UNIVERSITY OF WARWICK

INNOVATION REPORT

Development of Automated and Connected Testing Processes for Electric Vehicles

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Declaration of Authorship

I, Araan MOHANADASS, declare that this thesis titled, "Development of Automated and Connected Testing Processes for Electric Vehicles" and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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“The ultimate freedom for creative groups is the freedom to experiment with new ideas. Some skeptics insist that innovation is expensive. In the long run, innovation is cheap. Mediocrity is expensive and autonomy can be the antidote.”

Thomas Kelley, IDEO

University of Warwick

Abstract

Faculty Name
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Development of Automated and Connected Testing Processes for Electric Vehicles

by Araan MOHANADASS

Electric vehicles provide a practical transportation solution to overcome emission and energy deficiencies posed by combustion vehicles. However, high product costs driven by the price of components and immaturity of the processes to create them reduce the product's financial competitiveness. Manufacturers need to adapt their processes to develop cars more economically while adhering to emission requirements by legislative bodies. This EngD determined the estimated R&D cost saving made through innovating automated and connected technologies into the development process to reduce the development costs of vehicles holistically. The research targeted physical testing costs due to the potential increase in demand for testing to improve the characterisation of virtual models while the automotive industry transitions to vehicle electrification. The research established objectives to target human, capital and facility costs as significant cost drivers for physical testing. Three applications of automation and connected systems were ideated and investigated to evaluate the saving potential of each cost driver. Firstly, an automated dynamometer was designed and experimentally tested to demonstrate its capability in reducing man-hours for powertrain component testing. Secondly, a distributed test network was virtually modelled to understand the opportunities to supplement physical prototype vehicles by utilising connected component test facilities. Finally, an automated test management system with test case generation capability was proposed and evaluated to determine its capability to improve testing productivity. Using the results from each technology innovation and Jaguar Land Rover's historical strategy, a numerical model identified an estimated saving of £225m across 12 vehicle models representing a net change of 1.71%. Changes in human resources demand were the most significant contributor toward total development cost savings. DTS and automated dynamometer innovations provided 90% and 9% of human resource cost-saving, respectively. The results suggested that these technological innovations would make only a marginal impact on saving for customers. Ultimately, a combination of further developing of these technologies to maximise application and saving made on other portions of the vehicle development process is necessary to bridge the gap between combustion and electric vehicle. However, the savings proposed would benefit manufacturers financially and allow them to also gain additional revenue by providing opportunities to release vehicle models marginally earlier.

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List of Abbreviations

AC	**A**lternating **C**urrent
AER	**A**ll **E**lectric **R**ange
API	**A**pplication **P**rotocol **I**nterface
ATMS	**A**utomated **T**est **M**anagment **S**ystem
BEV	**B**attery **E**lectric **V**ehicle
BLDC	**B**rush**L**ess **D**irect **C**urrent
BMS	**B**attery **M**anagment **S**ystem
BWF	**B**ack**w**ard **F**acing
DC	**D**irect **C**urrent
DTS	**D**istributed **T**est **S**ystem
DUT	**D**rivetrain **U**nder **T**est
ECMS	**E**quivalent **C**onsumption **M**inimisation **S**trategy
ECU	**E**lectronic **C**ontrol **U**nit
EKF	**E**xtended **K**alman **F**ilter
EV	**E**lectric **V**ehicle
EMF	**E**lectro **M**otive **F**orce
ESP	**E**ngineering **S**ervice **P**rovider
FC	**F**uel **C**ell
FL	**F**uzzy **L**ogic
FWF	**F**orward **F**acing
GUI	**G**raphical **U**ser **I**nterface
HEV	**H**ybrid **E**lectric **V**ehicle
HIL	**H**ardware **I**n the **L**oop
HTTP	**H**yper**T**ext **T**ransfer **P**rotocol
HVAC	**H**eating **V**entilation and **A**ir **C**onditiong
ICE	**I**nternal **C**ombustion **E**ngine

IEKF	**I**terated **E**xtended **K**alman **F**ilter
IGBT	**I**nsulated **G**ate **B**ipolar **T**ransistor
JLR	**J**aguar **L**and **R**over
LAN	**L**ocal **A**rea **N**etwork
MIL	**M**odel **I**n the **L**oop
MOSFET	**M**etal **O**xide **S**emiconductor **F**eild**E**ffect **T**ransistor
NEDC	**N**ew **E**uropean **D**rive **C**ycle
OEM	**O**rigonal **E**quiment **M**anufacturer
OOP	**O**ptimum **O**perating **P**oint
OSI	**O**pen **S**ystems **I**nterconnection
PCL	**P**rimary **C**ontrol **L**oop
PD	**P**otential **D**ifference
PID	**P**roportional-**I**integral–**D**erivative
PMSM	**P**ermanent **M**agnet **S**ynchronus **M**otor
QoS	**Q**uality of **S**ervice
R&D	**R**esearch and **D**evelopment
RBC	**R**ule **B**ased **C**ontrol
REKF	**R**obust **E**xtended **K**alman **F**ilter
ROIN	**R**esolution of **O**ptimum **IN**stance
RT	**R**eal **T**ime
RTOS	**R**eal **T**ime **O**perating **S**ystem
SEI	**S**olid **E**lectrolyte **I**nterphase
SIL	**S**oftware **I**n the **L**oop
SOA	**S**tate **O**f **A**rt
SOC	**S**tate **O**f **C**harge
SOH	**S**tate **O**f **H**ealth
SRM	**S**witch **R**eluctance **M**otor
SUT	**S**ystem **U**nder **T**est
TCP/IP	**T**ransmission **C**ontrol **P**rotocol **I**nternet **P**rotocol
TTR	**T**hrough **T**he **R**oad
UC	**U**ltra **C**apacitor

UDP	**U**ser **D**atagram **P**rotocol
UN	**U**nited **N**ations
VLAN	**V**irtual **L**ocal **A**rea **N**etwork
WLTP	**W**orldwide harmonised **L**ight-duty **T**est **P**rocedure

List of Symbols

C_d	Coefficient of drag	Dimensionless
D	Diameter	Metres
F	Force	Newtons
G	Gear ratio	Dimensionless
I	Current	Amps
In	Inertia	Kilogram per metre squared
P	Power	Watts
Pr	Pressure	Pascals
R	Resistance	Ohms
r	Radius	Metres
T	Torque	Newton-metres
t	Time	Seconds
V	Velocity	Metres per second
μ	Co-efficient of kinematic friction	Dimensionless
ω	Rotational velocity	Radians per second
ρ	Air density	Kilograms per metre cubed

Chapter 1

Introduction

Transportation as a concept is a critical function for the movement of people and goods at the required capacity as well as rate for economic and societal growth. This function in the automotive sector requires the conversion of on-board stored energy (typically hydro-carbon based fuels, electricity in batteries, hydrogen gases) through power conversion technologies (such as combustion engines and electric machines) to create the necessary kinetic power to propel vehicles at the desired speed. These processes are imperfect with some of the generated power being lost to the environment through heat and noise. While some of this energy is recoverable, the proportion of lost energy is dependent on the technical and economic feasibility of the chosen power generation method.

