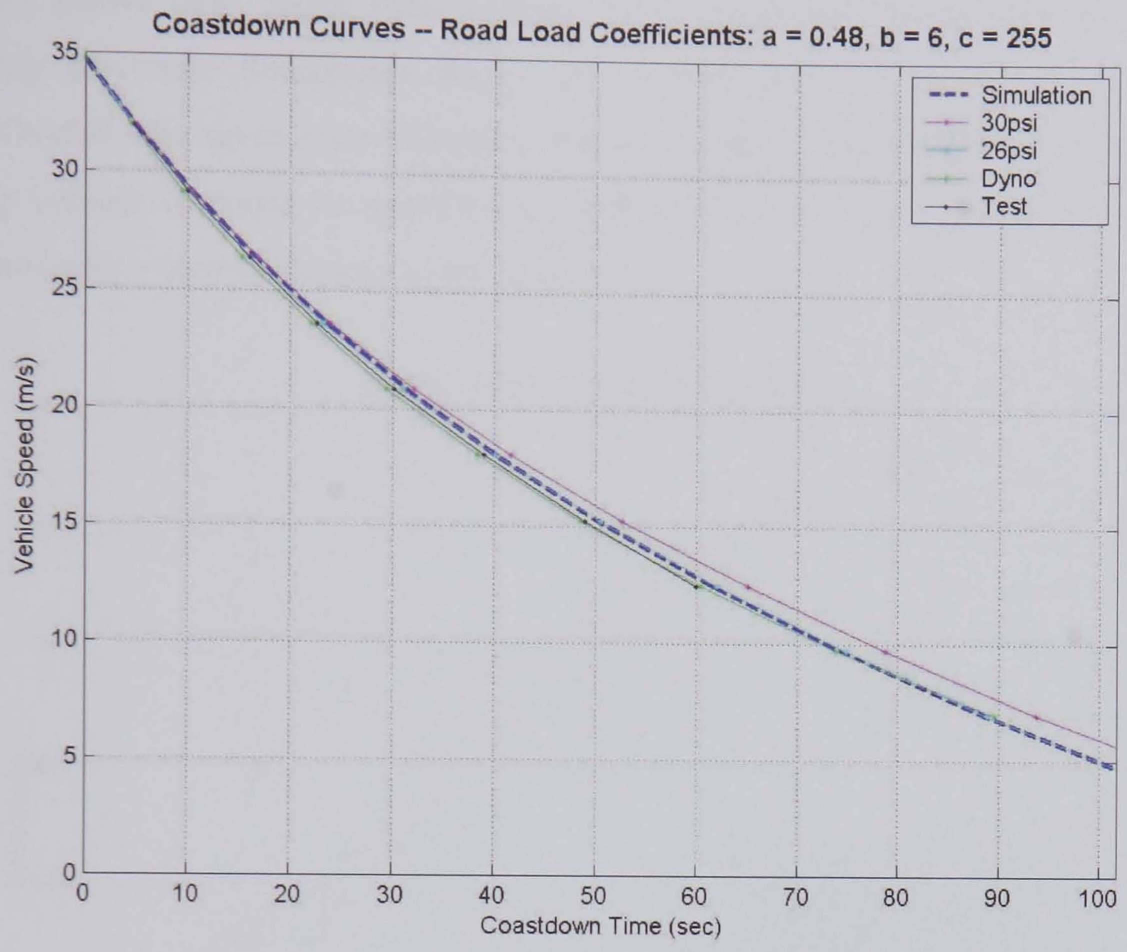


*Figure 49 –Coastdown Results*

*Tip-in Validation Results*

In Figure 50, example results for tip-in tests obtained during experimental testing are compared with replicated simulation tests. There is an excellent match between simulation and experimental engine and turbine speeds over the duration of the test. Turbine speed is directly proportional to vehicle speed. Before tip-in, the simulation speeds drop slightly below the values of the experimental speeds. This indicates that at very small throttle angles and low speeds, the torque predicted by the engine model is slightly below the torque actually produced. The likely reason for the difference is that, in this region, the simulation model relies on extrapolated engine data.

In the instant after the throttle tip-in, the simulation results show a marginally faster response than the experimental results since there is no transient engine response representation in the model. Error arising from the difference in response times (a few tenths of a second) is not, however, significant when considering overall vehicle behaviour. At approximately 13 seconds, the torque converter clutch engages, equalising the engine and turbine speeds. Simulated engine and turbine speeds throughout the period in which the torque converter is slipping match experimental results extrememly closely, demonstrating that the modelled torque converter characterisitic is representative.

The results shown here, along with a larger set of tip-in test results that are reported in Engineering Doctorate Submission Eight, give a high level of confidence in the model validity. Overall, the tip-in tests indicated that the model is satisfactory for the purpose of predicting vehicle response to specified throttle inputs and hence performance and mean acceleration rates – two of its main applications.

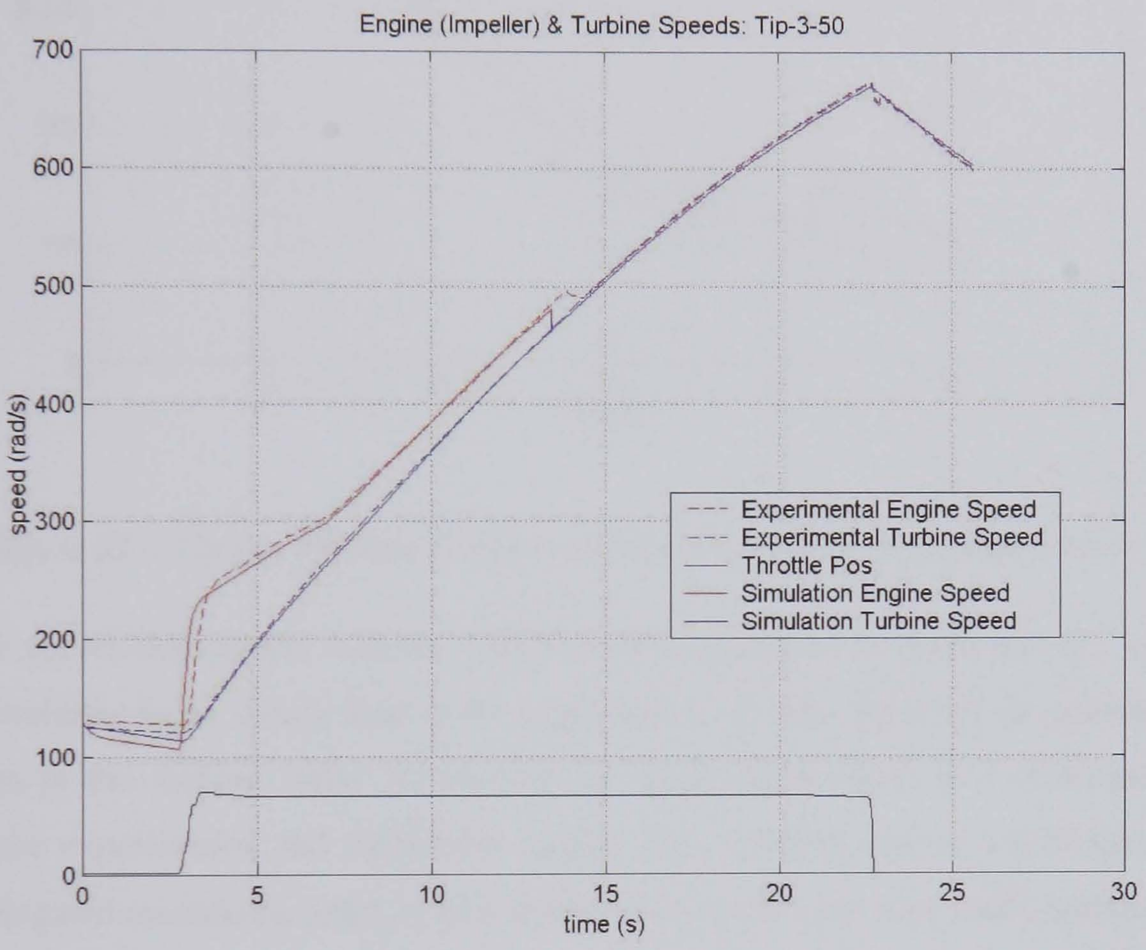


*Figure 50 – Tip-in to 25% Throttle Position Manouvre in Second Gear from 1000 rpm*

*Tip-Out Validation Results*

Tip-out testing validates simulation behaviour during the ‘overrun’ operating condition, in which the throttle pedal was completely released. During overrun, the vehicle momentum is driving the powertrain through the wheels.

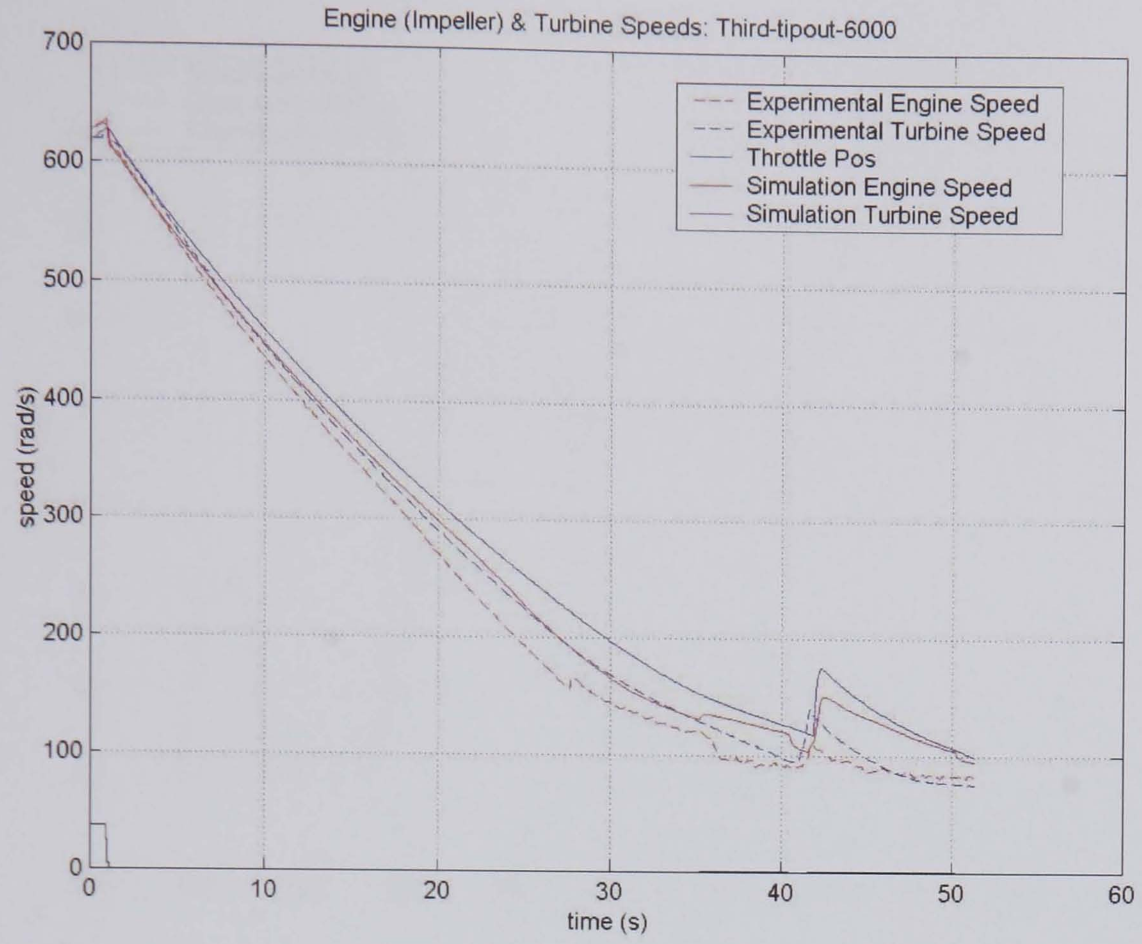


*Figure 51 – Tip-out Throttle Position Manouvre in Third Gear from 6000 rpm*

Figure 51 shows that, in the overrun condition, the simulation predicts that the vehicle and engine decelerate more slowly than in the experimental results, although the general shape of the curves is the similar. After 30 seconds of deceleration, there is a difference of 12% between the experimental and simulation results. This could be due to a difference between the homologated coastdown times, which were used to derive the road load coefficients in the simulation, and the coastdown times on the day of testing (Figure 49). Other sources of experimental error might be ambient conditions on the test day and undulations in the test track. The most likely cause of error, however, is the estimation of overrun (zero throttle) BMEP in the model, since no engine experimental test data was available in that region. Underestimating overrun BMEP would reduce the effect of engine braking and cause the difference between experimental and simulation results seen in these plots.

### *Drive Cycle Validation Results*

Figure 52 to Figure 54 show a comparison between the behaviour of an actual vehicle and the simulation over a section of the NEDC. When following the drive cycle trace, vehicle speed must fall within defined limits. As long as this occurs, the test is acceptable. From Figure 52 and Figure 53, it evident that there is an excellent match between the simulation vehicle speed and the drive cycle velocity profile and the limits are not transgressed. This shows that the driver model is effective in controlling the vehicle speed.

*Figure 52 – Simulation v Experimental Vehicle Speed During One Section of the NEDC*

The error between the specified drive cycle speed and the simulation and experimental speed profiles is illustrated in Figure 53. Legislative error bands are shown as solid black lines. Both speed profiles fall into the error bands, with the exception of the experimental speed at 708 seconds. Simulation and experimental error is of a similar shape, suggesting that the simulation driver model controls the vehicle in like manner to the experimental driver. Analysis shows that the the mean error is small in both cases, with the experimental results giving a slightly lower value (Table 5). Observation of Figure 53 and the simple analysis in Table 5 show that the vehicle speed tracking by the simulation is acceptable, and as capable as the experimental driver.

*Table 5 – NEDC Speed Tracking Error*

| | **Simulation Error** | **Experimental Error** |
|---|---|---|
| **Mean Value (m/s):** | 0.036 | 0.028 |
| **Standard Deviation (m/s):** | 0.183 | 0.363 |

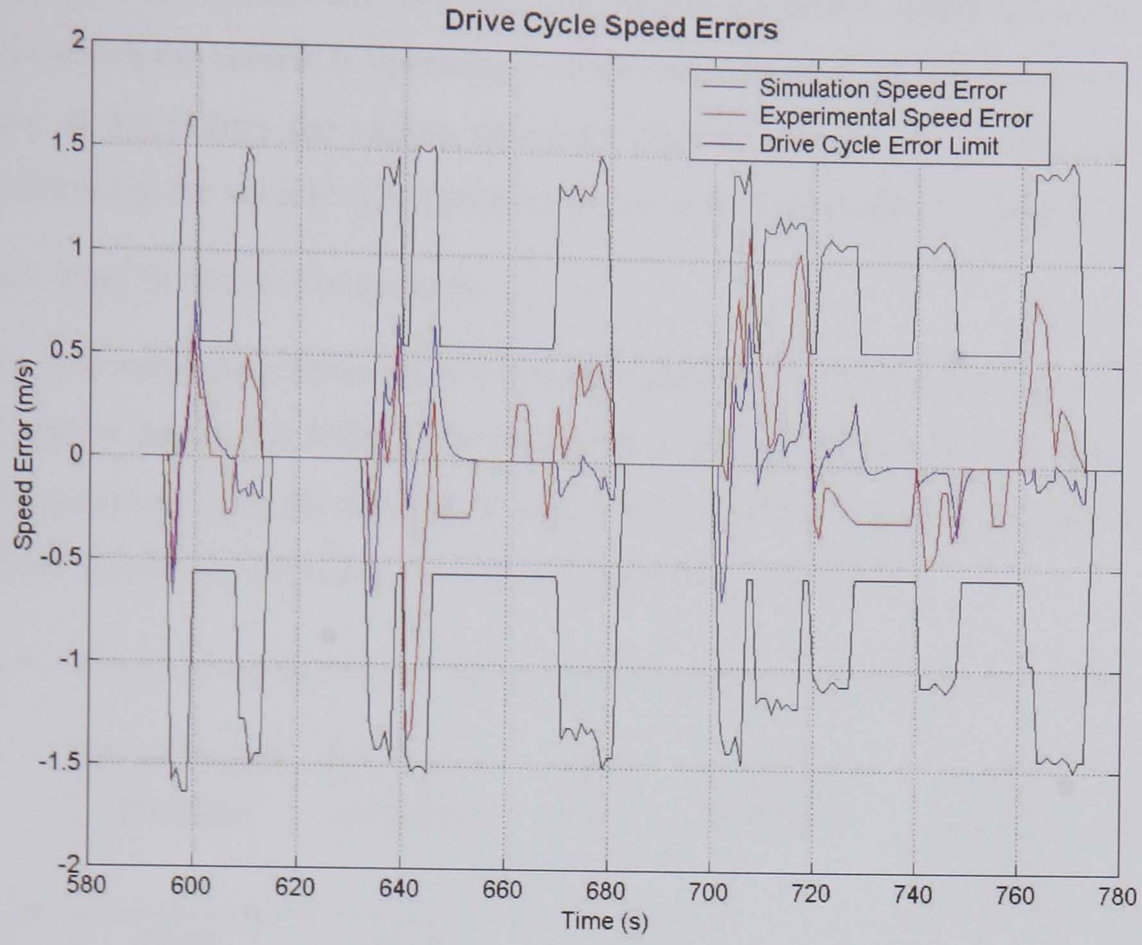


*Figure 53 – Speed Error During Drive Cycle*

*Figure 54– Simulation v Experimental Gear Positions During One Section of the NEDC*

Simulation gear positions (Figure 54) match the experimental gears almost exactly, with no more than two seconds difference in the timing of shifts. Where these minor differences do occur, it is due to differences between the behaviour of the driver model and the actual driver. The gear in which the vehicle is operating is highly significant from a transmission calibration perspective. It determines the engine speed and throttle pedal position that are required to continue following the vehicle speed profile, which in turn determine instantaneous fuel flow.

*Drive Cycle Fuel Economy Comparison*

The drive cycle validation above shows that the behaviour of the model closely matches that of a real vehicle during the NEDC. On this basis, a simulation test over the full NEDC was performed, parameterising the simulation model with a production shift schedule, to compare predicted and actual fuel economy. Results are presented in Table 6.