An ideally designed automobile looks to satisfy the consumer requirements to deliver the appropriate driving ranges, and ensure that the product as a whole remains economically competitive for both customers as well as manufacturers. This requires a fine balance between technical capability, product costs, and vehicle complexity. As a result, with the transition to vehicle electrification it is important we maximise vehicle efficiency to best use on-board stored energy to reach desired target ranges and reduce high product costs associated with batteries.

1.1 Motivation

1.1.1 Drivers for electrification and significance of vehicle efficiency

Climate change

Rising temperature because of green house gases pose a critical threat to habitability of our planet. The growth of human activity over the last century is a significant contributor to the emission of green house gases to atmosphere. This rapid change has led to catastrophic occurrences of melting ice caps, wild fires and negative consequences to natural habitats. The continuance of these effects are likely to lead to the irreversible changes, destruction to parts of the earth ecosystem and negative impacts to human political/economical/social activities [1]. The increase in carbon dioxide is a critical contributor to this effect [2]. As the concentration of this atmospheric constituent grows, a larger portion of solar thermal radiation is retained within the earth's atmosphere. This retained thermal energy creates a green house effect that is detrimental to the planet. Government bodies have recognised dangers of climate change and have made into law requirements to reduce total emission over the coming decades [3, 4].

Fossil Fuels

A large portion of carbon dioxide emissions are linked to power generation through non-renewable fuels [5]. Typically, hydrocarbon based fuels in the form of gasoline and diesel undergo combustion with oxygen to extract power from an exothermic reaction by reforming intra-molecular bonds of the fuel. The resultant thermal reaction is used to generate pressure, which is converted to kinetic energy in an combustion engine. Byproducts of carbon dioxide and water vapour are released into the atmosphere. However, this reaction can be imperfect resulting in the incomplete combustion of fuels into Carbon monoxide, un-burnt hydrocarbons and Carbon particulates being emitted to the atmosphere. Further, improper control of combustion as result of running a lean air-fuel mixture can result in higher temperatures and pressures that oxidises Nitrogen present in the air to a variety of NOx species (NO, NO_2, N_2O, N_2O_2, N_2O_3, N_2O_4 and N_2O_5) that contribute to reduced local air quality and respiratory diseases.

Moreover, phasing out this form of power generation used for personal mobility and transportation, in favour of less polluting technologies such as battery electric or fuel cell vehicles represents a key opportunity to tackle society's contributions towards greenhouse gases. Current records show there were 1 billion on-road vehicles in the world as of 2010, with non-peer reviewed sources suggesting the current value is closer to 1.4 billion as of 2016, and projections estimating this number will increase to 1.7-1.9 billion by 2040 [6, 7, 8, 9]. Most of these vehicles are solely reliant on combustion as their form of power generation. Replacement of these vehicles with cleaner power generation methods would likely have a positive effect in reducing greenhouse gases and the rate of climate change.

Furthermore, the scarcity and increasing extraction costs of the raw crude oil supply required for gasoline production, creates a strain in the economy for fuel usage for transportation methods. The combination of the finite supply of crude oil and continuous growing demand for vehicles in the developing world [10, 11, 12], reduces the availability of crude oil supplies and thus inflates its price. As this resource increases in price, there will likely be a point where the use of crude oil as a fuel becomes uneconomical for both consumers and industry alike. This tied in with emissions impact, air quality and geo-political security of fossil fuel sources has driven the sector towards vehicle electrification.

Vehicle Electrification

Ultimately, the search for alternative power sources for mobility has led to a renaissance of vehicle electrification. This form of power generation stores electrochemical energy in a battery on-board the vehicle, then uses a series of electromagnets and switches to convert electrical charge into kinetic energy through an electric machine. The key benefits of this power transformation are: zero local air quality emissions and high vehicle efficiency. The identified primary and many secondary benefits, result in a powertrain more suitable for consumer and industrial use while achieving objectives of tackling climate change globally.

With the transition to vehicle electrification, the point of emissions is transferred up-stream to national utility power generation. In a holistic view, the energy stored on vehicle batteries are provided through national electrical utilities, generated by a mixture of renewable and non-renewable energy supplies. This mechanism results in the utilisation of power generation methods such as nuclear, solar and wind that are less applicable as a mobile source power for vehicles, and reduces local emissions as combustion of non-renewable fuels occur away from settlements and communities. Tied in with government requirements for reduced emission, the mix of energy generation methods are shifting towards reliance on non-renewable fuels with the advancement of national infrastructure across the globe.

Consequently, the purchasing factors for consumer vehicles have been transformed with the transition to vehicle electrification. At the height of combustion powertrains use, theoretical maximum efficiency is limited to 30-40% [13]. The efficiency barrier has required manufacturers to differentiate vehicles through other attributes to gain a competitive edge (comfort, styling, performance, driver aids). With the transition to electrification in vehicle powertrains, the focus on product differentiation has shifted back to vehicle efficiency. This evolution of customer focus is now centred the metric on all electric range (AER), lmited are a recognisable consequence of poor efficiency and the cost of product (of which 50% is associated the battery) to provide this range. Consumers are aware of the differences between the predecessor technology through vehicle range and relatively longer duration for energy storage replenishment. The outcome of which affects accustomed use of vehicles.

Alternative technologies exist for energy storage purposes on vehicles. Devices such as Fuel Cells (FC), Ultra Capacitors (UC), kinetic flywheels all hold the capability to store or extract energy from alternate fuel source. The applicability of these energy storage methods are dependent on the amount of deliverable power, its density to hold energy and its efficiency (Table. 1.1) [14]. For certain mobility platforms other energy storage methods could be more applicable due to alignment capability and requirements to its use case. With the current industrial and business strategy for JLR, alternate energy storage mediums and conversion techniques were considered less relevant due to their energy capacity, power output and efficiency.

Device	Power	Energy	Maturity	Storage duration	Efficiency
Electrical Battery	0.3MW	300KWh	Mature	Medium-term	80-90%
Fuel Cell	10MW	n/a	Novel	Long-term	40-55%
Ultra Capacitor	2MW	33KWh	Novel	Short-term	>90%
Kinetic Flywheel	30MW	50KWh	Mature	Short-term	>90%

TABLE 1.1: Various energy storage technologies applicable to vehicle mobility.

Non-exhaust emissions

However, adoption of electrification technologies alone will not eradicate harmful emissions produced directly by the vehicle. Tires and mechanical brakes can also contribute to the overall harmful release of emissions in the form of particulate matter under normal operating conditions. Wear of mechanical brakes have been identified and experimentally measured through laboratory tests conditions. These tests have shown that up to 50-85% of PM10 and finer PM2.5 emissions are caused by non-exhaust sources[15]. Tire wear has also been experimentally demonstrated under lab condition's to have a 3-11% contribution to PM10 emissions [16]. The out of particle matter is influenced by the component's design, materials, vehicle weight, brake intensity and driving style. With the current trajectory of emission improvements driven by vehicle electrification, non-exhaust emissions will have raised focus as governments and legislative bodies attempt to improve air quality[17].

Shift in Industrial demands

Importantly, vehicle manufacturers are required to adapt their development strategy to reflect consumer requirements. With the demand to provide an optimal AER and a reduction in battery costs through down-sizing battery pack sizes, refinement of component and system development to maximise vehicle efficiency has direct business impact to increasing revenue and product profitability.