*Table 6 – Comparison between Predicted and Actual Fuel Economy during the NEDC*

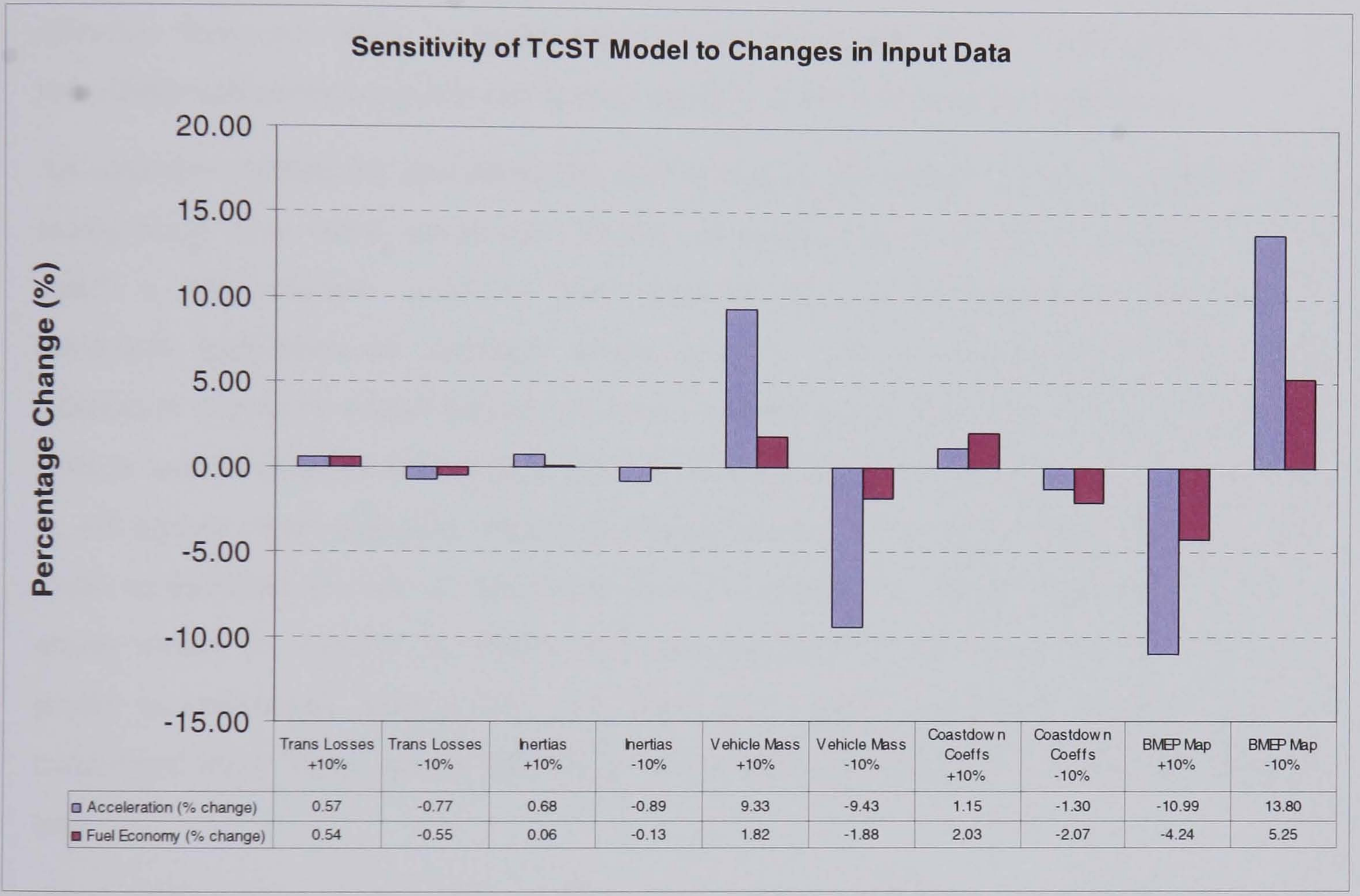
| | **Experimental (l/100km)** | **Simulation (l/100km)** | **Raw Error** | **Cold Start Correction** | **Corrected Economy (l/100km)** | **Error After Correction** |
|---|---|---|---|---|---|---|
| **Phase 1:** | 19.92 | 13.72 | -31.12% | | | |
| **Phase 2:** | 15.87 | 13.71 | -13.61% | | | |
| **Urban:** | 17.2 | 13.71 | -20.29% | 23% | 16.86 | -1.96% |
| **Extra-Urban:** | 9.7 | 9.6 | -1.03% | 0% | 9.60 | -1.03% |
| **Combined:** | 12.4 | 11.11 | -10.40% | 10% | 12.22 | -1.44% |

The simulation represents a condition in which the engine and transmission are fully warm. At the start of the NEDC, it is a legislative requirement that coolant and oil in the engine are at ambient temperature. During the urban section of the drive cycle (the first 780 seconds), the powertrain is warming up and as a result system efficiency is lower than when operating in a fully warm condition. Hence, fuel economy is reduced. Common practice is to apply a correction factor to the simulation results to represent the effect of a cold start on drive cycle fuel economy. The correction factor can be obtained by warm-start and cold-start chassis dynamometer drive cycle tests. Calculation of the difference in urban and combined fuel economy between the two tests yields the cold-start correction factor. The correction factors in Table 6 were derived by comparing fuel economy predicted by a standard simulation programme with published fuel economy figures. For combined fuel economy, the correction factor is usually in the region of 8-12%.

Corrected predicted fuel economy figures (Table 6) are marginally lower than experimental results. The percentage errors, of –2% for urban fuel economy, -1% for extra-urban and – 1.4% for combined economy, are within the variability observed between experimental fuel economy tests. These results indicate that the simulation can be used with confidence, so long as correction factors are known, in place of dynamometer testing to identify the effect on fuel economy of changes in the transmission shift schedule.

*Simulation Sensitivity to Input Data*

A simulation study was undertaken to gain a better understanding of the effect on the simulation results of errors in parametric data. From a baseline set of simulation results, various parameters were adjusted by plus or minus ten percent to identify the sensitivity of the simulation to each parameter. Wide open throttle acceleration time to 100 kph and the fuel economy around a sample section of the NEDC are used to gauge the sensitivity of the model to changes in parametric values. Results are presented in Figure 55.



| | Trans Losses +10% | Trans Losses -10% | Inertias +10% | Inertias -10% | Vehicle Mass +10% | Vehicle Mass -10% | Coastdown Coeffs +10% | Coastdown Coeffs -10% | BMEP Map +10% | BMEP Map -10% |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟪 Acceleration (% change) | 0.57 | -0.77 | 0.68 | -0.89 | 9.33 | -9.43 | 1.15 | -1.30 | -10.99 | 13.80 |
| 🟥 Fuel Economy (% change) | 0.54 | -0.55 | 0.06 | -0.13 | 1.82 | -1.88 | 2.03 | -2.07 | -4.24 | 5.25 |

*Figure 55 – Sensitivity Study*

From Figure 55, it is evident that the BMEP Map, the vehicle mass and the coastdown curve are the parameters to which the simulation model results are most sensitive. Small errors in the accuracy of these parameters can result in significant errors in the simulation results, so special care must be taken in defining these parameters. In particular, a 10% change in the BMEP has an effect of more than 10% on the acceleration prediction. BMEP map interpolation error must be minimised by specifying a fine mesh of steady-state points during engine testing to acquire data that is to be used for parameterising simulation models. In contrast, errors in the estimates or values of transmission losses, inertia values and torque converter characteristics can be tolerated without seriously compromising the accuracy of the model.

## 6.5 An Objective Shift Schedule Driveability Quality Assessment

Optimising the trade-off between shift schedule driveability quality and fuel economy is an important activity during transmission calibration development. When shift schedule development is reliant on physical prototypes, very few iterative loops are possible due to time and resource constraints. It has been shown that valid predictions of drive cycle fuel economy can be made using the TCST. Calibration engineers, however, have only ever assessed shift schedule driveability quality subjectively, which means that there is no objective basis on which to make trade-off decisions and the personal preferences of individual calibration engineers can feature strongly in the decision-making process.

An objective method for describing the shift schedule driveability quality is required. This would bring three major advantages. Firstly, an understanding would be obtained of what makes a shift schedule 'good' or 'bad'. Quantification of this measure would enable a consistent application of standards across different vehicle programmes. Training new calibration engineers would become far more straightforward since the knowledge that they need to acquire could be clearly presented. Secondly, shift schedule driveability quality could be set against other objective vehicle attribute measures, such as fuel flow during a drive cycle, to facilitate the use of analytical decision making for design trade-offs. Thirdly, a means would be available by which calibration engineers could interpret TCST simulation results to understand 'vehicle feel'. The driveability quality of a shift schedule could be understood using TCST results, thus enabling complete shift schedule development using the tool.

Other authors have tackled the problem of describing subjective assessments of vehicle behaviour using objective measures in a number of different areas. Examples of areas in which analogous work has been attempted are brake feel [151]; ride quality [152]; vehicle handling [153, 154]; vehicle response to throttle pedal tip-ins and tip-outs [155]; engine stability and response [156]; manual and automatic gearshift quality [157, 158, 159, 160]; continuously variable transmission driveability [161, 58]; and whole-vehicle driveability [162, 163, 164, 165]. No literature has been identified that focuses on the correlation between the objective measurements and subjective assessments of discrete ratio automatic transmission shift schedules. In this subsection, a basic approach to quantifying one aspect of shift schedule driveability quality is described.

Establishing a link between objective measures of vehicle behaviour and subjective assessments requires a set of experimental tests. A legitimate approach to establishing a link is to acquire vehicle data concurrently with calibration engineers making subjective assessments of the vehicle response or the positioning of gearshifts [158]. Having gathered linked subjective and objective data, the two can be correlated by the application of basic visual and statistical techniques. A defined relationship should be the product of this process, which can be used to infer subjective driveability quality from measured or simulated vehicle behaviour.

### *6.5.1 Experimental Methodology*

A series of constant throttle acceleration tests were conducted using a vehicle on a test track. The scope of the work was limited to acceleration upshifts due to time constraints. Transmission calibration engineers sometimes use this test during the early development stages of a shift schedule to ensure that the shift schedule is consistent. The vehicle was driven according to the test design and the timing and appropriateness of each shift event was rated. Concurrently, data logs of critical vehicle parameters were acquired. The drivers assessed three distinct shift schedules.

In addition to the vehicle testing, a set of structured discussions was held with transmission calibration engineers. The objective of these discussions was to improve understanding of the calibration engineers' individual approaches to subjectively assessing shift schedules.

Vehicle and Experimental Set-up

Vehicle data was acquired during the tests using a standard calibration tool, logging on a laptop computer at a data acquisition rate of 50 Hz. Acquired data included vehicle speed, engine speed, transmission input speed, gear number, torque converter lock-up state, and vehicle longitudinal acceleration. Vehicle longitudinal acceleration was measured using a DC accelerometer mounted on the vehicle centre-line and the signal was logged as an analogue input on the same time base as the other signals.

Six trained transmission calibration engineers were selected as the drivers and assessors for the experimental testing. Since transmission calibration engineers are the end-users of the results from the study, and it is important to link their subjective assessments of transmission shift schedules to objective measures. Ultimately, generic customer subjective assessments should be correlated to vehicle objective behaviour, but establishing that link is beyond the scope of this study.

A method was required for rating shifts that enabled calibration engineers to identify specific driveability effects related to the shift schedule. The work of Dorey and Martin [156] illustrated the importance of clearly identifying objective characteristics associated with each general driveability feature. To this end, shift timing or positioning was selected as an objective measure associated with the constant throttle acceleration tests.

A subjective rating scale was developed for use during these tests, as illustrated in Table 7. A coarse scale was selected to minimise ambiguity in the minds of the calibration engineers. Rather than providing a rating number, calibration engineers were asked to rate each shift in descriptive terms. Numerical ratings were recorded on the test sheets based on the descriptions provided by the calibration engineers.

*Table 7 – Shift Schedule Rating Scale*

| **Numerical Rating** | **Acceleration & Roll-Out Tests** |
|---|---|
| 1 | Shift far too late |
| 2 | Shift too late |
| 3 | Shift about right |
| 4 | Shift too early |
| 5 | Shift far too early |

### Vehicle Testing Procedure

As in Schwab's work [158], objective data and subjective data were acquired concurrently during the experimental testing described here, so that each rating could be assessed in conjunction with its specific vehicle behaviour.

Calibration engineers drove the vehicle and made subjective assessments. They were asked to accelerate the vehicle from rest at a defined constant throttle pedal position. Pedal positions of 10%, 20%, 30%, 50%, 75% and 100% were selected. At lower throttle pedal positions, the rate of change in engine torque as a function of pedal position is greater, hence a higher concentration of tests were conducted at lower pedal positions. At each transmission upshift event, the driver was asked to rate the appropriateness of the upshift point based on the rating scale in Table 7.

### Structured Discussions with Calibration Engineers

Structured discussions were conducted with the calibration engineers in order to gain an improved understanding of their thought processes when they assess shift schedules. Each discussion took place on an individual basis. Discussions were focused around a questionnaire that was designed to provide an understanding of the important conscious and subconscious criteria that are used by calibration engineers when assessing shift schedules (Appendix A). Discussions took the following form.

1. Calibration engineers were asked to describe the criteria that they would use for the assessment of an initial shift schedule.
2. Results from four constant throttle acceleration tests were presented to the calibration engineers. They were asked to rate each shift based on time traces of engine speed, gear position, throttle pedal position and vehicle speed. As they went through the process of assigning ratings, they were asked to justify each value and their comments were noted.
3. As a final question, calibration engineers were asked whether additional data would have been helpful in assigning ratings.

Secondary benefits were produced through conducting these structured discussions. For instance, calibration engineers were provoked to make their shift schedule assessment criteria explicit. The discussions contributed to training the calibration engineers to assess shift schedules using quantitative measures – a requirement if the calibration engineers are to interpret simulation results.

### *6.5.2 Findings*

The experimental testing described above provided three sets of results: (a) calibration engineers' subjective ratings and (b) an associated set of time-series logs of vehicle behaviour, and (c) the outcome from a series of structured discussions with the calibration engineers. This information can be used to establish some form of correlation between the objective behaviour of the vehicle and the subjective assessment of the calibration engineers. Once a correlation has been established, it should be possible to predict anticipated subjective constant throttle upshift ratings from experimental or simulation test results. A full set of results is presented in Engineering Doctorate Portfolio Submission Nine.

There are a number of vehicle variables that could be used as a basis of correlation. Engine speed, engine tone and time between shifts were the most popular suggestions provided by the calibration engineers during the structured discussions. Since engine tone for a given throttle position is a strong function of engine speed, for the purposes of this investigation, it will be considered as one with engine speed. Acceleration continuity was also an idea that featured in the calibration engineers' comments. The time between shifts gives a 'rhythm' to acceleration upshifts that may also be important.

The first proposed correlation to be considered is between acceleration continuity and subjective rating. It was found that, even for similar throttle pedal positions and change in acceleration values, there was a high level of scatter in the subjective ratings that were assigned. For instance, a shift at a throttle pedal angle of 50% that gives a change acceleration of 0.6 m/s$^2$ is assigned ratings of '2', '3' or '4' in different instances. Deriving a relationship between calibration engineers' subjective ratings and the change in acceleration during a shift, and then using that relationship to predict an anticipated rating therefore seems to be unfeasible. The second proposed correlation to be considered is between subjective rating and the time between shifts. Once again, on attempting to apply linear least-squares regression to the data points for each rating, the correlation coefficient for this relationship was found to be very low. Instances of different ratings being assigned to the same operating condition were present again. Predicting the driveability of a shift schedule based on the time since the previous shift using these data was therefore found to be infeasible.

The third proposed correlation, between upshift engine speed and the calibration engineers' ratings, was found to give better results than the previous attempts (Figure 56). Quadratic least-squares regression curves indicate that the upshifts rated by calibration engineers as being 'too late' or 'much too late' (rating '1' or '2') tend to occur at higher engine speeds than those rated 'about right' (rating '3'). Conversely, upshifts that occurred at low engine speeds were generally rated as 'too early' or 'much too early' (rating '4' or '5').

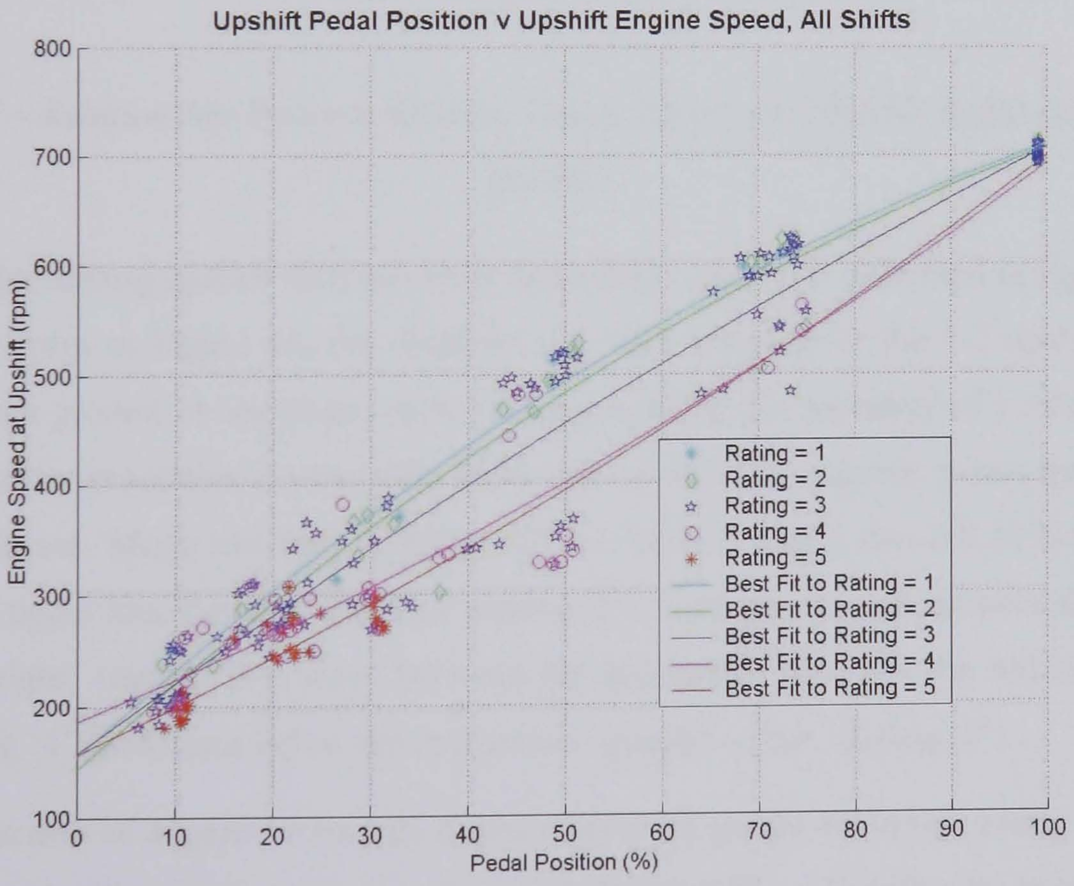


*Figure 56 – Relationship between Rating, Engine Speed and Throttle Pedal Position*

The basic relationship that has been identified in Figure 56 can only become useful in predicting the subjective rating of shift schedules if it can be captured in an assessment tool that calibration engineers can use with ease. Creating an assessment tool that is based purely on regression techniques would be inappropriate given the variability in the subjective ratings assigned by the calibration engineers. Information gleaned from the structured discussions with the calibration engineers can be incorporated into the assessment tool.