Equally, the change in consumer perspective on air quality and climate change mean that big reductions in vehicle emissions are being mandated by legislative bodies. Over the last decade new regulations have been introduced to bring industry wide emissions to acceptable levels and most notably completely remove combustion vehicles from society's roads by the mid-point of the century. These are outlined by regulations requiring vehicle manufacturers to achieve a fleet average of $95g/km$

of CO_2 by 2020, introduction of improved vehicle certification standards and a ban on sales of combustion vehicles in countries such as United Kingdoms and France in 2030-2050 [18].

Opportunity for Market Growth

With the shift in requirements for the consumer transportation industry, opportunities for capturing market share exist for both incumbent manufacturers and new entrants. As current combustion vehicles are increasingly phased out and prohibited in certain locations, manufacturers that maximise vehicle efficiency gain a competitive advantage to deliver a product with similar AER with a reduced product cost through downsizing of the on-board battery. The additional capture of revenue and profits for a manufacturer can create further opportunities for expansion and financial stability. This also extends across the supply chain where a large proportion of research and development costs exist, successful manufacturers can establish partnerships with suppliers to gain a further advantage.

1.1.2 The need for better tools to optimise electric vehicle efficiency

Holistic Optimisation

Crucially, the definitive solution to maximise successful development of next generation vehicles requires the consideration of all aspects of the manufacturers contributing activities. Both the cost of raw products and overhead activities need to be carefully controlled to ensure profitability, one such area is the costs attributed to R&D of products. This activity has a significant influence on a company's ability to adapt to industrial and consumer changes.

Capacity

Predominantly, to reflect the rapidly changing demands of vehicle development, organisations within the sector must be capable in undertaking the required volume of work to change existing processes and activities to meet the market as well as product requirements. The changes in technical competence and experience towards vehicle electrification require R&D of components, systems and processes. The rate of change to meet early adopters and growth markets would therefore need acceleration of research into these areas to achieve objectives faster than competitors.

Organisational Efficiency

Furthermore, the relative cost of developments are highly important to the profitability of the automotive organisation. The optimal investment into processes, technologies and assets are crucial for continual growth. Operating below or above designed capacity are key indicators that these operations are inefficient for its purpose. Developing both the productivity and quality of product development processes are critical aspect to reducing overhead costs, retaining market agility and fulfilling product warranty/reliability requirements.

1.1.3 Approach for development of new auditing methods

Measuring and Analysing Energy losses

Firstly, an in-depth study was undertaken with JLR to analyse the disparities between vehicle modelling methodologies used in the design and development process. A statistical comparison was conducted into the sources of error experienced in the techniques used to derive parasitic losses of vehicle platforms. The study highlighted the variation in accuracy between virtual estimations, empirical models derived from component tests and full vehicle coast-down tests. This was attributed to simplification of component or environment behaviours as well as interactions. Component and system Inaccuracy was recognised as a contributing factor to reduced quality of vehicle efficiency estimations. Thus with the transition to vehicle electrification, refinement of virtual modelling and physical testing are necessary advancements to ensure feasible development and production of electric vehicles.

Specific Component loss measurements

Furthermore, research was conducted to determine the performance and future paths of optimisation for vehicle electrification technologies. A thorough analysis of peer reviewed papers and legislation was conducted to understand the operation, current state of the art and evaluation methods of components/systems. The insight provided from these papers recognised the increased performance sensitivity of electrification technologies towards system efficiency, the future trends of development, as well as the distinct technical/economical maturity of evaluation methods.

Distributed Systems

Therefore, as part of the innovative development of the existing issues within vehicle energy auditing methods, solutions centred on connected systems were prioritised due to opportunities to transform the vehicle-testing environment. Traditionally, vehicle components are developed in isolation with limited data on the interactions between associated components that form a system. By providing interaction between these components at an earlier stage, acceleration of development process can be facilitated through de-risking the occurrence of product development issues experienced at the system and full vehicle prototype integration.

Furthermore, digital connections between systems and facilities also created opportunities to further develop existing investments. Development of new assets require extensive capital. With the rapid change to vehicle electrification, the creation and building of new test resources required could reduce the financial gain of adopting electric powertrains. Re-investment in these facilities, offer an opportunity to repurpose existing facilities without major capital and scrapping.

Automation

Equally, automation and improved control of processes generate opportunities to overcome capacity and efficiency restrictions. Automation of test rigs and facilities have in other cases allowed improved consistency and throughput of technical operations. Similar improvements could minimise the time require to develop components, and introduce improved consistency of energy auditing methods.

1.2 Portfolio

The EngD was sectioned into individual submissions to ensure a thorough investigation was conducted to maximise the applicability of an overall solution. These consisted of:

- Problem Identification
- Problem Investigation
- Solution development
- Implementation and Test solutions
- Statement of Innovation and Personal development.

This framework expressed the flow of the work conducted. The current State of the Art (SOA) in this field was critically assessed to understand the issues with vehicle energy testing, alternate solutions and substitutes. The outcome of this was then used to conceptualise an innovative solution that could be used to meet the requirements of the industry. Due to the novelty of the solution, specific technology developments were undertaken to expand system knowledge and reach technical milestones to allow its functionality.

1.2.1 Problem statement

The portfolio is intended to investigate opportunities for economic sustainable development of electric vehicles to tackle climate change. The overall success of electric vehicles is determined by their ability to reduce the rate that global CO2 emissions are entered into our atmosphere. This outcome is driven by the growth of electric vehicle through conversion of existing and new consumer automobiles units from combustion alternatives. To achieve this manufacturers must provide an electric vehicle product that is capable of persuading customer to substitute the role that combustion vehicles currently provide. Influencing customer to make this decision is dependent on a multitude of factors. Manufacturers have a direct influence to consumer persuasion through either the cost or the technology/features of the product. The former of which is the biggest difference with the two type of automobile, while the latter is predominantly achieved with through the new generation of electric powertrain's superior performance at reducing emissions. Upfront prices for vehicles are a deterrent for consumers to buy or substitute existing combustion vehicle stock. This is driven by part of COGs for components which includes both material costs and development costs. Electric vehicle batteries are seen as one of the biggest challenges towards this due to their high prices. Automotive manufacturers must either find cheaper alternatives or optimise the efficiency of electric vehicles to improve the energy density and cost-energy density to provide the desired product characteristics. Both of these factors require expedited development of battery, powertrain and ancillary components to sufficiently reduce their combined cost and on-set to consumers. As a result, this study focused on optimising the time taken for product development to reduce overall bottle-necks that lengthen the vehicle development process and therefore increase the cost. The aim of this study was to improve the economic sustainability of developing electric vehicles and components. This includes understanding the future trajectory of current component and test structure that enable their development; identify areas in the vehicle development process to adopt changes that could reduce the development cost of components, systems and vehicles; propose feasible technology solutions to streamline the vehicles development process; and explore the capability of these concepts to improve the vehicle development process. This approach was adopted to ensure that the solutions proposed reflect the requirements of real-world issues.

1.2.2 Core Portfolio Structure

Importantly, due to the potential coverage of the proposed solution, the structure chosen reflected the wide influence of connected and automated test systems. While both the problem investigation and solution conceptualisation embraced a holistic role in improving vehicle testing, three technology developments were undertaken in parallel to further the two variations in the application DTS, and a key technology development of test resource feature to enable operation of DTS (Figure. 1.1). This layout allowed full exploration of innovative solutions that maximised the impact of the collective industry.