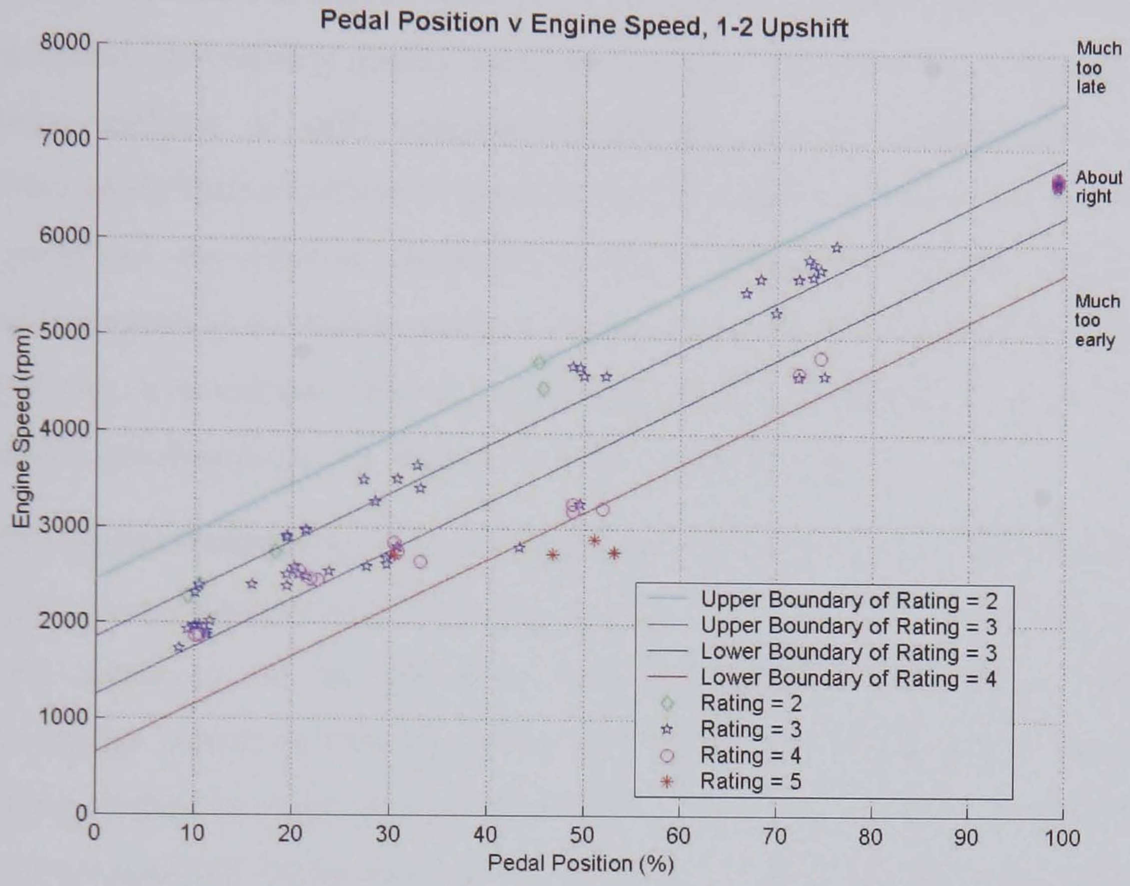


*Figure 57 – Relationship Between Ratings, Engine Speed and Throttle Pedal Position (1-2 Upshift)*

A model representing upshift shift schedule driveability quality is presented in Figure 57. It is in the same form as Figure 56, but displays only data relevant for the 1-2 upshift. A set of lines has been plotted on the chart, each line representing the boundary of a rating zone. As indicated by the annotation on the right hand side of the chart, upshift points that fall above the cyan line are 'Much too late' (a rating of '1'). Upshift points that fall between the cyan line and the upper blue line are 'Too late' (rating '2'). Upshifts that fall between the blue lines are 'about right' (rating '3'), those between the lower blue line and the red line are 'Too early' (rating '4') and those below the red line are 'much too late' (rating '5').

Visual inspection of Figure 57 reveals that a number of points lie in the wrong rating zone. For instance, at 75% pedal, a number of upshift points with a '3' rating lie in the '2' rating zone. It is worth noting, however, that there are also points with a '3' rating in the '4' rating zone. Once again, this highlights the variability in the experimental test results and demonstrates the need for consistent criteria by which shifts can be assessed. Although not in perfect agreement with the calibration engineers ratings, the methodology presented here gives a baseline for development that broadly correlates with calibrator's ratings.

### *6.5.3 Discussion*

Calibration engineers can use a chart in the form of Figure 57 to imply likely constant throttle acceleration upshift driveability quality subjective ratings. This provides a simplistic method for the initial analysis of shift schedule driveability quality. Transmission calibration engineers must apply their expertise to interpret the information in the charts. For instance, if an upshift point lies very close to a boundary of the '3' rating zone, it is the responsibility of the calibration engineers to decide whether or not the speed at which shift occurs should change. Likewise, at low pedal positions, upshift points that nominally lie in a '2' zone may be unacceptably late due to the low engine speed at which they occur.

Several shift schedule features are not evident during constant throttle acceleration testing, but are important during normal (unstructured) driving. These include hysteresis in the shift schedule; the sensitivity of the vehicle to downshifts produced by tip-in throttle pedal movements; torque converter lock-up clutch behaviour; and coastdown to rest downshift positions. Most of these features relate to downshifts rather than upshifts. Despite this, a shift schedule that is consistent during structured driving should form a basis from which the shift schedule can be tuned during in-vehicle testing. By providing an enhanced starting point, the number of changes that are required to the transmission calibration during physical prototype development should be lower than with historical approaches.

The objective of using a chart in the form of Figure 57 is not to give a definitive prediction of vehicle shift schedule driveability quality. Rather, the objective is to assist calibration engineers to develop a sensible first iteration of a shift schedule by giving a good indication of the appropriateness of the upshift points at each throttle pedal position. A chart of this format can be incorporated into the TCST for use during initial shift schedule design.

There are a number of areas in which further work would enhance the method for assessing upshift driveability quality that has been presented here. A broadened scope could consider tip-out upshifts, downshifts, and torque converter lock-up clutch behaviour. The method has been derived from tests conducted on one type of vehicle and a relatively small sample of drivers. Validation of the system would be required before it could be applied with any confidence to other vehicles. For instance, engine speeds that are acceptable for upshift at a specific throttle pedal position may depend on the inherent characteristics of the vehicle and the torque produced by the engine. Likewise, if the characteristic of a vehicle was to be changed, for instance by the application of a sport mode, then the calibration engineers' expectations of the vehicle behaviour would change and the upshift driveability quality charts would require adjustment. Another avenue for further work is to develop the experimental technique used in this study. Revised experimental testing could reflect the calibration engineers more normal unstructured approach to acquiring data, using a similar approach to Chen et al [153].

## 6.6 A Comparison of Experimental and Simulation-Based Methods for Basic Transmission Calibration Exercises

Transmission calibration engineers have a standard set of core tests that they use when developing a shift schedule. Although many other tests are also used, constant throttle acceleration tests, vehicle acceleration performance tests, and fuel economy tests are particularly important. These tests would typically be used to verify a shift schedule that had been developed using a desktop analysis, and these are the tests that have been built into the capabilities of the TCST.

The aim of this subsection is to demonstrate the appropriateness of the TCST for its intended application. To this end, a series of parallel tests was conducted which allowed a direct comparison the traditional, vehicle-based method to shift schedule development and a simulation-based method. The TCST was used to perform the requisite simulation tests.

Three shift schedules were designed to support the method comparison. These represented initial shift schedules that have been designed using basic desktop methods. A comparison between the schedules was required to assist transmission calibration engineers to determine which is the most appropriate, and ultimately to produce a shift schedule that blended positive attributes from each. Each shift schedule was designed to give the vehicle distinctive driving characteristics. For convenience, the three schedules were given the codenames 'GK1', 'GK2' and 'GK3'.

GK1 (Figure 58) was designed to provide late upshifts, willing downshifts and hence give a 'sporty' feel to the vehicle.

GK2 (Figure 59) provides early upshifts in the region of the shift schedule traversed during legislative drive cycles. Outside this region, changes will not have any effect on homologated fuel economy, and so GK2 provides later upshifts that will give a more sporty feel.

GK3 (Figure 60) provides early upshifts and demands higher throttle pedal angles before activating a downshift.

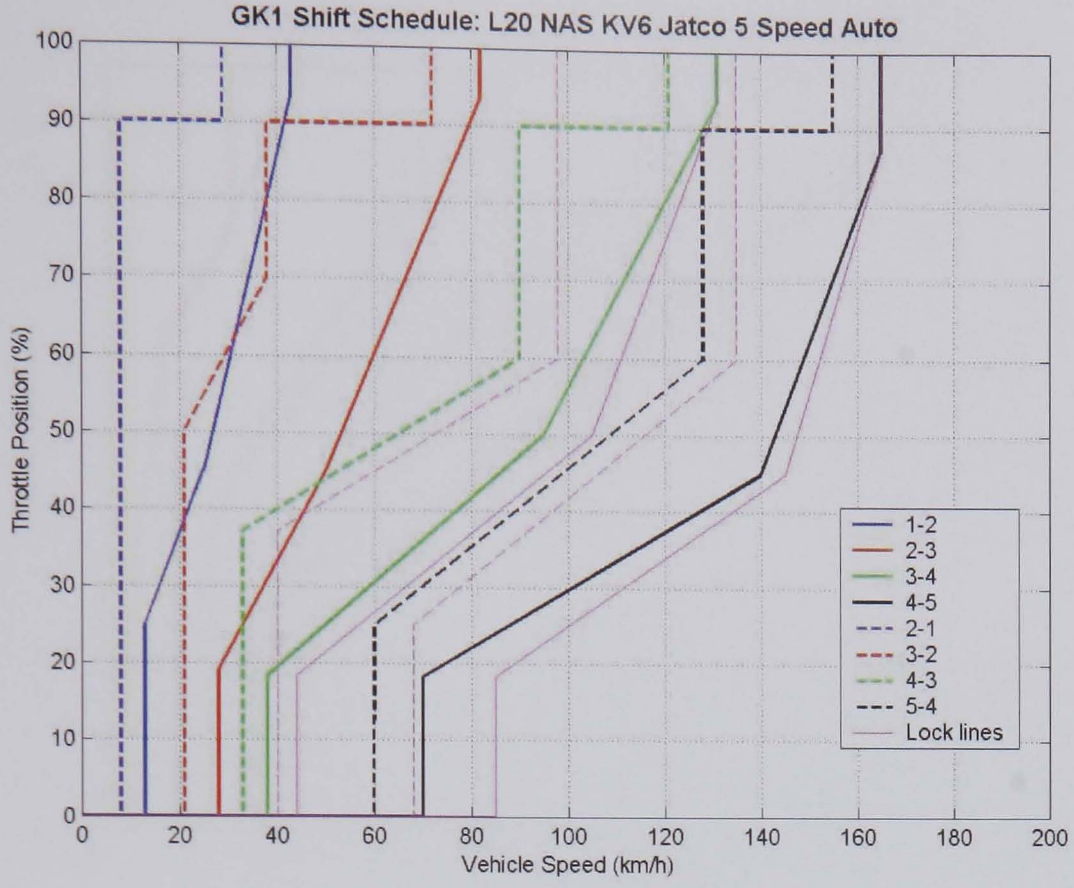


*Figure 58 – GK1 Shift Schedule*

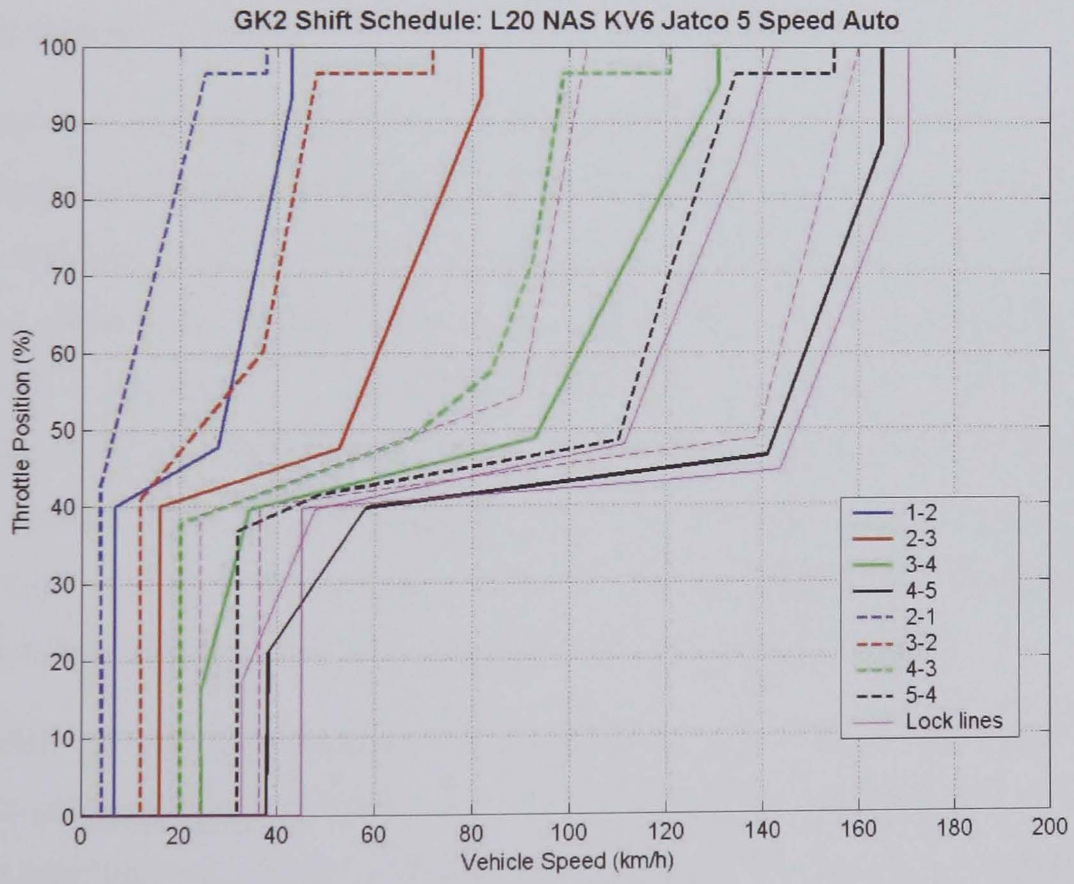


*Figure 59 – GK2 Shift Schedule*

*Figure 60 – GK3 Shift Schedule*

### 6.6.1 *Experimental Testing*

Two standard fuel economy drive cycles were selected as a basis of the experimental testing. Most test work was undertaken using the US EPA FTP-74 drive cycle, with a drive cycle intended to represent typical customer driving in a rural environment (the Rural CDC) being used to give additional insights. Testing was conducted on a chassis dynamometer that is equipped with a full array of exhaust emissions analysis equipment. Tests were conducted using a single vehicle on two different days, and the driver in each case was different. This scenario is typical of a normal calibration testing exercise, which would take place over a number of days and may use a variety of drivers. The experimental testing methodology is described in full in the Engineering Doctorate Portfolio Submission Nine.

A point worthy of note regarding the experimental set-up is that a new test technique was introduced to measure fuel flow during the chassis dynamometer testing. An AVL Fuel Mass Flow Meter was used to provide a continuous, fast transient response measurement of fuel flow. A Coriolis Effect fuel mass flow sensor is at the heart of the meter. Pressurised fuel is passed through a small diameter u-shaped piece of piping. The sensor is constantly vibrating, and the resultant force acting on the sensor is proportional to the fuel flow.

Figure 61 shows mean fuel economy results from the FTP-74 and Rural CDC drive cycles. Two FTP-74 tests were conducted using each of the three shift schedules. The tests were conducted in two sets. 'Test 1' refers to the first set of tests and 'Test 2' refers to the second set. The FTP-74 drive cycle is divided into two phases. Phase 1 is the first 505 seconds and Phase 2 lasts from 505 seconds to 1372 seconds. Weighted fuel economy is calculated from a complex combination of phases 1 and 2 emissions [166]. One set of Rural CDC tests was conducted, and the results are included in Figure 61 for convenience.

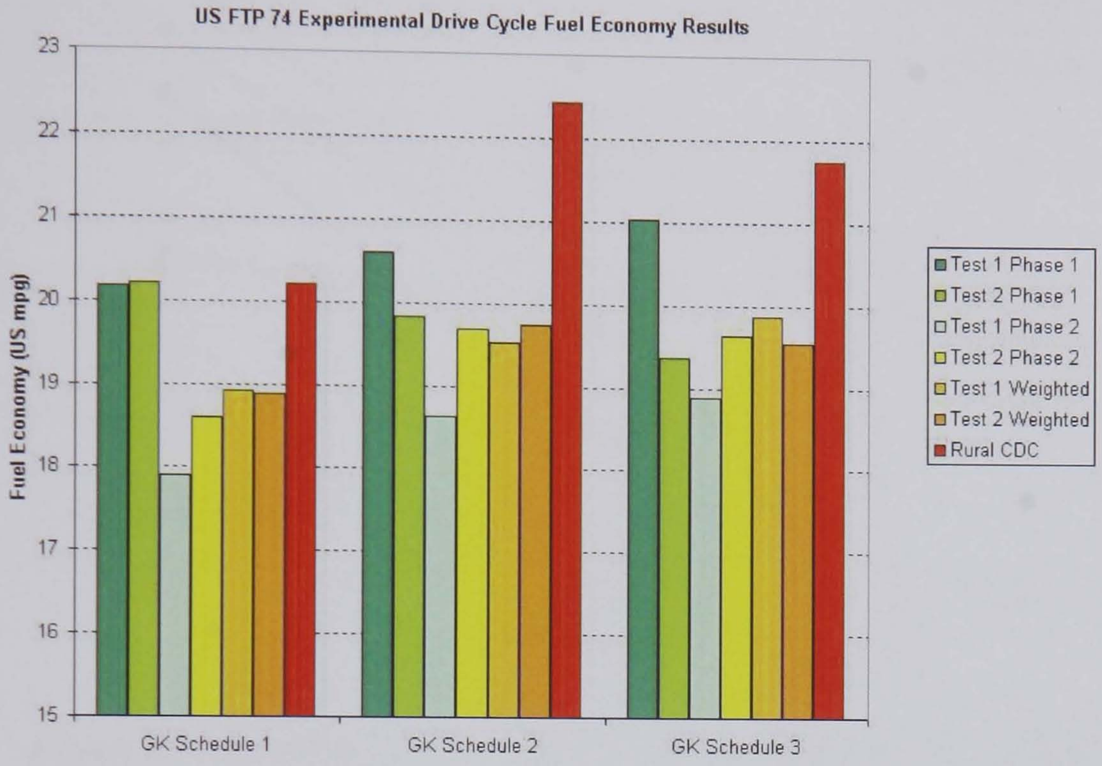


*Figure 61 – US FTP-74 and Rural Drive Cycles Fuel Economy*

Comparing the difference in fuel economy between shift schedules as seen in Figure 61, GK2 gives a mean 3.9% improvement over GK1 in weighted fuel economy around the FTP-74 drive cycle, and an 11% improvement in fuel economy around the Rural CDC. GK3 gives a mean 4.2% improvement over GK1 in fuel economy around the FTP-74 drive cycle and 7.6% improvement around the Rural CDC.