Ultimately, it was decided that improvements in vehicle energy auditing should be matched across all levels within the automotive industry. As such, Submissions 3, 4 and 5, targeted component, vehicle product and testing processes levels respectively to introduce automation and distributed systems to vehicle energy testing. The portfolio in this provides guidance on the route to fully understand the overall perspective of the points, arguments and analysis brought forward from this body of research.

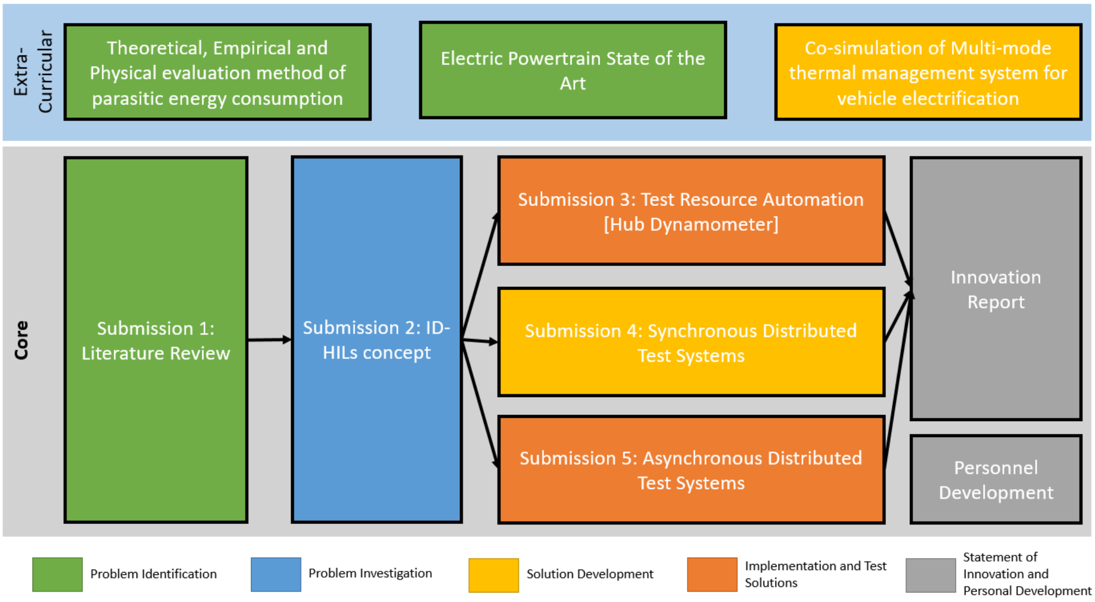


FIGURE 1.1: The adopted EngD portfolio.

Submission road-map

The EngD portfolio was laid out to constructively identify and create solutions to improve the energy auditing process for electric vehicles sustainably. Submission 1 explored published academic research to build a robust knowledge base in understanding energy characteristics, future trends, and gaps in electric vehicle powertrain components. This was coupled with an internal study in JLR on theoretical, empirical, and physical evaluation of parasitic energy losses to ideate the potentials of Internet distributed Hardware-in-the-loop systems. Submissions 3, 4, and 5 explored and provided in-depth research regarding the application and maturity of crucial solution elements from three different project perspective levels. The innovation report then compiled the submissions together and reflected on the business innovation and impact of technical research. The research ensured an informed approach from academia and industry contributed to identifying existing problems, relevant ideation of solutions, and evaluating the technology for improving the energy auditing process of electric vehicles.

EngD sponsorship

JLR sponsored and supported this body of research to investigate and uncover the knowledge that could aid their future strategy in developing electric automotive vehicles. Financial top-ups on research funding, access to internal staff members, testimony, and materials were the main tools provided by JLR's research division. This provided the ability to carry out the research in a full-time capacity without the additional sources of funding that could bring complications towards the access and sharing of sensitive materials. In addition, this also benefited JLR as the research was conducted from an inside perspective that could utilise direct knowledge to provide a bespoke research answer. An outside-in perspective would need to rely on external accounts and material through an indirect approach that would require critical evaluation to explore its validity.

1.2.3 Additional Work

Alongside the core portfolio of the EngD, extra-curricular activities in the form of research studies and publication were undertook to investigate relatable content that was influential to objective of improving vehicle energy auditing techniques. These activities were conducted in conjunction with JLR, WMG and CATAPULT UK. Experience gained through these activities provided insight into industrial processes in vehicle energy auditing and a platform to demonstrate engineering professional competencies as well as knowledge in a research environment.

Parasitic Losses Modelling Study

Initially, a collaborative approach was adopted with a JLR research project that investigated the differences in accuracy between various energy auditing techniques. In this study, a comparison was made between parasitic energy consumption models derived of theoretical estimations, empirical models from components tests and full vehicle coast-down tests. Observations made from statistical regression techniques and analysis of variance from this study, identified recognisable forms of error from both theoretical and empirical based models, while the data provided from physical vehicle tests suggested areas of modelling improvement that could further refine modelling techniques within the initial stages of vehicle development process. This study as a whole provided a fundamental comprehension of the techniques used and their point of adoption along the vehicle development process. The inaccuracies discovered as part of this study accentuated the necessity to improve modelling of thermal and transient behaviours of components and subsystems.

Electric Powertrain State of the Art

Notably, the comprehension of vehicle electrification technologies was echoed in a contribution made towards the publishing of 'Advanced Energy Management, Modelling and Control for Intelligent and Efficient Transport Systems' [19]. Within this book, an in-depth review of conventional powertrain combustion and electrification technologies was carried out, with an additional discussion made on the future of these technologies. The knowledge articulated through this publication assisted to fortify my understanding of current and future technology requirements in vehicle electrification. The continual recognition of these developments were necessary to understand the motivations and requisites for innovative energy testing techniques.

Catapult Thermal Management System

In addition, research was done parallel to the EngD to further energy evaluation of automotive subsystems. As part of a small team of researchers, an investigation was carried out to develop a test system to characterise powertrain and cabin Heating, Ventilation, And Cooling systems (HVAC) for vehicle electrification. The specific subsystem was of interest in the development of energy auditing techniques due to the system's sensitivity towards component thermal management, opportunities for energy recycling, and overall energy consumption.

Importantly, contributions were made to the innovation of the co-simulation process to improve the design and configuration of a multi-mode thermal management system for a consumer vehicle. This study implemented a co-simulation methodology to allow a calibrated virtual vehicle model to be interfaced with a configurable thermal control system to evaluate HVAC energy management strategies. The study demonstrated an alternate approach to HVAC control development by conjoining the models in this fashion; a set of transient tests allowed virtual optimisation of the control strategy that would not be possible in a physical transient test environment presently, and their related high costs and resources. The development of this tool was hoped to economise research opportunities into HVAC components and control systems development.

Chapter 2

Literature review

The literature review as part of this EngD provided a critical understanding of the technological state of electric vehicles, their components, and development processes to best address existing challenges and opportunities. The knowledge around the hardware and systems concerning how they function, their limitations, their impact on vehicle performance, and their future development helped select specific areas where advancements in testing and modelling would produce a meaningful investment that helped consumers and manufacturers economically. This broad approach provided a foundation to develop holistic solutions to address the technical challenges collectively in the development of EV powertrain testing.