Considerable variability is evident between Test 1 and Test 2 for the same shift schedule and phase of the FTP-74 test. Figure 62 gives a clearer indication of the variability by plotting results from each phase together. For Test 1 results, the trends in GK1, GK2 and GK3 are very similar, with GK3 showing slightly better fuel economy then GK2 for both phases of the cycle and the weighted result. In all cases, the lowest fuel economy is evident in Phase 2 of the test. Test 2 results, however, do not show the same clear trends. The phase-to-phase variation is greatly reduced, although the weighted fuel economy is similar for each shift schedule.

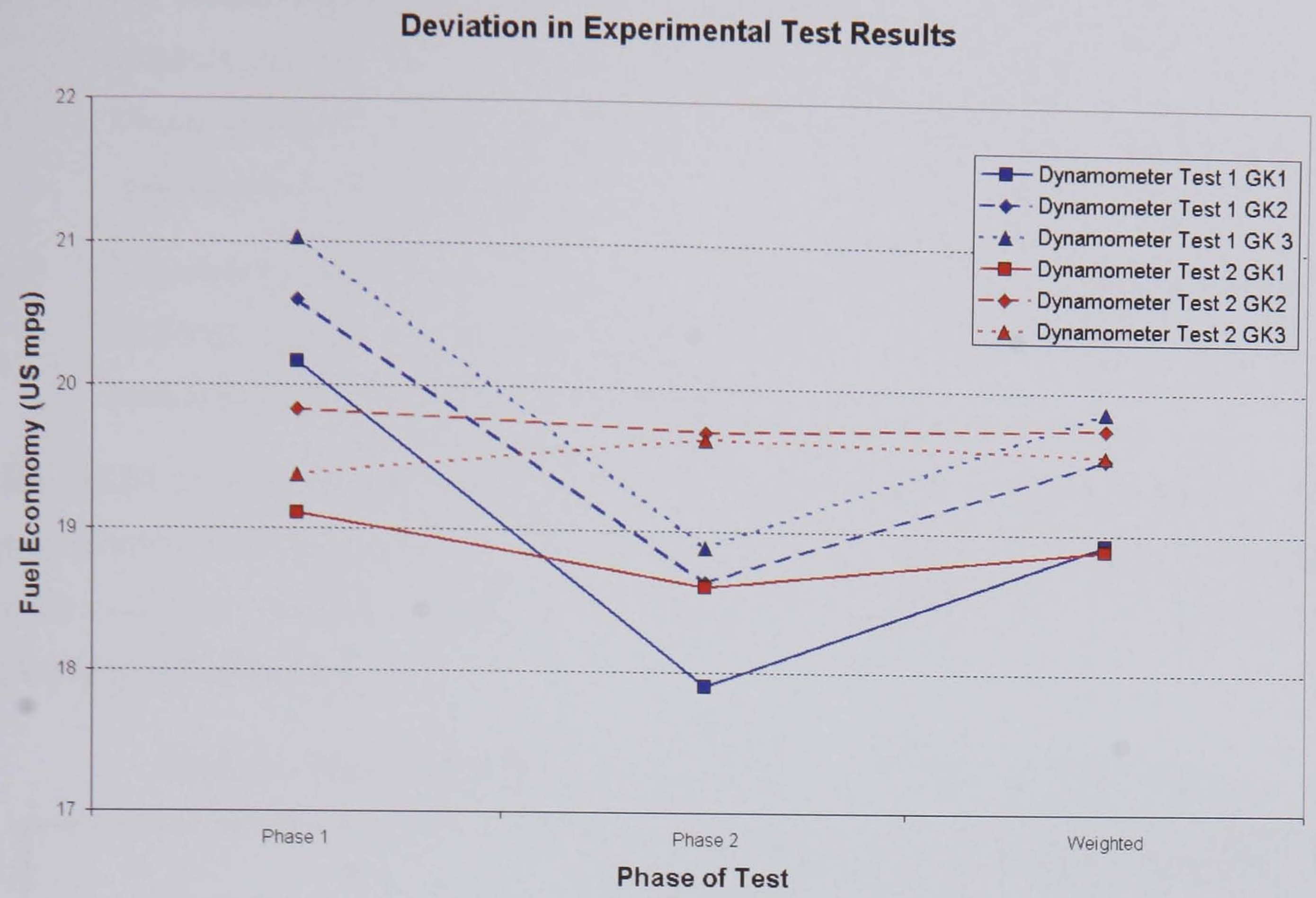


*Figure 62 – Deviation between Tests during US FTP-74 Drive Cycle*

*Table 8 – FTP-74 Percentage Difference between Test 1 and Test2*

| | **Test to Test Variability** | | |
|---|---|---|---|
| | **Phase 1** | **Phase 2** | **Weighted** |
| **GK Schedule 1** | 5.58% | 3.75% | 0.25% |
| **GK Schedule 2** | 3.87% | 5.34% | 1.05% |
| **GK Schedule 3** | 8.60% | 3.85% | 1.60% |

Table 8 shows the percentage difference between Test 1 and Test 2 for each phase of the FTP-74 drive cycle, and for each shift schedule. Only two sets of tests were conducted due to constraints on facilities time, so a statistical measure of standard deviation cannot be defined. The results in Table 9, however, show the difference between results of the two sets of tests is up to 8.6%. Weighted fuel economy shows a smaller difference, at between 0.25% and 1.6%. Likely reasons for the test-to-test variability are as follows.

(i) Under normal legislative test conditions, the vehicle is left in soak at standard ambient temperature (25°C) for twelve hours before a drive cycle is commenced. These tests, however, were conducted back-to-back, and so the powertrain components were warm at the start of the test. A narrow band of acceptable engine oil, coolant and transmission oil initial temperatures were established before each test commenced, but due to differential warm-up of the fluids, it was not possible to obtain identical temperatures. Differences in the temperatures of fluids may have contributed to test-to-test variability.

(ii) Test-to-test variation in driver inputs was another likely source of variability. Different drivers have different styles of following the drive cycle trace, which translates into different throttle pedal rates and positions.

The results in Table 9 shows that changes in the shift schedule can cause FTP-74 drive cycle fuel economy variations of up to 5.5% (Phase 2). The magnitude of this change is very similar to the test-to-test variability for Phase 2, despite the fact that schedule GK1 is very different to schedules GK2 and GK3.

*Table 9 – Effect of Change in Shift Schedules on FTP-74 Fuel Economy*

| | Effect of Change in Shift Schedule | | | Rural CDC |
|---|---|---|---|---|
| | Phase 1 | Phase 2 | Weighted | |
| GK Schedule 2 v GK Schedule 1 | 2.96% | 5.00% | 3.87% | 10.99% |
| GK Schedule 3 v GK Schedule 1 | 2.91% | 5.54% | 4.25% | 7.62% |

Since the effect of changes in the shift schedules is of a similar magnitude the effect of changes between tests, the experimental method is not sufficiently robust for optimisation of shift schedules for fuel economy purposes. Taking ensemble averages of a number of identical tests is one way to reduce experimental variability. Unfortunately, this comes at a high cost and a significant time penalty, since a large number of tests are required to establish acceptable confidence.

Average drive cycle fuel economy results are useful as an indication of the relative merits of different shift schedules, but to understand the impact that specific features of a shift schedule have on fuel economy, more detailed analysis is required. Examining measured fuel flow is a useful means by which shift schedules can be compared. A lower fuel flow rate will indicate regions in which one shift schedule has an advantage over another.

Figure 63 shows a comparison between Test 1 and Test 2 measured fuel flow and gear number between tests, for a sample section of the FTP-74 drive cycle. The GK1 shift schedule was used in both cases, so ideally the fuel flow and gear number should be identical. Gear change points differ by up to 2.5 seconds between tests, but there are some considerable differences in fuel flow between the two sets of results, which probably arise from differences in driving styles.

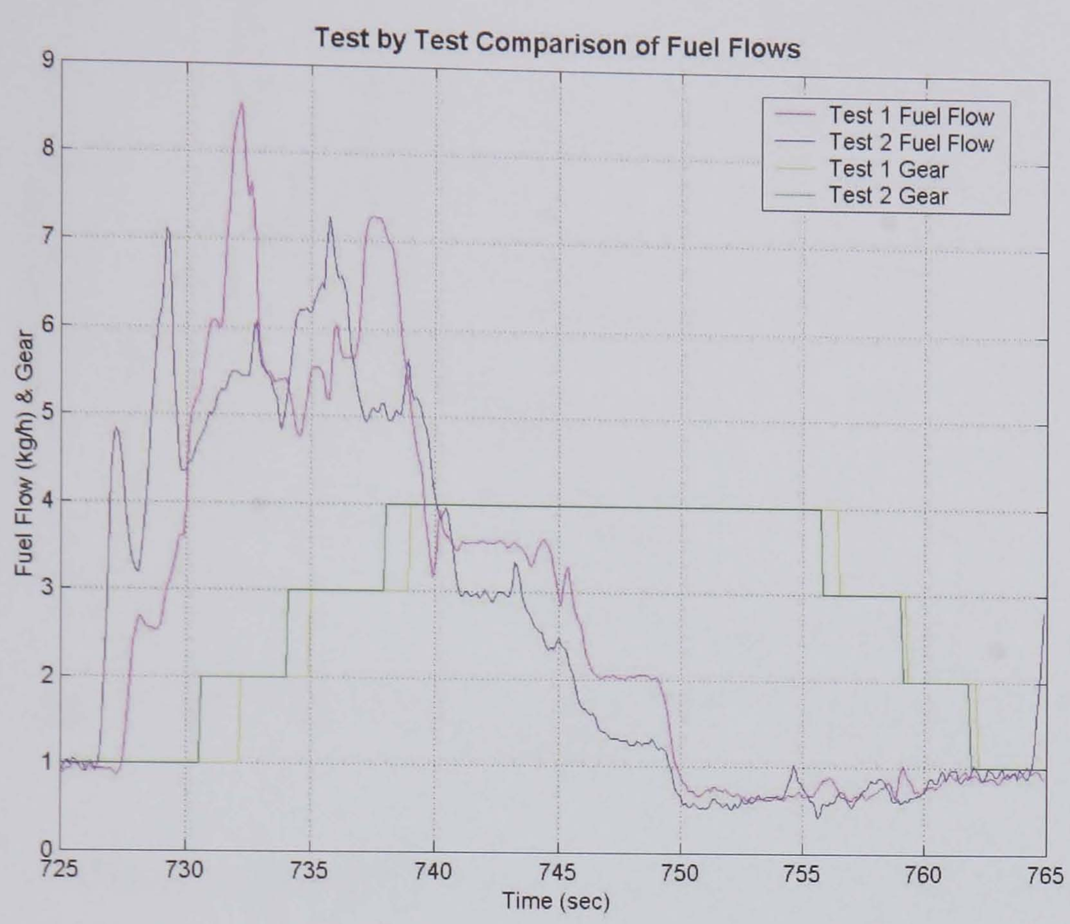


*Figure 63 – Test-by-Test Comparison of Fuel Flow*

Figure 64 shows a comparison of the fuel flow and gear position for GK1 and GK3 schedules during the same portion of Test 1 as displayed in Figure 63. The fuel flow plots for GK1 and GK3 follow a similar general trend, with much fluctuation in the individual traces. Fuel flow into the engine, if the air to fuel ratio is to maintain stoichiometry, is a function of the mass airflow into the engine, which in turn depends on the engine speed and throttle pedal position. Variations in the fuel flows in Figure 64, therefore, reflect the driver's throttle pedal modulation and the engine speed.

Comparing Figure 63 and Figure 64, it is difficult to differentiate between test-to-test variability in fuel flow and the effect of changes in the shift schedule. Therefore, although the effect of a change in the shift schedule can be observed in more detail using instantaneous fuel flow data, it cannot be confidently used as the basis of engineering decisions.

Figure 65 shows that comparing cumulative fuel usage during a specified time period is a useful alternative to comparing second-by-second fuel flow data. Over the 40 second period examined, the benefit of earlier upshifts becomes evident. Overall, the GK2 and GK3 shift schedules use approximately 6.5% less fuel than the GK1 shift schedule. Most of this benefit is gained after 745 seconds when GK2 and GK3 cause 5th gear rather than 4th gear to be selected for the cruise section.

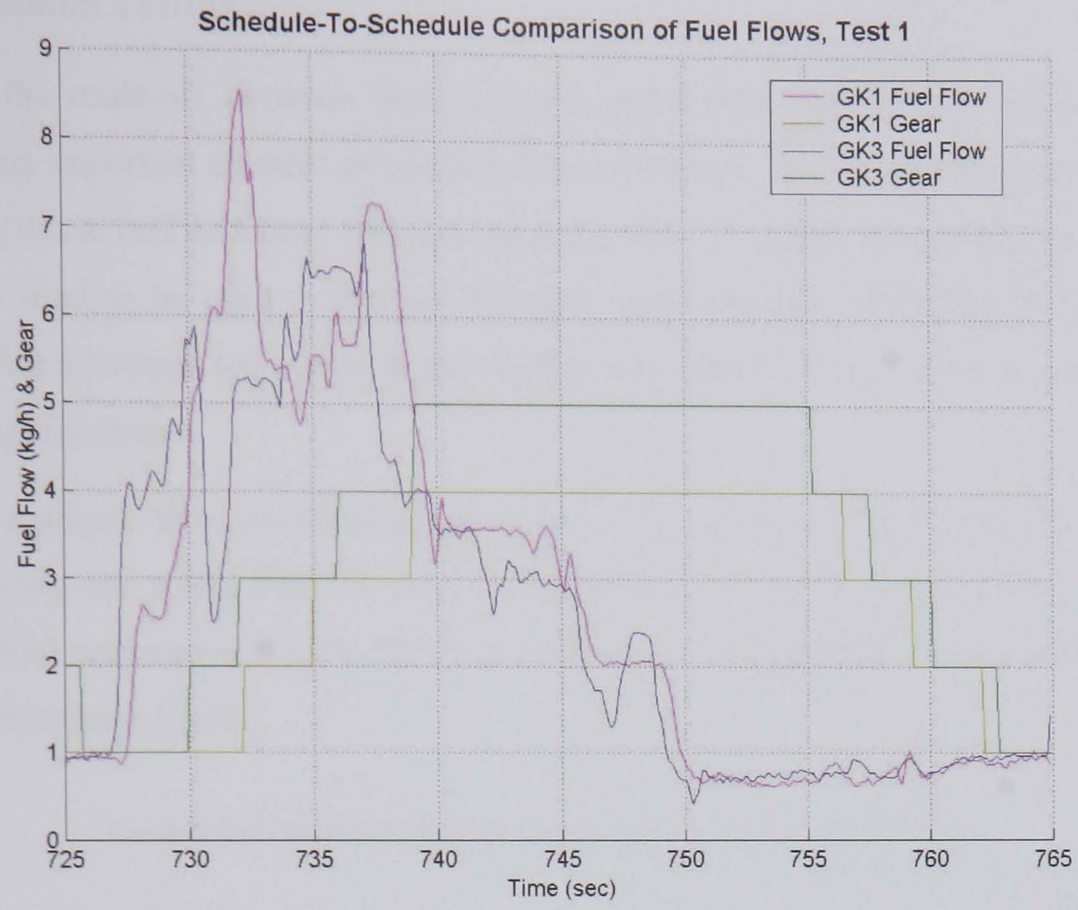


*Figure 64 – Schedule-by-Schedule Comparison of Fuel Flow*

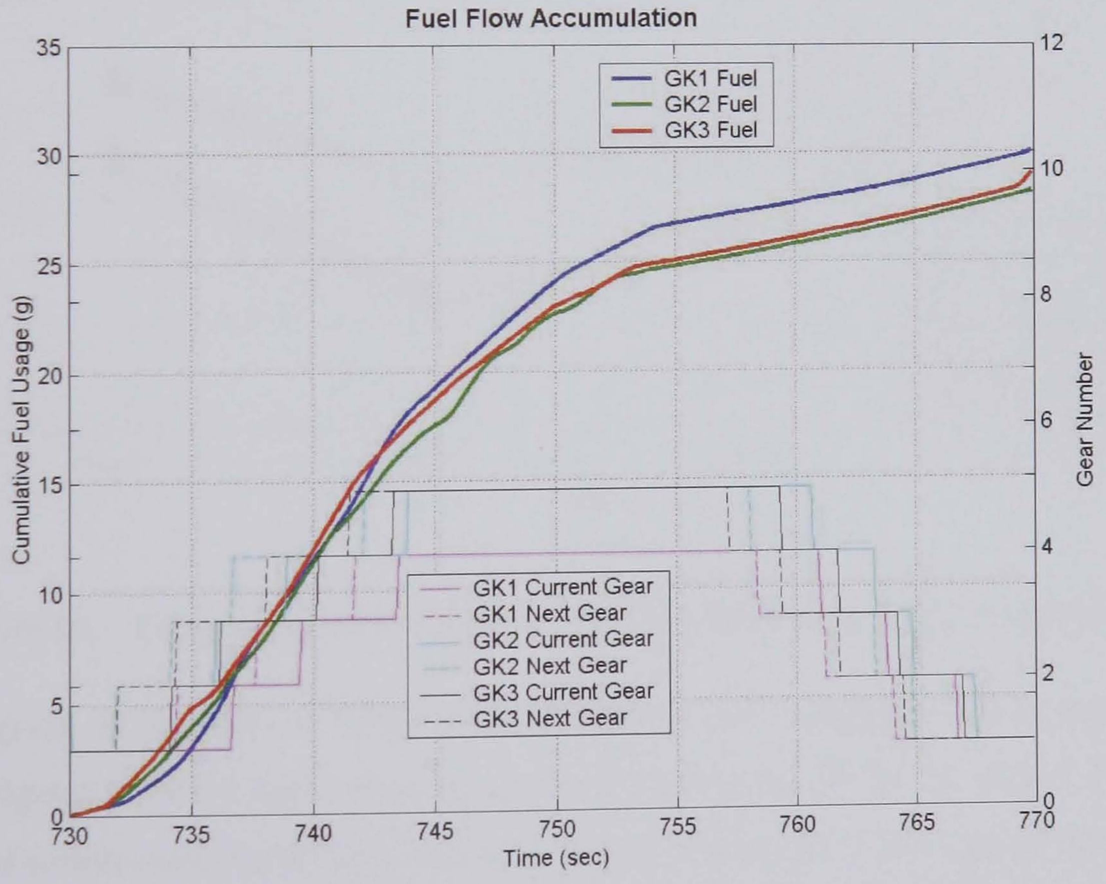


*Figure 65 – Schedule-by-Schedule Cumulative Fuel Usage*

### *6.6.2 Simulation Testing*

Optimising the trade-off between shift schedule driveability quality and drive cycle fuel economy is an important element of transmission calibration. The TCST has been designed to predict drive cycle fuel economy and give an indication of upshift driveability quality. It can therefore be used to be used to analyse the three shift schedules described in the previous section, so that a comparison can be made between the relative merits of the experimental and simulation approaches.

In order to replicate the experimental test method for assessing shift schedules, mean fuel economy during the entire FTP-74 drive cycle must be assessed. A method for calculating drive cycle fuel economy using the TCST simulation was described in Engineering Doctorate Portfolio Submission Eight.

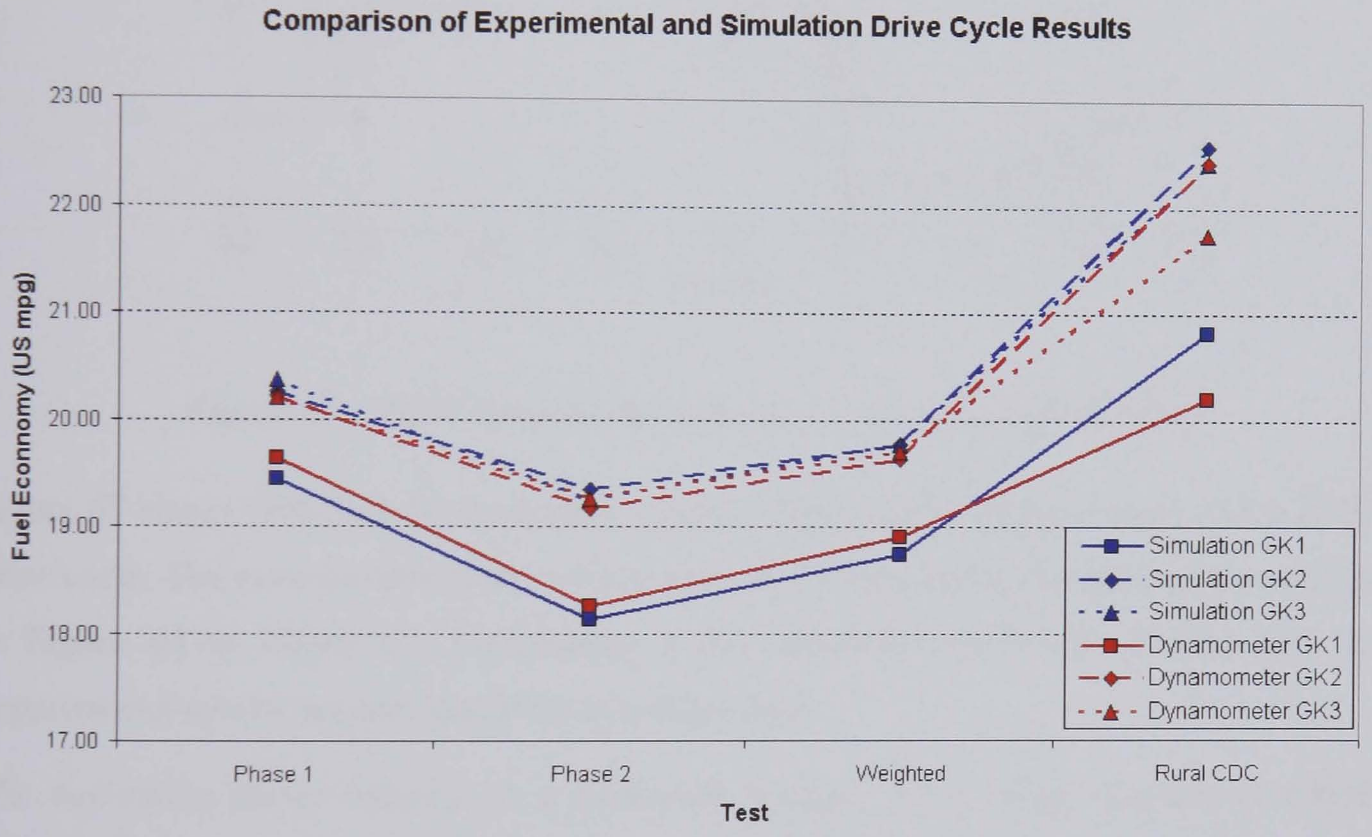


*Figure 66 – Comparison of Simulation and Experimental Drive Cycle Results*

Figure 66 gives a comparison between experimental and simulated fuel economy data. Overall, weighted FTP-74 fuel economy predicted using the TCST is within 1% of the experimental results, and Rural CDC fuel economy is within 3% of the experimental results. This is a satisfactory result given that the quality of the experimental data was moderate and there was inherent variability between tests. Intermediate Reduction Drive (IRD) efficiency data was limited to a single efficiency value. As a part of the final drive, IRD is a significant contributor to the driveline losses, but no information was available about the influence of speed or load on torque losses in the component. Part of the reason for a deviation between the experimental and simulation results during the Rural CDC, which uses higher vehicle speeds and engine loads than the FTP-74 cycle, may be a variation in actual IRD efficiency with speed and load. The most important observation from Figure 66 is the TCST results give a good indication of the relative effect of a change in the shift schedule.

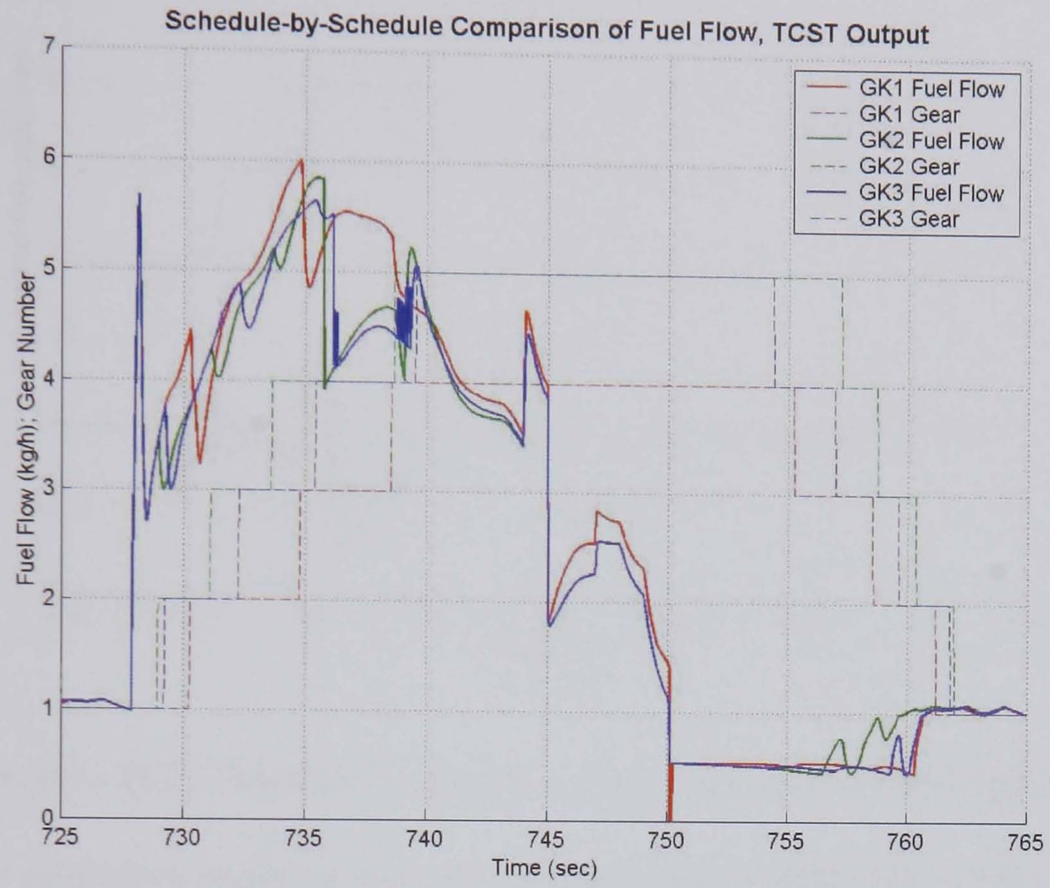


*Figure 67 – TCST Schedule-by-Schedule Comparison of Fuel Flow*

Figure 67 shows fuel flow for each shift schedule during a 40 second sample of the FTP-74 drive cycle. The same portion of the cycle is used as for the analysis for the experimental tests in Figure 63 to Figure 65. Correlation of the simulation prediction of fuel flow with experimental results has previously been demonstrated.

The simulation driver behaves in a consistent manner. As a result, schedule-to-schedule variations in throttle position are the result of differences in the shift schedules, assuming that all other vehicle parameters are unchanged, simplifying the comparison of shift schedules. This is evident in Figure 68, where the GK2 and GK3 deviation of fuel flow from that of GK1 is, for the most part, identical between 740 and 765 seconds. Using this chart, it is clear where GK2 or GK3 yield a benefit over GK1. For instance, a significant benefit can be observed in two regions. Firstly, between 736 and 739 seconds, GK2 and GK3 save between 1.2 kg/h and 0.6 kg/h, where GK1 selects third gear but GK2 and GK3 select fourth gear. Secondly, between 740 and 750 seconds, GK2 and GK3 save between 0.1 and 0.3 kg/h over GK1, where they select fifth rather than fourth gear. The total saving is of GK2 and GK3 over GK1 is 1.4g of fuel, or 0.139% over this section of the cycle.

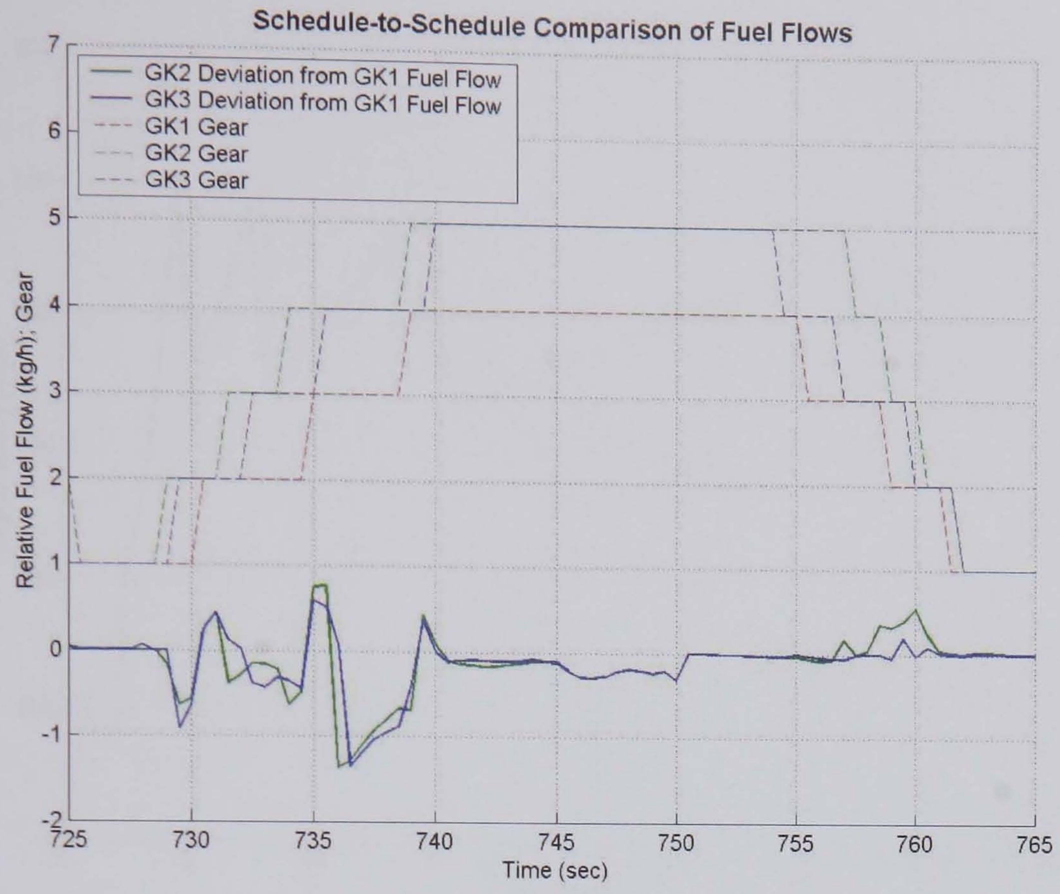


*Figure 68 – TCST Schedule-by-Schedule Comparison of Fuel Flow Difference*

Transmission calibration engineers can gain a much better understanding of the effect of shift schedule changes on fuel flow using simulation results, which are highly repeatable, than they can from experimental results, which display a high level of variability. This should assist in the identification of which elements of a given shift schedule provide fuel economy benefits.

The TCST can be used to predict vehicle behaviour during simple manoeuvres. Analysis of vehicle behaviour during simulated constant throttle acceleration tests, by application a shift schedule driveability quality chart in the format of Figure 57 (Section 6.5), would allow transmission calibration engineers to produce higher quality initial shift schedules and thus reduce the level of in-vehicle development.

The TCST shift schedule driveability quality chart is based on engine speed at upshift points as a function of throttle pedal position. Therefore, confirming the correlation between experimental and simulation upshift engine speeds is particularly important. It is evident from Figure 69 that the engine speeds are generally well matched, despite the fact that engine speed at the 1-2 upshift (occurring at 4.6 seconds) is 8% higher in the simulation than in the experimental test. Less error is exhibited between simulation and experimental engine speeds at consecutive upshifts (occurring at 8, 14.5 and 32 seconds), with all being within 2%.

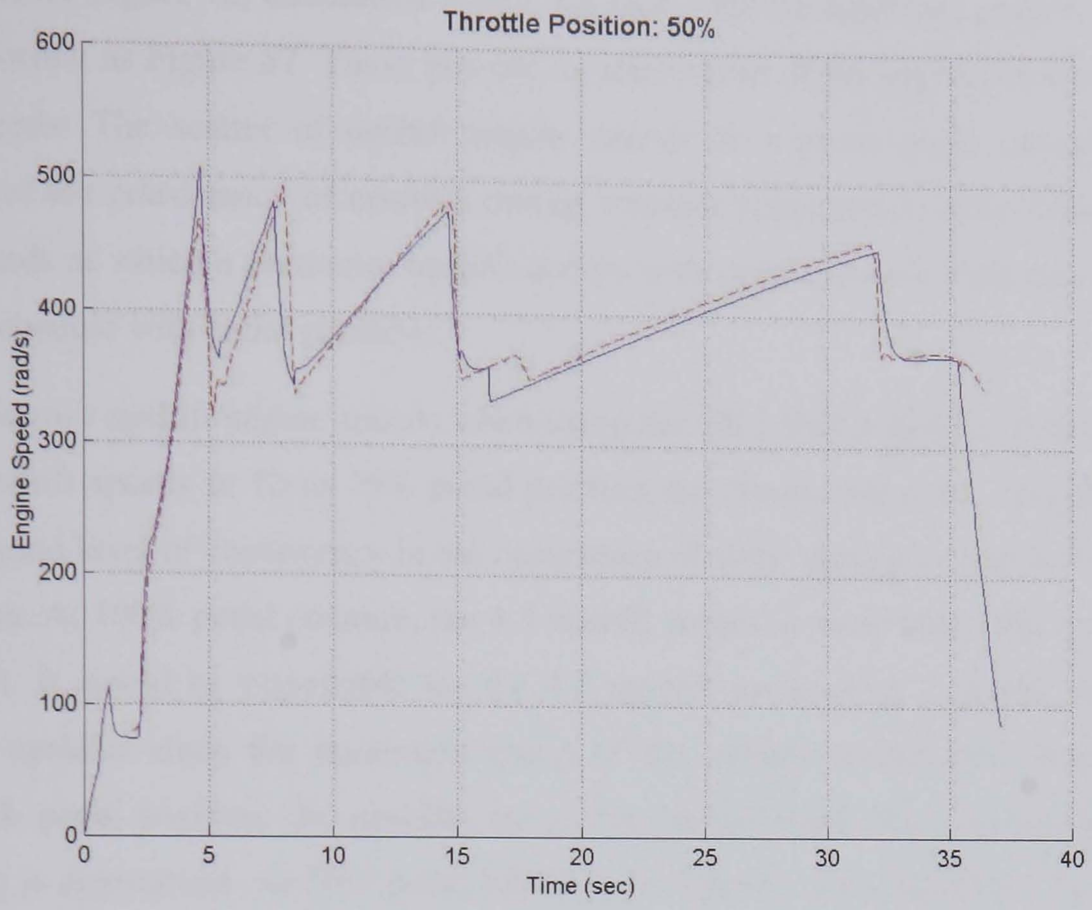


*Figure 69 – Correlation between Simulation and Experimental Constant Throttle Acceleration*

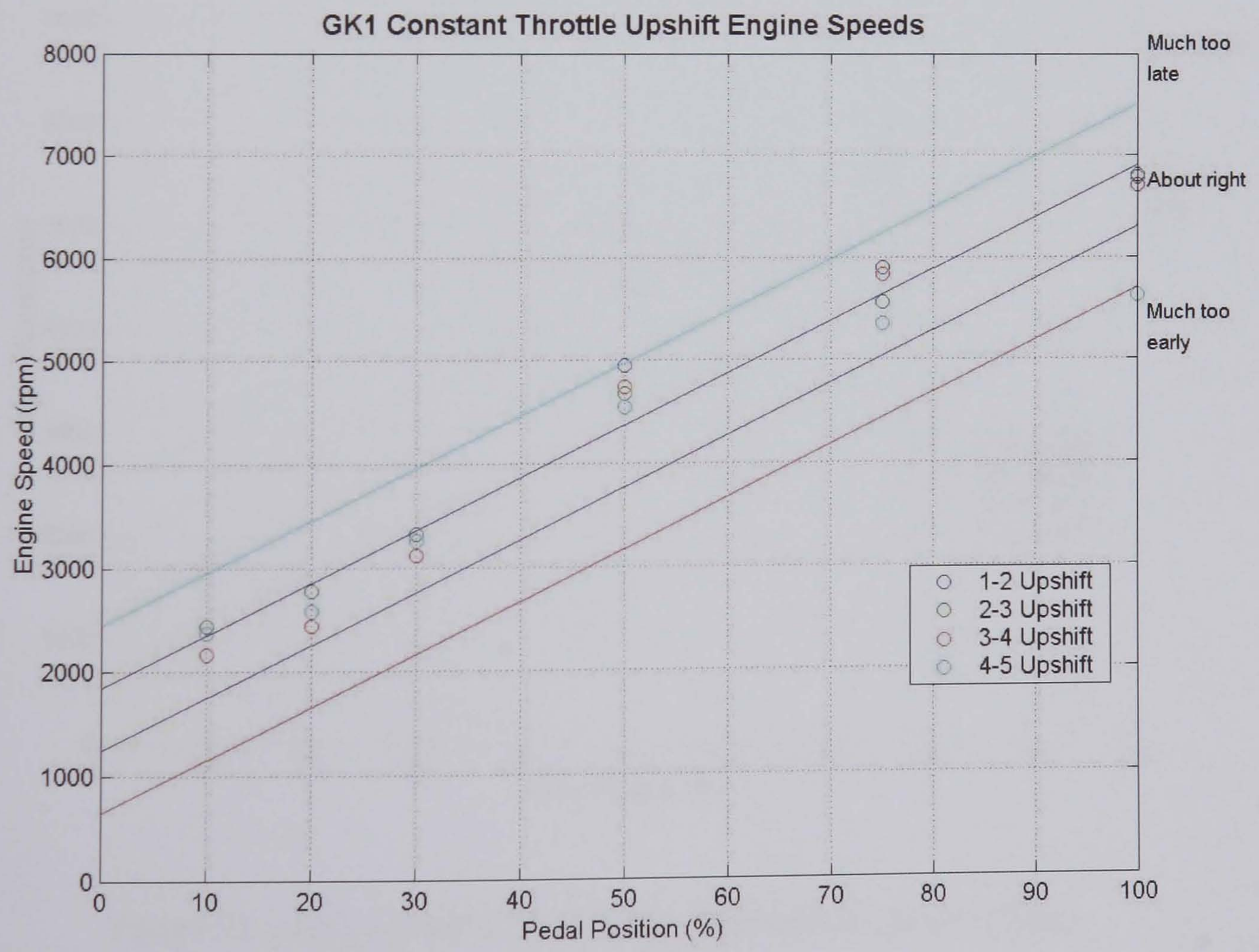


*Figure 70 – GK1 Upshift Shift Schedule Driveability Quality Charts*

In Figure 70 to Figure 72, simulation results for each shift schedule are plotted on charts of the same format as Figure 57. These provide an impression of the appropriateness of upshift engine speeds. The scatter of upshift engine speeds at a given pedal position gives an indication of the consistency of upshifts during constant pedal acceleration. Variation in the engine speeds at which a particular upshift occurs with pedal position indicates the linearity of a shift schedule with pedal position.