2.1 Vehicle Electrification Architecture

Firstly, research was conducted on the physical technologies that are set to be the building block for vehicle electrification. Pure electric and hybrid vehicles look to incorporate methods of kinetic power generation through an electric machines. Fundamentally, an electric machine appropriates power from a current conversion device (i.e an Inverter), that transforms direct current drawn from an energy storage device (Figure. 2.1). This overall structure for advanced motive systems are required among battery electric vehicles (EV/BEV), combustion-electric hybrids and many other exotic hybrid variations. No matter the final desired product for transportation and personal mobility, motive power through electrification is likely to be a constituent part due to its high efficiency and limited direct emissions.

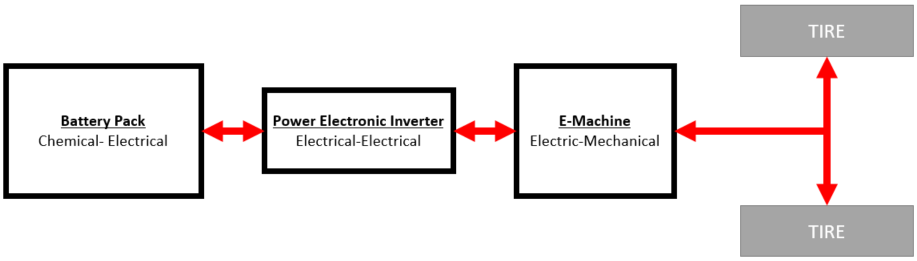


FIGURE 2.1: Battery electric vehicle architecture.

2.1.1 Hybrids

Vehicle hybridisation relies on the principle of maximising the benefits of various powertrain technologies. The recognised definition of this term describes a vehicle that utilises two or more methods of energy storage to provide tractive power. In present vehicles, this is generically seen in the form of Combustion-Electric powertrains that store energy in hydrocarbon based fuels, and electrical charge stored in electro-chemical battery packs. Alternative hybrid layouts are exhibited with Hydrogen-Electric and Combustion-Flywheel applications. The combination of two or more powertrains provides the capability to optimise the operation of the inefficient powertrain (usually combustion engines) through supplementation of power generation or recovery of energy through electric based tractive technologies.

The combination of different energy storage forms and tractive power generation allows the optimisation of vehicle energy consumption by compensating performance shortfalls of each singular powertrain [20] [21]. For Combustion-Electric hybrids, the exact purpose is to compensate the efficiency and emission disadvantages of combustion engines, and limitations of AER of electric powertrains. The existing format of hybrid vehicles cannot satisfy net zero emissions due to the continued reliance of fossil fuels. The use of combustion-electric hybrids would provide a transitional platform until battery and charging infrastructure technology advances.

2.1.2 Vehicle Electrification Terminology

Ultimately, various forms of powertrain electrification can exist to balance usability of vehicles and overall efficiency in energy consumption. Recognised architectures such as Battery, Series, Parallel, Combined, and Through The Road (TTR) (Figures.

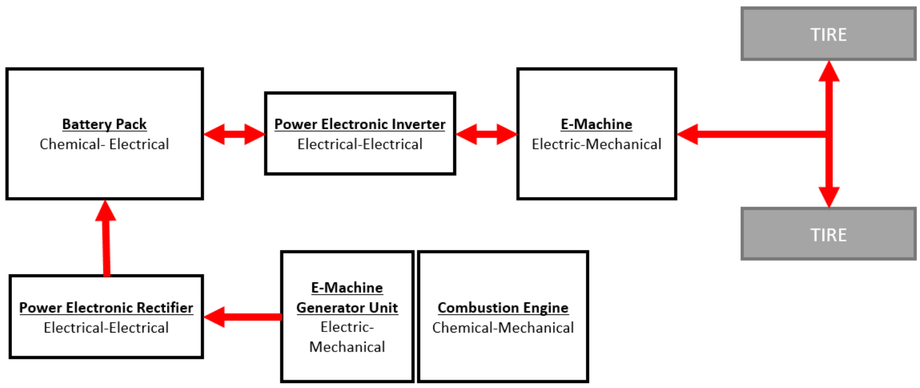


FIGURE 2.2: Series hybrid architecture.

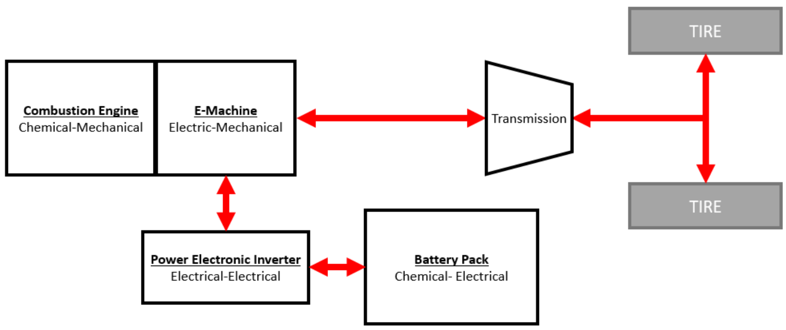


FIGURE 2.3: Parallel hybrid architecture.

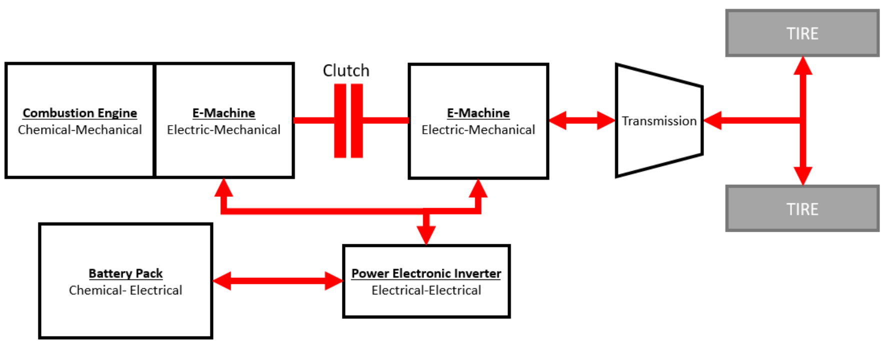


FIGURE 2.4: Combined/Powersplit hybrid architecture.

2.1-2.5) define the physical layout and functionality of which motive power devices converts stored energy into tractive power. Other more niche architectures and variants of the illustrated examples also exist. In addition, terms such as Micro, Mild, Full and Plug-in denote the degree of electrification (Table. 2.1) in which electrical power is used. Utilisation of these term assist in the classification of various architectures possible through their applicability to consumers, and their ability to reduce personal and commercial emissions.

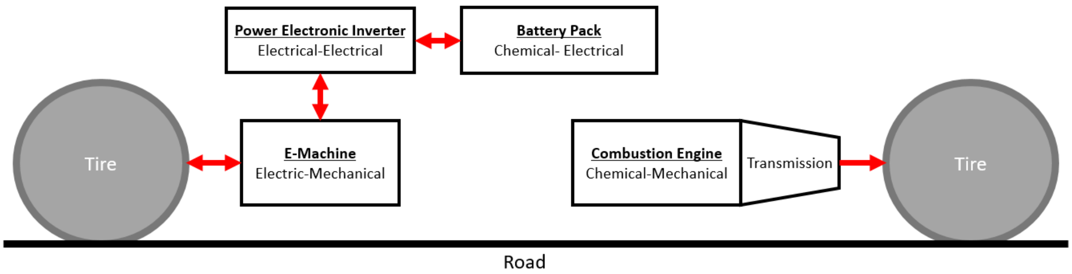


FIGURE 2.5: Through the road hybrid architecture.