Figure 70 shows upshift engine speeds when using the GK1 shift schedule. Points to note are that the upshift speeds at 10 to 75% pedal position are closely bunched. This indicates that there is a good level of consistency in the occurrence of shifts during a constant throttle pedal acceleration. At 100% pedal position, the 4-5 upshift occurs at more than 1000 rpm below the 3-4 upshift. It would be impossible for the 4-5 upshift to occur at a similar engine to the preceding upshifts since the maximum speed of the vehicle would have been exceeded. Below 50% pedal position, the upshifts are in the 'About right' zone, indicating that their positioning is appropriate. At 50% pedal position, the upshifts move into the 'Too late' zone. This reflects a shift schedule that is slightly more aggressive at higher pedal positions.

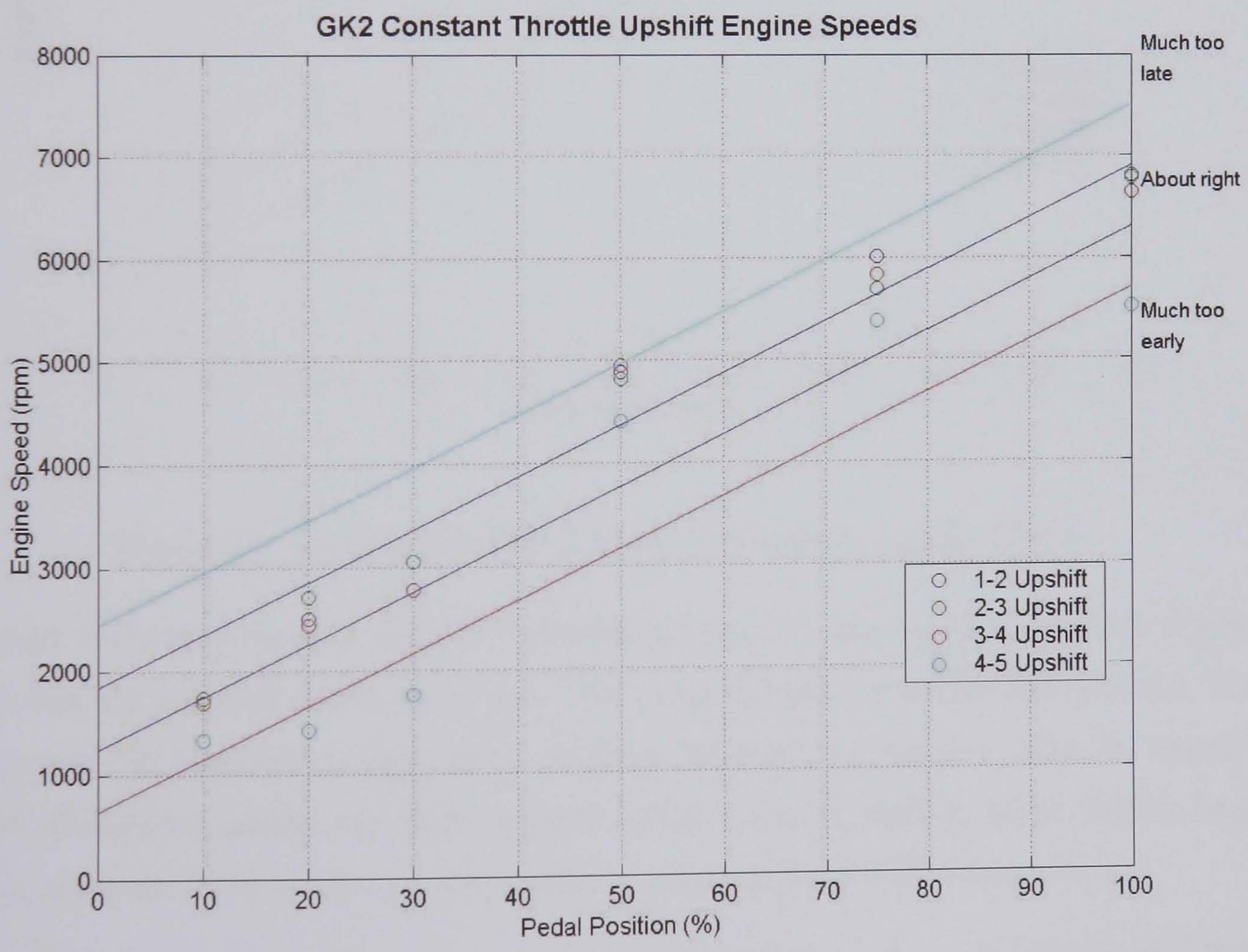


*Figure 71 – GK2 Upshift Shift Schedule Driveability Quality Charts*

Figure 71 shows a wide scatter of upshift engine speeds for constant pedal accelerations at pedal positions of 75% and below. In each case, the 4-5 upshift occurs at a significantly lower engine speed than the other upshifts, falling into the 'Much too early' zone at 20 and 30% pedal positions. At 50 and 75% pedal position, the upshift engine speeds lie in the 'Too late' zone. Therefore, there is also an inconsistency between the low and high pedal upshift engine speeds, which could produce fussiness when driving the vehicle. This result reflects the orientation of this shift schedule, which obtains early upshifts at low pedal positions and later upshifts at higher pedal positions. Whilst this strategy gives better drive cycle fuel economy than GK1, there seems to be a cost in the shift schedule driveability quality.

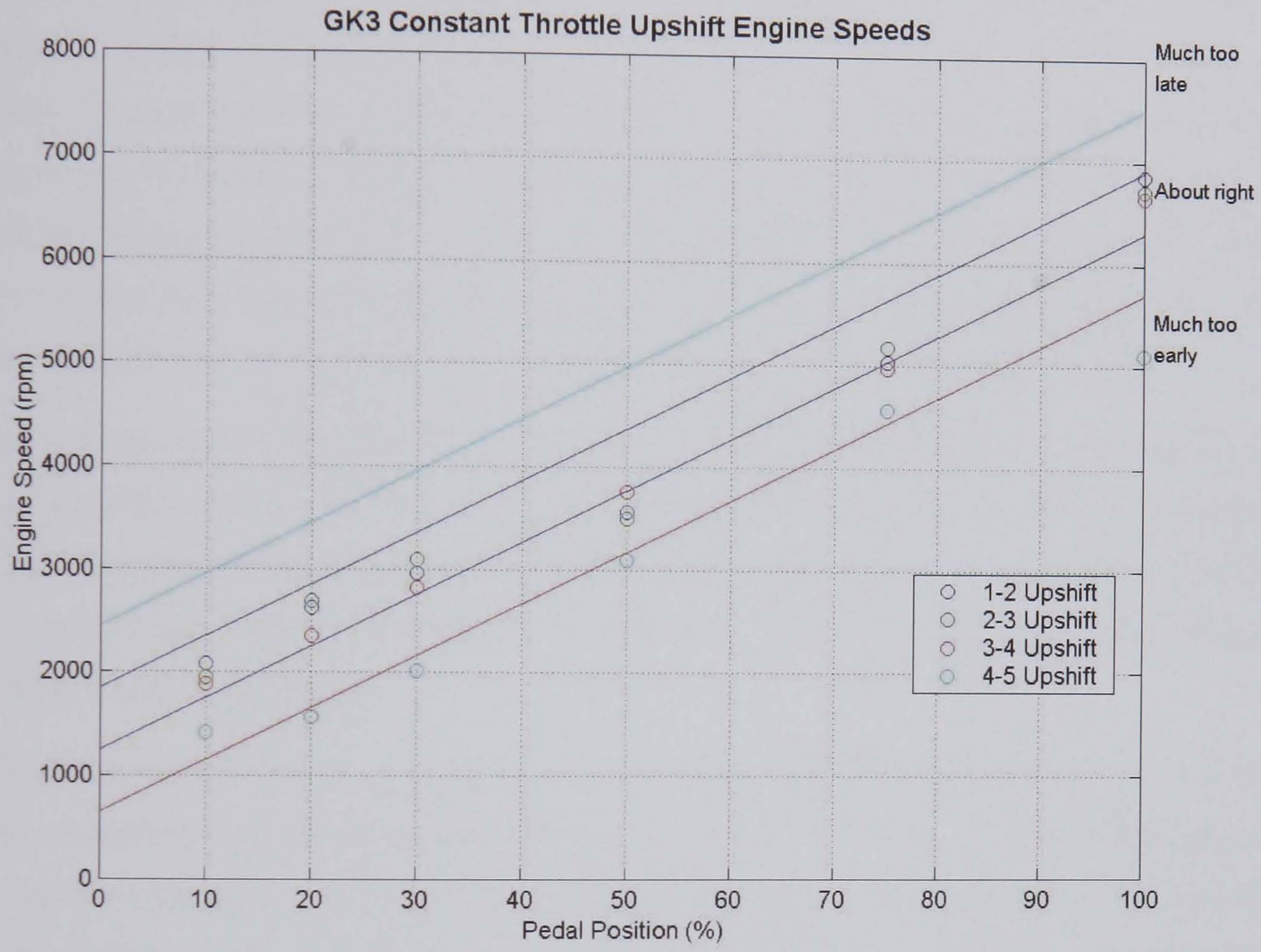


*Figure 72 – GK3 Upshift Shift Schedule Driveability Quality Charts*

The main difference between the GK3 schedule (Figure 72) and the GK2 schedule (Figure 71) is that GK3 upshift points at 50 and 75% pedal positions generally fall into the 'Too early' zone. GK2 upshifts at these pedal positions fall into the 'Too late' zone. To improve upshift driveability quality, the shifts at these speeds could be made to occur slightly later. This is, however, likely to have a slight negative impact on Rural CDC fuel economy.

When the three reference shift schedules are compared, GK1 seems to give the highest level of consistency in upshift engine speeds, although there is a tendency for the shifts to occur too late. However, GK1 also gives the worst fuel economy. GK2 is the least consistent shift schedule of the three, with upshifts occurring too early at low throttle pedal positions and too late at higher throttle pedal positions. The GK3 shift schedule is designed to give good drive cycle fuel economy, but the shift schedule driveability quality charts show that the 4-5 upshift occurs too early in all gears. An improvement could be made in that region and then repeat tests be performed to assess the impact of the changes on fuel economy and upshift shift schedule driveability quality.

## 6.7 Conclusion

In this section, the typical process of discrete ratio transmission calibration has been reviewed and an enhanced process, incorporating systems modelling and simulation, has been proposed. A review of automatic transmission modelling has shown that modelling effort is generally focused on solving specific problems or on transmission controller algorithm development. Very little emphasis has been placed on the effective application of simulation models to enhance the powertrain product development process. Therefore, a simulation tool, the TCST, has been designed with the objective is that it should integrate directly into the revised transmission calibration process to reduce dependence on physical prototypes.

A need that was specifically identified by transmission calibration engineers was the ability to predict the effect of shift schedule changes on drive cycle fuel economy, vehicle performance and shift schedule driveability quality. The TCST, therefore, replicates standard calibration tests to predict those vehicle attributes. It is constructed in two parts: an underlying simulation model and a user environment.

The simulation model has been constructed in accordance with the architecture for powertrain systems modelling that was described in Section 4.3. A core element of the simulation model is the vehicle subsystem, which has been created in the Modelica language using the Dymola systems modelling and simulation tool. Library models were integrated, in some cases modified, in order to construct the vehicle model. Specifically, the automatic transmission library model was modified to incorporate spin related, torque related and pump losses. In the engine model, a torque-down function was introduced.

To ensure that calibration engineers with little or no systems modelling and simulation experience are able to derive value from the simulation model, it has been packaged in a user-environment that simplifies data management, selection of specific tests, running the simulation model, and post-processing of the results.

A range of experimental tests has been conducted on the test track and chassis dynamometer with the objective of validating the simulation model behaviour. Results from the experimental tests have been compared with results from identical tests performed using the TCST. It has been shown that the vehicle, engine and turbine speeds predicted by the TCST correlate well with the physical vehicle results during tip-in, tip-out, and coastdown tests.

When comparing predicted with actual vehicle behaviour during NEDC fuel economy tests, throttle position and gear number, as well as speeds in the system correlate closely. To confirm the accuracy of simulation results, a comparison of the predicted and actual fuel economy shows that there is a difference of less than 2%. Correlation of this sort is critical for establishing confidence in the simulation results produced by the TCST. Improving the correlation between experimental and simulation results still further would require parametric data of a higher quality, for instance a finer mesh of steady-state engine data and overrun BMEP data. Introducing higher order effects to the model, such as transport delays in the engine model, would improve the dynamic response

An objective method for assessing shift schedule driveability quality was required, so that an impression of shift schedule driveability quality can be derived from simulation results. A simple chart has been developed by which the consistency of engine upshift speeds during constant throttle acceleration tests can be assessed. The chart is based on detailed discussions with transmission calibration engineers and correlating objective and subjective experimental data acquired during constant throttle acceleration tests. Using the chart, an indication can be obtained of the subjective feel of a shift position. It is acknowledged that this approach is limited since a wide range of different ratings that were assigned by calibration engineers, even for identical vehicle behaviour, but it provides a means for initial assessment of shift schedule driveability quality.

Fuel economy can be predicted using the TCST, and an indication can be gained of one aspect of shift schedule driveability quality. Thus, calibration engineers are provided with predictions of both the major vehicle attributes that are set against one another in calibration trade-off decisions. Previously, sufficient information to make these trade-offs was only generated towards the end of the shift schedule development process, which means that there was little time remaining to influence the decisions that were made.

In order to demonstrate the effectiveness of the TCST when it is applied in a modified transmission calibration process, a parallel set of tests has been conducted so that traditional, physical testing-based techniques to shift schedule development and a simulation-based approach using the TCST can be compared. This involved dynamically measuring fuel mass flow during drive cycle testing. Three shift schedules have been appraised using both approaches. Five key conclusions can be drawn from this exercise.

Firstly, it has been shown that the FTP-74 drive cycle fuel economy is well represented using the TCST. In particular, the effect of changes in the shift schedule on fuel economy are recreated using the TCST simulation.

Secondly, chassis dynamometer vehicle-based testing did not produce overall drive cycle fuel economy results that were sufficiently repeatable to examine the effect of relatively small changes in the shift schedule. An advantage of using the TCST is that there is no test-to-test variability in the results. Therefore, if the only change to the model parameters is in the shift schedule, then any difference in the results between tests is due to that change. This makes it much easier for calibration engineers to identify the effect of small changes in the transmission calibration.

Thirdly, during chassis dynamometer testing, it was found that each driver controlled vehicle speed differently within legislative drive cycle limits. This produced a great deal of fluctuation in the throttle position between tests and hence in the fuel flow. Therefore, it was difficult to identify specific regions in which differences between shift schedules produced a benefit. The TCST driver model behaviour is consistent between tests, so it is easy to identify specific regions in which one shift schedule gives a benefit over another.

Fourthly, any variable in the simulation model is available as an output using the TCST, but any information that is not available in the engine or transmission controllers is very difficult to acquire and needs special instrumentation when undertaking experimental testing.

Fifthly, defining and executing new tests can be difficult using an experimental approach, especially if they need to be highly repeatable. For instance, introducing a typical Rural Customer Drive Cycle required several hours of a technician's time to set-up the test. By contrast, using a new drive cycle using the simulation is simply a matter of saving it as a new file.

In addition to these conclusions, it is interesting to compare the time taken to develop a shift schedule using the physical testing-based and simulation-based approaches. The TCST can be used most effectively only when the calibration process is adjusted to reflect the capabilities that are offered by the tool. To give an indication of the potential benefit of a revised, simulation-based process, let us consider the optimisation of a shift schedule for fuel economy and driveability. The left hand flow in Figure 73 represents the traditional, experimentally-based process, and the right hand flow, which is drawn from Figure 39, represents the process using simulation, in this case the TCST.

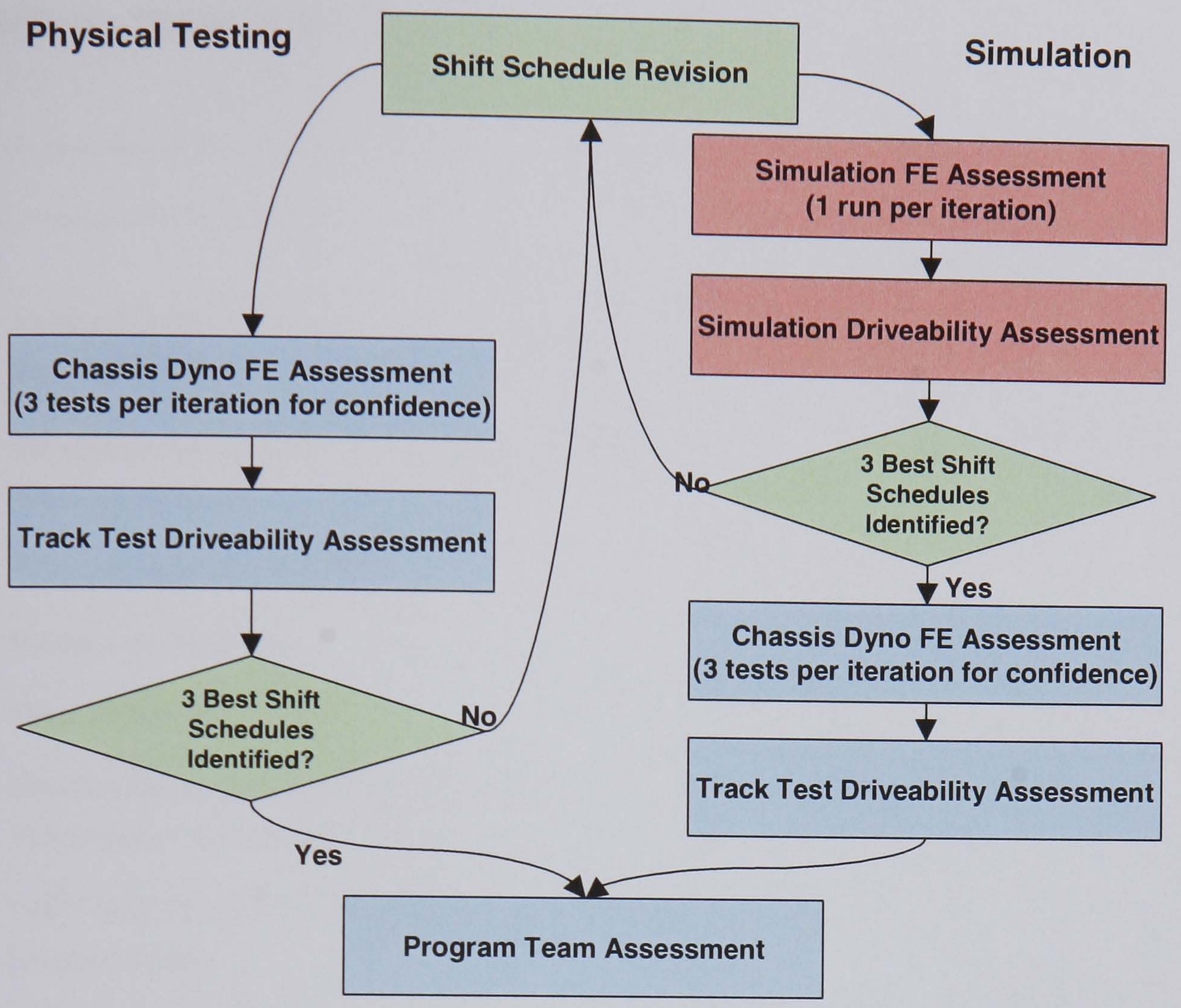


*Figure 73 – Comparison of Physical Testing and Simulation Process for Optimisation of Fuel Economy and Driveability*

*Table 10 – Timing of Physical Testing Approach to Shift Schedule Fuel Economy and Driveability Optimisation*

| | **Physical Testing** | |
|---|---|---|
| | Vehicle | Calibrator |
| **Chassis Dynamometer Fuel Economy Assessment per Iteration (Days)** | 3 | 0.1 |
| **Test Track Driveability Assessment per Iteration (Days)** | 0.5 | 0.5 |
| **Time per iteration (Days)** | 3.5 | 0.6 |
| **Number of Iterations** | 12 | |
| ***Total (Days)*** | ***42*** | ***7.2*** |

*Table 11 – Timing of Simulation Based Approach to Shift Schedule Fuel Economy and Driveability Optimisation*

| | **Simulation** | |
|---|---|---|
| | Vehicle | Calibrator |
| **Simulation Fuel Economy Assessment per Iteration (Hours)** | 0 | 0.4 |
| **Simulation Driveability Assessment per Iteration (Hours)** | 0 | 0.3 |
| **Time per iteration (Hours)** | 0 | 0.7 |
| **Number of Iterations** | 12 | |
| ***Total Simulation (Days)*** | *0* | *1.05* |
| **Chassis Dynamometer Fuel Economy Assessment per Iteration (Days)** | 3 | 0.1 |
| **Test Track Driveability Assessment per Iteration (Days)** | 0.5 | 0.5 |
| **Time per iteration (Days)** | 3.5 | 0.6 |
| **Number of Iterations** | 3 | |
| ***Total Physical Testing (Days)*** | *10.5* | *1.8* |
| ***Total (Days)*** | ***10.5*** | ***2.85*** |

Let us assume that twelve shift schedule iterations are sufficient to generate an acceptable solution[4]. Using the historical physical testing process, each schedule is firstly tested for fuel economy on the chassis dynamometer. Due to the variability in the chassis dynamometer fuel economy results, a number of tests (say three) are required per shift schedule to give sufficient confidence in the result. Only one test can be conducted per day because the vehicle must be soaked at a temperature of 25°C for twelve hours prior to the test. Next, a driveability test is required for each shift schedule. From the twelve shift schedules, three may be selected for assessment by the program team. Using the proposed simulation based approach, the twelve shift schedules would be compared using the TCST. The best three would be selected for validation of the simulation results using physical testing, and are passed to the program team.

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[4] Twelve iterations was suggested by a Transmission Calibration Team Leader as being sufficient to give a reasonable shift schedule solution.

An analysis of the time taken using each approach is presented in Table 10 and Table 11. The simulation-based approach saves approximately 31 days of vehicle testing time and 4.4 days of calibrator time. Removing this amount of time from a vehicle programme is very desirable, and a motivating factor to fully implementing the TCST.

The aim of this fourth work package has been met: a transmission calibration simulation tool has been developed and its implementation has been demonstrated. Once again the usefulness of the PTIV approach and library of models has been illustrated. It is clear that, in order to obtain the greatest benefit from the application of systems modelling and simulation in powertrain product development, the engineering process must be redesigned.

# 7. Conclusion

This portfolio presents a project that was conducted over a period of approximately four years. The aim of the portfolio was to demonstrate the benefit of applying systems modelling and simulation in a modified powertrain product development process. To fulfil this aim, the project consisted of a number of stages. Firstly, the effectiveness of the current application of CAE in the powertrain development process had to be assessed. Secondly, the way in which systems modelling and simulation should be used in powertrain development was reviewed. Thirdly, systems modelling and simulation was applied to real powertrain development problems. Finally, the benefits of modifying the powertrain development process to incorporate the use of systems modelling and simulation were assessed.

Findings from published literature and an investigation into the use of CAE in five engineering companies enabled best practice in the implementation of CAE in the product development process to be distilled. Current practice in the use of CAE in the powertrain department of a leading automotive manufacturer was assessed against best practice and gaps between the two were identified. The first major gap is that, although CAE is used extensively for solving specific problems, there is insufficient coherence in its usage and little integration of CAE into the powertrain development process. The second major gap is that a systems approach to product development is not adopted and there is an associated shortfall in the use of systems modelling and simulation tools.

As a first step in rectifying the shortfall in the use of systems modelling and simulation, a set of criteria for assessing systems modelling and simulation packages has been developed, and a range of packages have been appraised against the criteria. As a result, a unique systems modelling simulation architecture has been devised that uses MATLAB/Simulink, Dynasim Dymola, other MATLAB-based utilities such as Stateflow and Handle Graphics in an integrated fashion. A library of powertrain models, the PTIV library, has been developed as a result of this work.

CVT and discrete ratio automatic transmission calibration have been selected as areas that could benefit from the application of systems modelling and simulation. CVT plant and controller models have been developed from the basis of the PTIV library models and integrated into a vehicle model. The purpose of this model was to address needs that have been identified in CVT calibration activities. The model has been validated, and its potential benefit in tackling calibration tasks has been demonstrated. In addition, the usefulness of the PTIV library was demonstrated through this application. Unfortunately, due to a change in company environment, it was not possible to continue this work to a stage of full application.

The application of systems modelling and simulation to discrete ratio automatic transmission calibration has been tackled by firstly considering needs that exist in the calibration process. From this basis, a strategy has been devised by which those needs could realistically be tackled using systems modelling and simulation. The Transmission Calibration Simulation Tool (TCST) has been developed to facilitate the implementation of systems modelling and simulation in the transmission calibration processes. The TCST can be used to predict vehicle attributes that are used by transmission calibration engineers in designing and developing shift schedules, namely vehicle fuel economy, performance and shift schedule driveability quality. A basic objective shift schedule metric method has been developed to enable an objective assessment of the shift schedule driveability quality.

It is anticipated that the TCST will be used in two phases of the transmission calibration process. Firstly, at the outset of the shift schedule design process transmission calibration engineers can use the tool as a coarse filter. At this stage, results from the TCST should facilitate the elimination of candidate shift schedules that prove to have unacceptable fuel economy or shift schedule driveability quality characteristics. Secondly, during later stages of the shift schedule calibration process, the TCST could be used to predict the effect of changes in the shift schedule on fuel economy or driveability quality. During both of these phases, prior to the existence of the TCST, there was a 'stumbling block' in the transmission calibration process due to the absence of this information. Therefore, a revised calibration process, incorporating the TCST, has been proposed for these phases.

A feasibility study has indicated that using the TCST as part of the revised process can save six weeks of prototype test time and one week of calibrator time on a typical vehicle programme, especially during the process of optimising the shift schedule for fuel economy. Savings of this magnitude result from matching systems modelling and simulation techniques to specific needs of calibration engineers and ensuring that simulation tools are integrated into their daily work. Although systems modelling and simulation has not previously been used in the transmission calibration process, from now on calibration engineers will use the TCST as an integral part of their normal engineering activity. This is an important step away from a reliance on physical prototyping towards more analytical techniques.

The aim of the Engineering Doctorate Portfolio has been fulfilled, since the benefit of applying systems modelling and simulation in revised powertrain product development process has been demonstrated. An important outcome of this portfolio is that the implementation of systems modelling and simulation in the Company now conforms to best practice for CAE implementation in powertrain development. At the outset of the study, no real systems modelling and simulation capability was available. Today, models from the PTIV library are applied as an integral part of the product development process in a growing range of applications. This project has made a significant contribution to the development of the systems modelling and simulation capability in the Company.

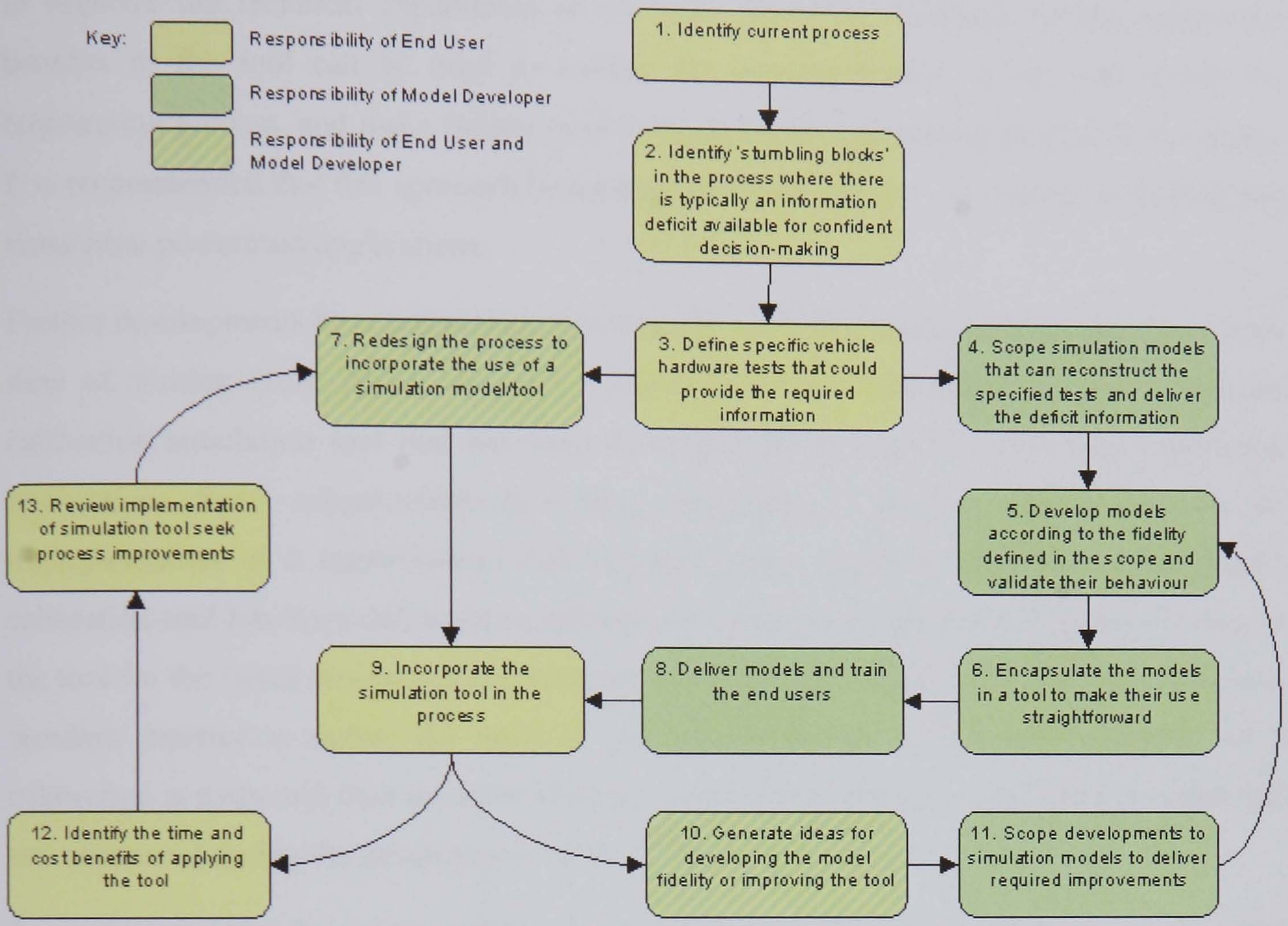

*Figure 74 – Approach for Integration of Systems Modelling and Simulation into Powertrain Processes*

The work in this portfolio has demonstrated that implementing systems modelling and simulation in a revised powertrain development process can yield significant improvements in the process efficiency. An important consideration is how to ensure that simulation models are effectively integrated into engineering process. The model in Figure 74 illustrates a proposal of how integration could be consistently achieved. It is based on the approach that was applied to the development of the TCST. Firstly, the current engineering process must be understood. A gap analysis can be undertaken to identify where information that is required for engineering decisions is routinely unavailable. Tests could be defined that would provide the required information if instrumentation, data acquisition, equipment and vehicle availability limitations on vehicle hardware testing were removed. From that point onwards, parallel activities are required. The model developer is responsible for creating a scope for the simulation models that are to be created, developing and validating the models. He is also responsible for encapsulating the models in a tool that enables simulation runs to be performed intuitively by the end user. At the same time, the engineering process may need to be redesigned to ensure that using the simulation models is fully integrated into normal working practices. The simulation model can then be delivered to the end users and incorporated into their engineering processes as planned. Two feedback loops exist in the model in Figure 74. Firstly, feedback on the usability and functionality of the tool can be used to improve the technical capabilities of the tool. Secondly, feedback on the application benefits of the tool can be used to modify the implementation of the tool within the engineering process, and make further modifications to the engineering process as necessary. It is recommended that this approach be used in the future for new all systems modelling and simulation powertrain applications.

Further developments have taken place based on the work described in this submission. At the time of writing (July 2002), the TCST has become the foundation for a new generic calibration simulation tool that has been developed for a range of powertrain calibration applications. Some enhancements have been undertaken to the basic model, such as the implementation of a transmission shift schedule mode changing capability. The generic calibration tool has been delivered to transmission calibration engineers, who are relying on the tool for the initial design and optimisation of shift schedules for future products. It is now standard practice to define the areas of information deficit, or 'stumbling blocks', in a calibration activity and then to tailor simulation tools to meet those needs. Such an approach was pioneered during the development of the TCST.

It is anticipated that the generic calibration simulation tool will be used to tackle a wide range of calibration tasks. For each new application, the process illustrated in Figure 74 should be applied. Ensuring that the application of the tool is accompanied by adjustments to the calibration process, according to Figure 74, is important further work. The effectiveness of each simulation tool application should be monitored, with the objective of improving the tool or adjusting the process. Applying simulation tools in this way requires a strong support network. Problems may arise and, if engineers are relying on the simulation tool as an integral part of their daily work, problems with the tool may disrupt their planned work and possibly even the vehicle programme timing. Thus, an important area of further work is provision of support to calibration engineers as they use the TCST and its descendants.

Further work is required in a number of areas. The models used in the TCST are relatively basic. Incorporation of additional features would improve the capability of the tool. For instance, engine and transmission thermal models would provide an improved representation of the effect of warm-up and ambient temperature on drive cycle fuel economy. Compliant driveline models and a full transmission model would facilitate representation of transmission shift dynamics.

The correlation between subjective and objective shift schedule driveability quality was derived using a single vehicle and a small sample of drivers. Further work could be undertaken using a range of different vehicles and a wider cross section of drivers that represents typical customers. The objective shift schedule assessment that has been presented in this submission could be validated for a wider range of circumstances and developed to better reflect customer desires.

This model in Figure 74, and the examples that were the focus of this Engineering Doctorate Portfolio, addresses the integration of systems modelling and simulation into local processes. At the level of the overall powertrain development process, it may be feasible to use a 'master' vehicle simulation model as the basis of programme decisions at the outset of the new product development process, before programme sign-off, and to verify the attributes of the vehicle against its targets at every stage of the process. As the programme progressed through the product development process, the definition of the simulation model would increase. Other CAE tools and physical testing would provide inputs to the model to verify its behaviour or provide parametric data. The master model is analogous to the single, overall model that is used for CAD geometric design data. A basic library of simulation models that would facilitate this approach is available, but further work is required to investigate how best practice in the implementation of CAE could be applied to the overall powertrain development process.