Type	Stop-start	Regeneration & boost	Charge depletion	Grid re-charge	Examples
Micro	Yes	Partial	No	No	BMW 1 / 3 series, Fiat 500 & SMART car
Mild	Yes	Yes	No	No	BMW 7 Series ActiveHybrid, Honda Civic, & Range Rover Evoque
Full	Yes	Yes	Yes	No	Toyota Prius, Ford C-Max & Honda CR-Z
Plug-in	Yes	Yes	Yes	Yes	Toyota Prius plug-in Chevrolet Volt, & Panamera S E-Hybrid

TABLE 2.1: Degree of electrification in hybrid vehicles [22].

	Power	Capacity	Cost	Durability
BEV	Low	High	Significant	High
Hybrids	High	Low	Less Significant	Low

TABLE 2.2: Energy storage requirements of battery and hybrid electric vehicles.

2.2 Energy Storage

2.2.1 Battery Developments

The vehicle battery acts as a form of energy storage in vehicle electrification. In application since conception and mainstream adoption, automotive battery technology has relied on the principle of storing electrical energy in chemical potential. Engineered chemical compounds are designed to provide electrical potential difference (PD) that can accumulate and dissipate charge. By doing so, this device can act as a mobile energy storage solution, suitable for motive power applications without the need for direct connection from other electrical power sources (national electrical infrastructure) that would inhibit the mobility of vehicles.

2.2.2 Battery Pack Design

Fundamentally, modern day vehicle battery packs are formed by an array of electrochemical cells to provide the required power specification. The configuration of these cells in series define the overall voltage of the battery pack, while establishing modules of cells in parallel expands the packs total storage (Figure. 2.6). The adaptability of this method of energy storage allows the development of a wide range of load devices in accordance to required magnitudes of power, but also the duration of power needed. Hybrids and BEVs architectures set distinct power requirements from their typical use cases. Application power requirements have dictated the increase of pack voltage to supplement circuit current to minimise current loses, however limitations to pack voltages also exist through the suitability and complexity of load components. Total charge capacity is influenced by the consumption of electrical energy and physical implementation constraints into the vehicle chassis. Henceforth, the electrical storage solution for hybrids are high power and low capacity centric, while BEV batteries are designed with high capacity, low cost and storage durability objectives (Table. 2.2).

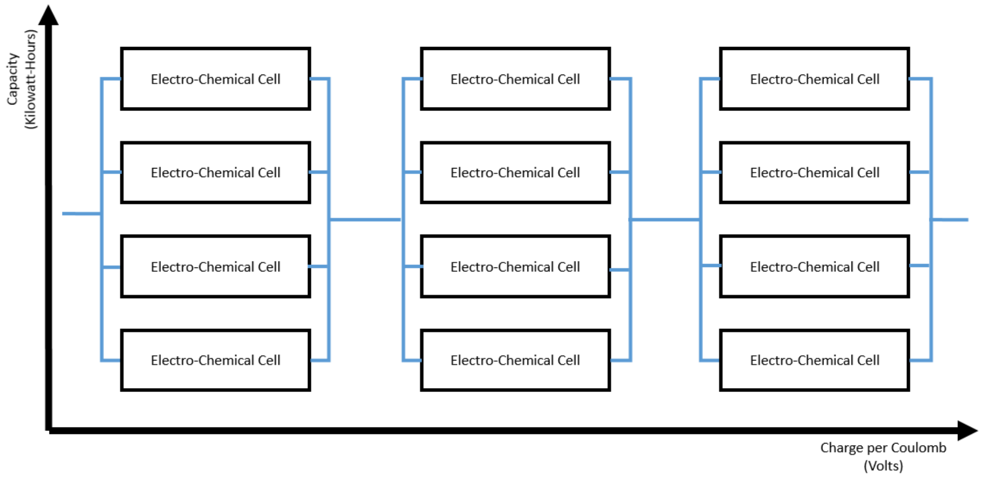


FIGURE 2.6: Battery pack scaling.

2.2.3 Cell Design

Presently, the majority of cells utilised for vehicle tractive energy storage are Lithium-ion (Li-ion) based. Within in battery cell a cathode is made of layers mixed metal oxides coated onto an aluminium foil, an anode graphite applied to a copper foil, and a stack of electrodes separated by a polymer film soaked in an electrolyte. Energy is stored and depleted through a process of intercalation and de-intercalation of Lithium-ions at the anode and cathode. Lithium-ions are transported through the polymer film within the electrode as an electron is passed onto the external circuit, generating a current used to charge or provide electrical load. Potential difference of a cell is influenced by the selection of the anode and cathode material as well as the state of charge of the cell, in Li-ion cells this is typically results in a range of 4.2 volts at high SOCs and 2.7 volts for depleted cells with low SOCs. Physical design considerations (pouch/cylindrical/prismatic) regarding he cells shape and volume also affect the:

- Heat rejection - The ability to dissipate thermal energy away from the cells. Poor thermal management leads to safety implications, degradation and reduction in efficiency.
- Internal resistances - Design considerations that lead to increased resistances would reduce the overall energy efficiency of the vehicle.

- Pack volumetric efficiency - The development of cells with greater volume capacity could provide manufacturers with greater flexibility to meet range estimates. In addition, utilise wasted space in battery pack designs.

2.2.4 Battery Performance

Efficiency

Automotive energy storage solutions suffer imperfect energy conversion and the execution of necessary extra functions resulting in a reduction in efficiency across the hierarchy of battery pack components. These can be defined into the cell, pack and ancillary levels. At each level, various events result in energy being lost as a byproduct of it being consumed to carry out a non-propulsive function.

Cell efficiency Significantly, electrical power lost in battery cells is influenced by the electrical and chemical properties of the electrolyte, anode and cathode. Energy losses in electric vehicles are typically observed through heat generation. Heat generation can be classed into irreversible and reversible heat generation.

Irreversible heat generation Irreversible heat generation consists of ohmic losses across the core three sub-components where electrical resistance properties exist, resulting in irreversible current losses [23]. The squared proportion of current interacting in product with the sub-components resistance can define the quantity of these losses (Equation. 2.1). Henceforth, the design of a battery cell are desired to operate at high voltages, where the inverse proportion of current can be reduced.

Reversible heat generation In addition, electro-chemical reactions within the cells have been referred to as entropic losses and form reversible heat generation mechanisms. This loss mechanism is defined as reversible heat generation through entropic changes within the cell. Atoms within the electrode are re-arranged within their lattice structures through positive and negative entropy as cells undergo intercalation and de-intercalation[24]. This is typically observed as cells increase/decrease heat generation rates through SOC ranges. The volume of waste energy is less significant for automotive applications, where current losses form the bulk rise in temperature

[25, 26, 27]. As a result, the design of these sub-components require careful consideration into their material choices and operating conditions to maximise efficiency. It should be noted that material restrictions of current generation of Silicon based semiconductor limit the theoretical maximum voltage applicable, desired higher voltage capability would require the necessary commercial and volume development of semiconductor materials such as Silicon Carbide, Gallium Nitride and Diamond to be economically feasible for automotive products [28].

$$P = I^2R \tag{2.1}$$

Where, P = Power, Watts: I = Current, Amps; and R = Resistance, Ohms.