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# Appendix A

# Shift Schedule Desktop Assessment Questionnaires

| | | |
|---|---|---|
| **Transmission Shift Schedule Driveabilty** | Calibrator:............................ | Date:............................ |

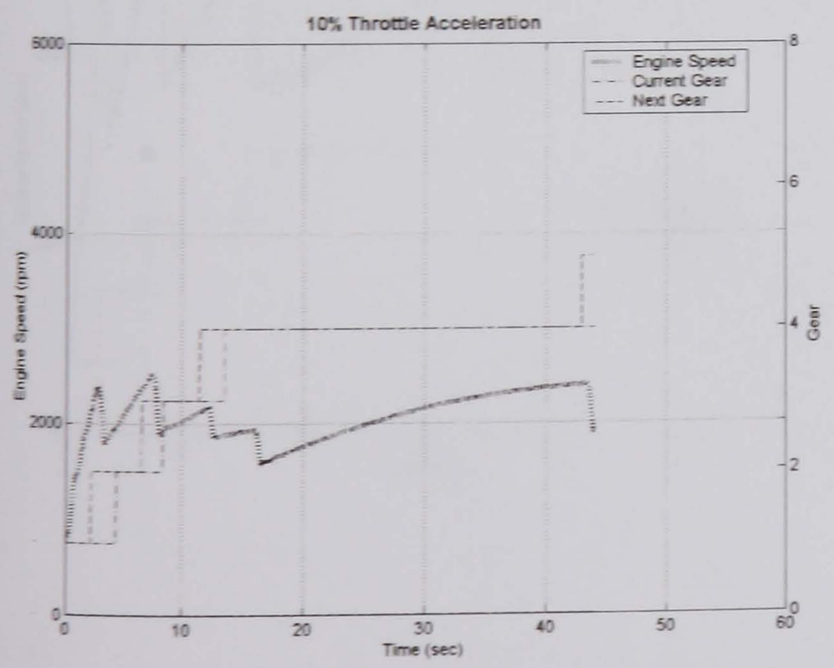
At present the assessment of transmission shift schedules in Land Rover is conducted, primarily, using vehicle based testing. Some analytical desktop development is used when the shift schedules are first designed and if modifications are required. In the future, greater use should be made of analytical techniques in the design and development of shift schedules. Driveability is a critical issue when developing a shift schedule. This exercise is designed to assist in the construction of a basic objective measure of shift schedule driveability.

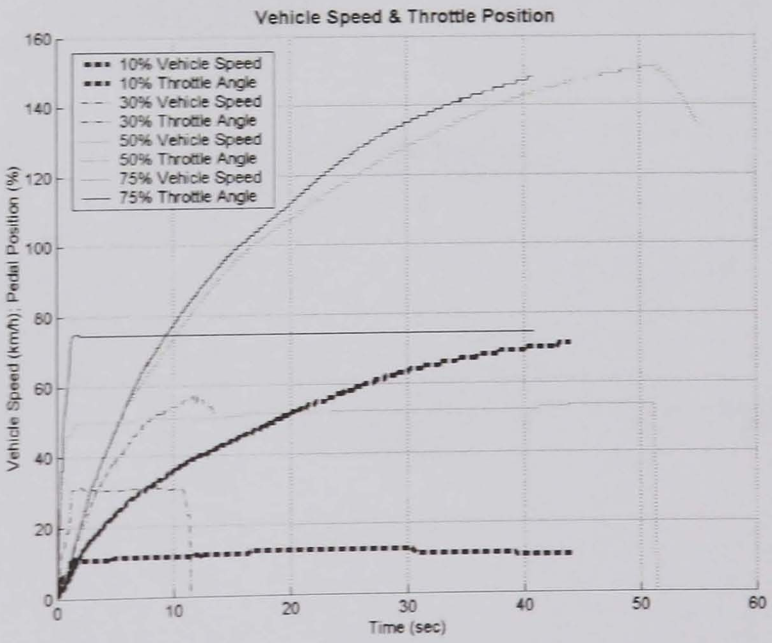
*What are the main criteria that would you use when assessing an initial shift schedule during in-vehicle testing?*

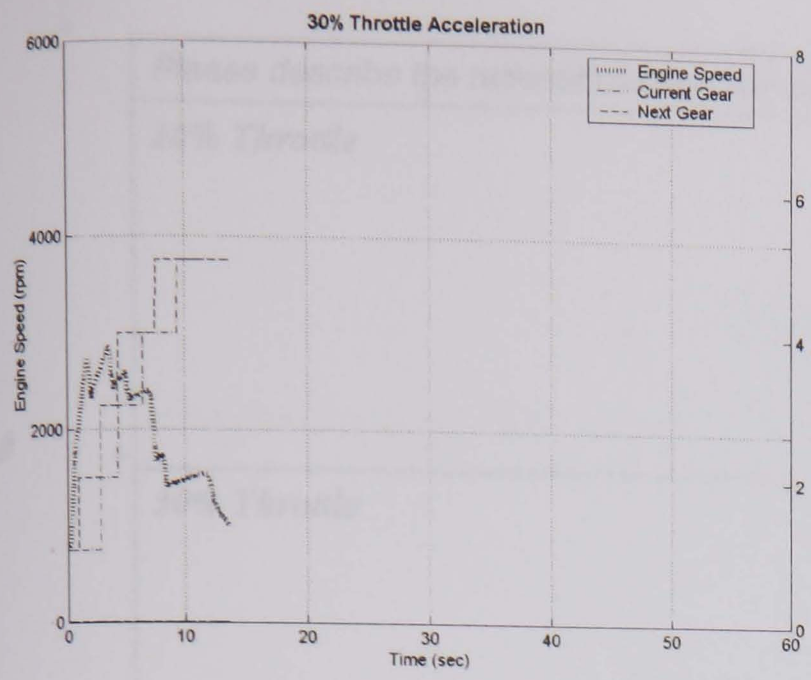
Below, a set of time traces is presented, which are the results from a set of vehicle-based experimental tests. Engine speed, gear position, vehicle speed and throttle angle are plotted for each test. Results from constant throttle pedal positions of 10, 30, 50 and 75% are plotted, each plot on the same scale.

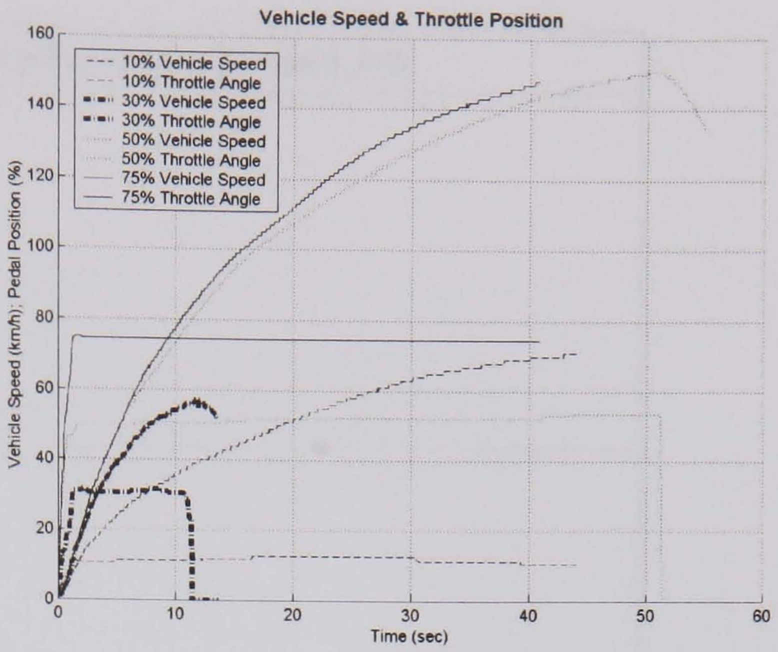
*Assign a rating to each upshift, writing the rating on the plot, according to the following scale:*

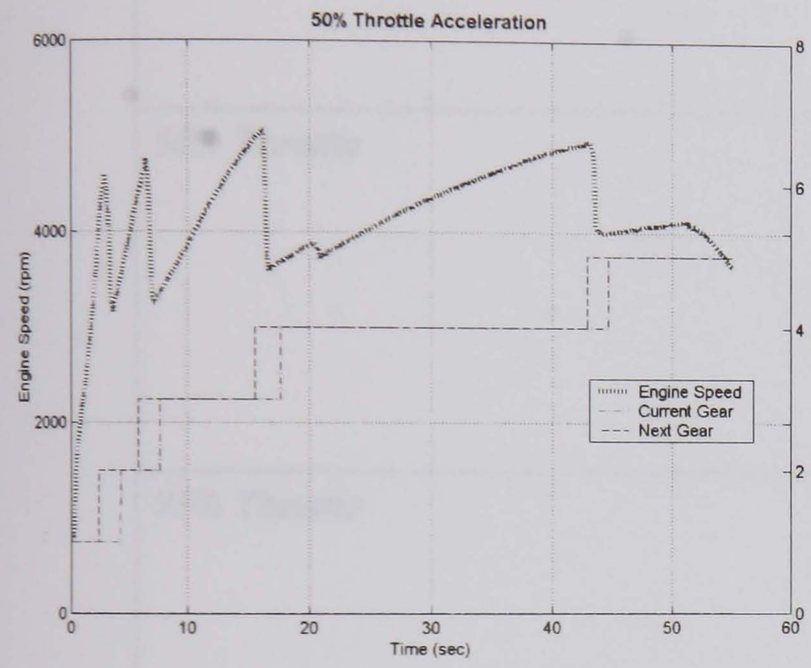
1: Much too late
2: A bit too late
3: About right
4: A bit too early
5: Much too early

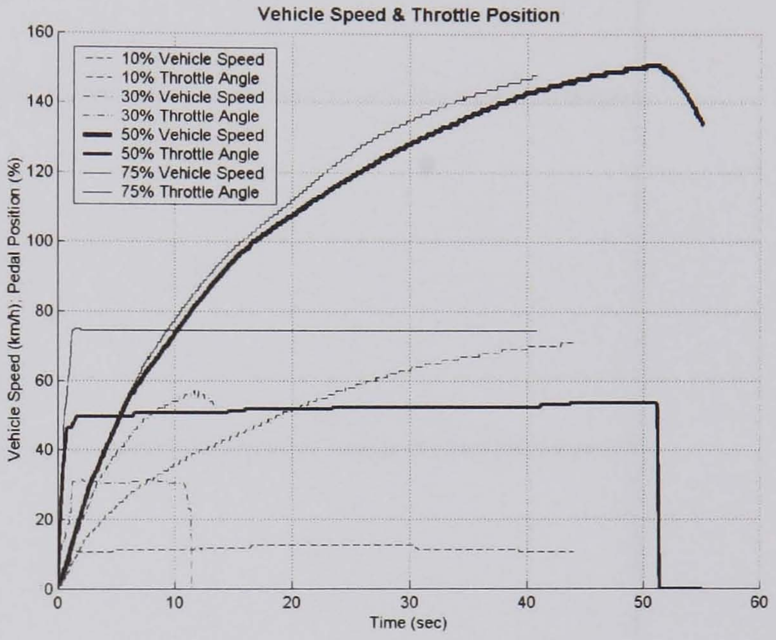


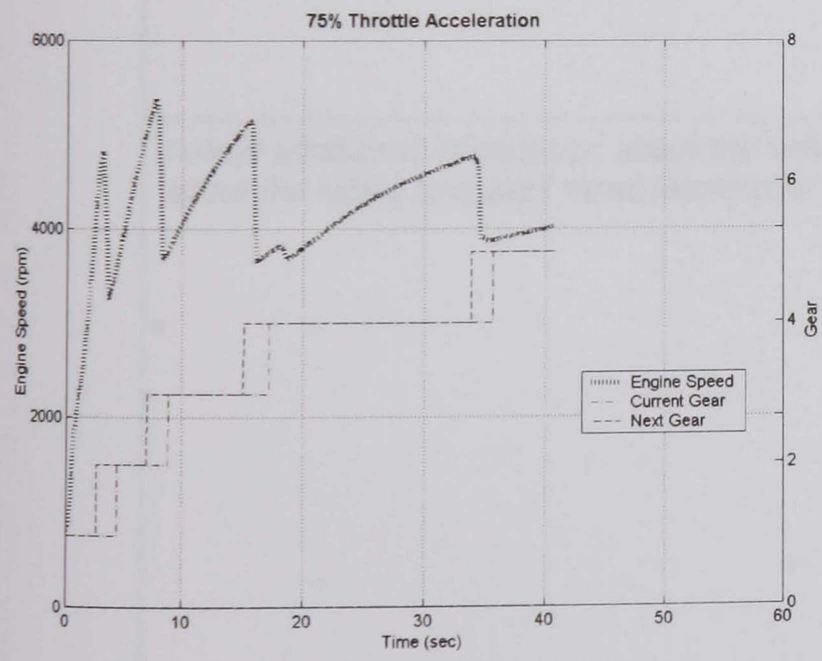


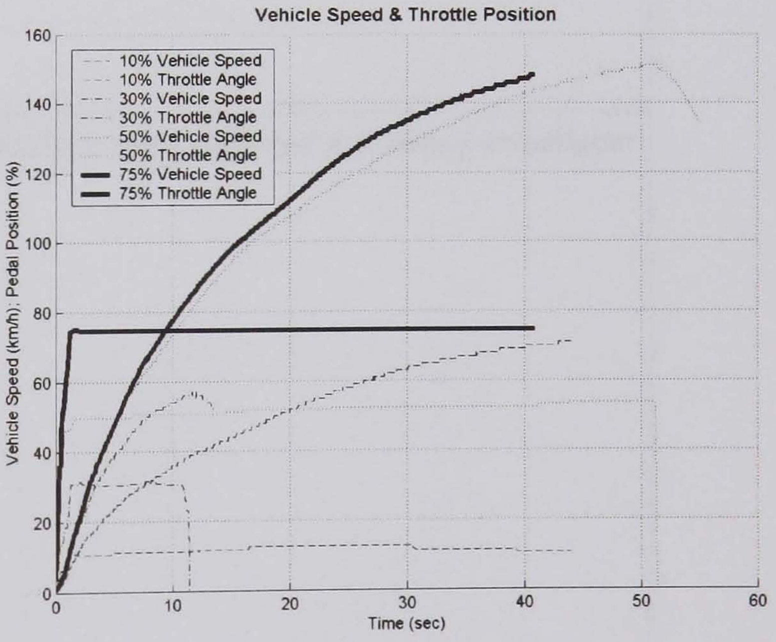

30% Throttle Acceleration
Engine Speed
Current Gear
Next Gear
Engine Speed (rpm)
Gear
Time (sec)
0
2000
4000
6000
0
2
4
6
8
0
10
20
30
40
50
60


Vehicle Speed & Throttle Position
10% Vehicle Speed
10% Throttle Angle
30% Vehicle Speed
30% Throttle Angle
50% Vehicle Speed
50% Throttle Angle
75% Vehicle Speed
75% Throttle Angle
Vehicle Speed (km/h); Pedal Position (%)
Time (sec)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60


50% Throttle Acceleration
Engine Speed
Current Gear
Next Gear
Engine Speed (rpm)
Gear
Time (sec)
0
2000
4000
6000
0
2
4
6
8
0
10
20
30
40
50
60


Vehicle Speed & Throttle Position
10% Vehicle Speed
10% Throttle Angle
30% Vehicle Speed
30% Throttle Angle
50% Vehicle Speed
50% Throttle Angle
75% Vehicle Speed
75% Throttle Angle
Vehicle Speed (km/h); Pedal Position (%)
Time (sec)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60


75% Throttle Acceleration
Engine Speed
Current Gear
Next Gear
Engine Speed (rpm)
Gear
Time (sec)
0
2000
4000
6000
0
2
4
6
8
0
10
20
30
40
50
60


Vehicle Speed & Throttle Position
10% Vehicle Speed
10% Throttle Angle
30% Vehicle Speed
30% Throttle Angle
50% Vehicle Speed
50% Throttle Angle
75% Vehicle Speed
75% Throttle Angle
Vehicle Speed (km/h); Pedal Position (%)
Time (sec)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60

| |
|---|
| *Please describe the rationale behind the ratings that you assigned to each shift.* |
| ***10% Throttle*** |
| ***30% Throttle*** |
| ***50% Throttle*** |
| ***75% Throttle*** |
| *Would additional information about the vehicle behaviour have assisted in making a decision about the rating to apply? What information?* |

# Appendix B

# Engineering Doctorate Portfolio Submission Summaries

*Table 1 – Engineering Doctorate Portfolio Submissions*

| No. | Submission Title | Summary |
|---|---|---|
| 1 | The Effective Implementation of Computer Aided Engineering in the BMW Powertrain Product Development Process | This is an MSc Dissertation that presents research undertaken in BMW and other manufacturing companies. Best practice in the implementation of Computer Aided Engineering is described, BMW status is assessed against best practice, and a development plan is proposed. |
| 2 | The Dissemination of CAE Implementation Concepts into BMW Powertrain | An internal report with a circulation to BMW and Rover Group Chief Engineers, this submission summarises the findings of Submission 1 and makes a business case for the modification of the product development process where CAE is implemented. |
| 3 | A Good Practice Model For Implementation Of Computer Aided Engineering Analysis In Product Development | This paper is based on Submission 1 and has been accepted for publication in the Journal of Engineering Design, Vol. 14 No. 3 (September 2003) |
| 4 | An Appraisal of Systems Modelling and Simulation Tools for Powertrain Development | A basic introduction to systems modelling and simulation and powertrain models is presented. A criteria for assessing systems modelling and simulation tools is proposed and a number of tools are assessed against the criteria. .An architecture for the application of systems modelling and simulation in Land Rover is proposed. |
| 5 | Current State-of-the-Art Continuously Variable Transmission Technology | The operation of various types of Continuously Variable Transmission (CVT) and current technology in the field is reviewed. This forms a foundation for CVT modelling. |
| 6 | Modelling of an Electo-Hydraulic CVT for Transmission Calibration Studies | A systems model of a vehicle equipped with a push-belt CVT and controller is developed and validated. |
| 7 | Developing a Land Rover Automatic Transmission Calibration Simulation Tool Strategy | A gap analysis identifies a number of areas of information deficit in the transmission calibration process where systems modelling and simulation would be particularly effective. A set of simulation tools for use in Land Rover is recommended, and a specification of development work that is required on the tools is presented. |
| 8 | Modelling of an Automatic Transmission Vehicle for Transmission Calibration Studies | A systems simulation model of a vehicle equipped with a discrete ratio automatic transmission is developed and validated. The model is encapsulated in a user environment. |
| 9 | Application and Enhancement of the Transmission Calibration Simulation Tool | The simulation model developed in Submission 8 is applied to an example transmission calibration exercise. The potential benefit of applying the simulation model is demonstrated. |
| 10 | A Presentation on the Transmission Calibration Simulation Tool at the Land Rover Powertrain Technical Review | This submission is a presentation that was given to Land Rover Powertrain senior management in which the potential benefits of applying the simulation model developed in Submission 8 to transmission calibration were explained. |