Pack efficiency Irreversible ohmic losses can be holistically expanded to the other charge interacting parts of the battery cell/pack, where cell terminals, tab welds and major conductors (bus-bar) also hold resistance properties. With an outward perspective of efficiency, heat sensitive on-board electrical storage methods can also indirectly result in the additional power consumption to manage thermal heat of the battery pack. Longer operating duration of fans and pumps used to cool battery packs could consume energy that would otherwise be used for tractive purposes.

Ancillary losses The necessity to carry out additional functions, such as cooling and operating battery management systems, could also be considered an energy loss mechanism. Electrical power used to operate pumps, fans, and electrical circuits consumes stored onboard energy to provide necessary functions to maintain the safety or functionality of the vehicle. Though these subsystems offer a useful function, they may only provide indirect enhancements to the total energy output of the battery pack to overcome the limitations of the core energy storage components.

Thermal and internal properties influence the performance of the electro-chemical cells. Low temperature testing of Li-ion cells have shown that battery cells show signs of power and energy loss[29]. The effects of power loss sharply increase (as a result of internal resistances) when cells are operated outside of of -20 to 25 centigrade[30]. Post-mortem analysis of cell ageing test show that cold temperatures increase the amount of lithium plating, while warmer temperatures result in cathode degradation and an increase in anode SEI growth[31]. Additional cold temperature tests on cell components verified that SEI was not a major concern at colder temperatures, but lithium diffusivity was reduced in the carbon electrodes used[32]. The traditional understanding of physical material and cell properties outline that as the temperature and SOC of a cell decreases, its electrical resistance increases. This phenomena occurs when a pack charges/discharges in cold conditions where a decrease in efficiency can be expected. However, the generation of thermal losses through this method creates a negative feedback effect on pack temperatures, subsiding the efficiency loss of the cold environment. Capacity changes have been noted through cold temperatures where a intercalation is limited at the anode/cathode leading to a loss in capacity through low ionic conductivity of the electrolyte material, reduced solid state diffusivity of lithium-ions, increased inter-facial charge-transfer resistance and lithium plating.

The power efficiency of a cell and battery pack are quantified from the relationship of input and output energy. This can be reliably measured through instrumentation of voltage and current properties. The formulation of this method ensures that only the battery's loss methods accounts shape the component efficiency, while using a standardised metric (joules) to provide evaluation of the net change in energy.

Durability

Critically, consumers will not accept significant reduction in range or performance of their vehicle over its useful life. Li-ion cells experience capacity fade through their use. The decomposition of liquid electrolyte into solid electrolyte interphase (SEI) consumes active lithium and electrolyte used to store energy [33] [34] [35]. SEI generation increases in proportion to the depth of battery discharge (change in SOC), elevation of cell temperature, and the total number of charge-discharge cycles. The loss of energy capacity is tracked through the State of Health (SOH) measurement that compares the current energy storage ability to its optimal capacity when new. For automotive applications, significant degradation of battery capacity is unfavourable due to consumer perception of linking capacity to vehicle's value and capability. Therefore, it is important that the development electro-chemical cells consider the lifetime performance of the battery.

The study of battery durability research spotlights reducing SEI generation, and increasing awareness on the rate of real world degradation modelling. Both fields are critical to optimising cell technology. Improvements made towards better lifetime characteristic of electro-chemical batteries looks to ensure they meet consumer demands, but also improve the sustainability of using electro-chemical storage for mobility.

Density

Cell density is a critical design consideration when developing suitable vehicle battery packs. Cell density references both gravimetric and volumetric qualities concerning energy held. Both must be optimised to meet the product requirements set out by consumers and manufacturers.

Gravimetric density Cell weight in association with energy held is an essential feature in designing a mobile energy storage solution. Unlike its predecessor in combustion energy storage, the battery's weight does not diminish with the consumption of available energy. Therefore, the overall static weight of the battery has a more significant effect on the vehicle's inertial property, requiring more force to achieve equitable acceleration throughout the vehicle journey. As a result, it is preferred that the development of cell technology improves capacity density to benefit vehicle motive efficiency.

Volumetric density Volumetric density is defined by the relation of consumed spaced to energy held by an electro-chemical cell. Typically, when a battery increases in size, its overall ability to store energy increases. This is only sustainable for a specific size due to cost, reliability and safety. The benefits of optimising volumetric cell density are to minimise the footprint of vehicle battery packs and increase the total achievable energy stored onboard while also having the flexibility to package a battery pack around existing vehicle chassis designs.

Impact on vehicle cost Furthermore, the improvement of battery density has a critical role in developing the economic adoption of battery technology. At present levels, the battery cost constitutes to a 50%, ($171 - $280 per Kwh) of the overall cost of the vehicle [36] [37]. An improvement in battery density would reduce the consumption of expensive raw materials required for cell production that elevates the price of this component. The optimisation of battery density would likely have a larger positive impact on the uptake of electric vehicles as product costs are reduced and the total charge capacity is enlarged through cost effective developments.

C-rates

Moreover, battery cells must be safely operated to ensure they do not exceed charge and discharge rates established by the cell's design. A cell's C-rate is defined by its ability to deliver the held charge capacity in a given period (typically an hour). A higher C-rate typically denotes that the cell could be used for more power-intensive charging and discharging. This is critical for electric vehicles as it is one of many contributing design factors to establishing total power output. It helps determine how fast a vehicle battery pack can be re-charged between journeys.

Safety

Notably, concerns are recognised with the safe use of electro-chemical battery packs. Use of cells out of their defined safe operation window, or destructive mechanical failures (i.e puncturing/crushing/shock) of cells are likely to cause oxidisation of the cell itself, and possible chain-reaction to the surrounding cells [38]. This uncontrolled reaction poses an imminent threat to the vehicle and its occupants. Cell development and control of the cell state are critical to ensure the pack remains for the safe use on roads.

Pack Management

Essentially, digital control systems are necessary to ensure critical controlled and independent battery variables are managed and accounted for. This supervisory system is termed as the Battery Management System (BMS). The primary objectives of a BMS can be outlined as [39]:

- Ensure the cells are kept within safe operating boundaries.

- Measure battery SOC and SOH.
- Detect cell/module failure.
- Manage pack temperature
- Balance cell/module voltages.
- Operate safety devices such as internal contactors.

The BMS's objectives are central to the battery ability to fulfil its purpose reliably, safely and consistently through it's operational lifespan.

Notably, research into BMSs have been focused on improving estimation of the pack's SOC. The generic solution to carry out this function is facilitated by the use of Coulomb counting, due to it's robustness and relatively low computational demand. Other techniques such as Kalman filters and it's extensions (EFK, REKF and IEKF) have been demonstrated to improve SOC estimation and reduce overall error [40, 41, 42]. The success of these SOA SOC methods require additional processing ability to ensure these advanced equations are executed fast enough. With the continual development of microprocessor/field programmable gate array technology and their reduction in cost, it is expected that these cutting-edge techniques will be deployed to vehicles to enhance SOC estimation and maximise charge extraction while operating the battery safely.

2.2.5 Future Advancements

Patently, developments towards solid-state battery technology looks to offer several advantages over current generation Li-ion cells in electric vehicles. These improvements can be outlined as:

- Increased energy - gravimetric density.
- Improved chemical reaction stability.
- Enhanced cycling performance.

Studies into LiSICON and NASICON solid electrolyte have recognised the potential to increase energy density of cells [43, 44, 45, 46], and thus reduce the number of cells for an equivalent energy capacity of current liquid alternatives. Due to the solid nature of the electrode, transportation of ion are more uniform across a wider range of temperatures and mechanical properties inhibit dendrite formation from electrodeposition of lithium, thus improving performance and safety of cell. The improved stability of the solid electrolyte (either organic solid polymer or inorganic crystalline-ceramic) creates opportunities However, solid electrolytes require significant research to overcome desired ionic conductivity of organic polymer at room temperature, reduction/oxidized inorganic electrolytes at low potential differences, improved understanding of potential grain lithium dendrite formation between the anode and electrode, methods to prevent contact loss due volumetric changes in the cell, and suppression of solid electrolyte-cathode active material reactions[47]. With reference to existent technologies, the introduction of solid state technologies are yet to satisfy the complete set energy and power requirements to be commercially employable, research studies have made credible advances though to achieving this, but thermal requirements and sensitivity will continue to be attributes for consistent performance of future solid-state batteries as experienced with current energy storage technologies.

Subsequently, SSBs could impact the approach/strategy of researchers & industrial stakeholders towards testing and developing EVs of the future. SSB strengths such as improved efficiency and increased reliability would raise the significance of enhancing other EV components, while also the novelty of SSBs could see the increased demand for test resources to evaluate compatibility to existing components and demonstration of cell degradation over the life of the vehicle.

2.2.6 Battery Modelling and Testing

Modelling

Virtual battery models come in various forms dependant on it's purpose. For common objectives, these can be categorised by the methodology of the model (Table. 2.3). The distinction in the methods used in each case prevent the a creation of a unified model that covers all purposes to be effectively used. Undoubtedly, the use of virtual models in battery development use a simplified representation of the physical behaviours and can only accurately estimate results with calibration (building look-up tables for

Purpose	Methodologies
Energy Consumption	Empirical Simulation & Equivalent circuits
Durability	Regression, N-term interpolation & statistical
Chemical	Physic based simulation
Thermal	Empirical simulation & computational fluid dynamics

TABLE 2.3: Virtual simulation methodologies applicable to battery model purposes.

empirical models and fine-tuning model parameters for physics-based models) and validation from physical tests and real-world data.

Physical tests

Importantly, due to the modularity of battery packs, testing and results of this system are scaled where necessary. The approach to testing single cells or complete packs all follow the same principle of charging/discharging cells and packs alike, in conjunction to control temperature where possible. Due to the large demand for improvements in battery technology, physical testing of these components is mature and applies to future expected changes in battery technology.

2.3 Power Electronic Devices

Critical for the tractive power generation for electric vehicles, power electronic devices such as inverters provide the capability to convert the Direct Current (DC) of electrochemical battery packs to the required Alternating Current (AC) used to control and power tractive electric machines. The current waveform's transformation is achieved by using an arranged set of power electronic switches that operate in sequence to create the necessary AC waveform. These devices are designed to work at the required switching speeds (operating frequency) and power requirements of paired electric machines.

Notably, inverter technology facilitates the functionality of regenerative braking in electric and hybrid powertrains [48, 49]. Due to the Lorentz' Law, tractive electric machines can also act as electric generators. By appropriate control of switches within the inverter to apply negative torque, precise control of the electric machine waveform enables operation in all four power quadrants. This occurrence allows the

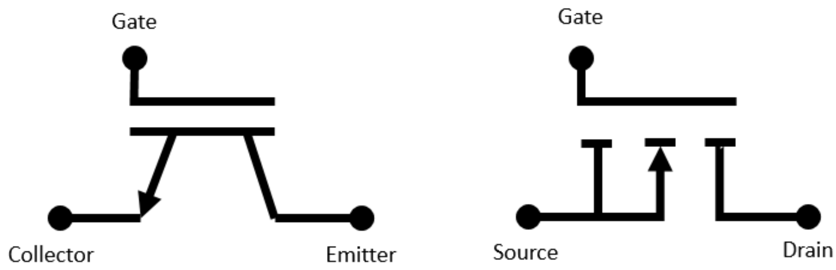


FIGURE 2.7: Insulated Gate Bi-polar Transistor (Left), Metal-Oxide Semi-conductors Field Effect Transistors (Right).

absorption of mechanical power at electric machines to be transported back to the battery, through free-wheeling diodes in the inverter, thus providing an opportunity to recover kinetic energy held by the motion of the vehicle. This action allows energy recuperation that is not possible through conventional combustion engines. Due to safety implications, regenerative braking in vehicles are required to be blended to account for system failure. Various regenerative braking strategies exist to maximise the effect of regenerative braking.

The operating modes of an inverter can be illustrated through a quadrant diagram. This diagram demonstrates the distinct areas where an inverter-electric machine can operate concerning vehicle velocity and drive-axle torque. In quadrants one and three, the inverter outputs power through sequencing of the power electronic switches, while two and four power electronic switches are in an off-state to allow electrical power to flow back to the vehicle battery.

2.3.1 Design

Modern inverters, utilise solid-state power electronic switches such as Insulated Gate Bi-polar Transistors (IGBT), or Metal-Oxide Semi-conductor Field Effect Transistors (MOSFET) to effectively provide AC waveforms (Figure. 2.7). These specific transistors are electronically controlled by common low voltage signals applied to their gate, which in turn either increase or decreases resistance between the two remaining terminals that provide switching capability. Other forms of high power switching such as mechanical and electrical relays are avoided due to performance, efficiency and durability limitations.

2.3.2 Efficiency

Fundamentally, modes of losses for power electronic devices are sourced to three electrical phenomena. These are:

- Switching Losses.
- Conduction Losses.
- Off-state blocking.

The total magnitude of losses experienced through inverters are roughly 5-15% of total energy provided [50, 51]. As switching speeds increase, in proportion switching losses accordingly grow. In this study, the two major losses from switching and conduction modes will be discussed due to their larger impact on the efficiency of the device.

Switching Losses

Naturally, within these solid-state switches, power is lost as they turn-on or turnoff. Turn-on losses are caused by electrical capacitance properties between the gate and emitter (drain for MOSFETs) terminals resulting in an overlap in collector-emitter voltage and current (Figure. 2.8). Turn-off losses are similarly formed by the overlap of drain current and voltages, though this is caused when the reduction in gate voltage drops the gate current, the overlap occurs as the emitter voltage rises during this period until the current decays (Figure. 2.8). These losses are difficult to model numerically and are only determined through experimental means.

Conduction Losses

Conduction losses (or known as current losses) in relevance to inverters occur primarily at the IGBT/MOSFET. Likewise, with other electrical components, ohmic losses occur in power electronic devices with a similar relationship of elevated voltage drop with increasing throughput current across the component. As the switch is placed in an on-state and current passes through, the forward saturation voltage (voltage passing through an on-state transistor) drops due to the internal resistances of the materials. Improvements can be made by increasing the size of the power electronic device (increase the material size) or choosing materials with lower internal resistance. In

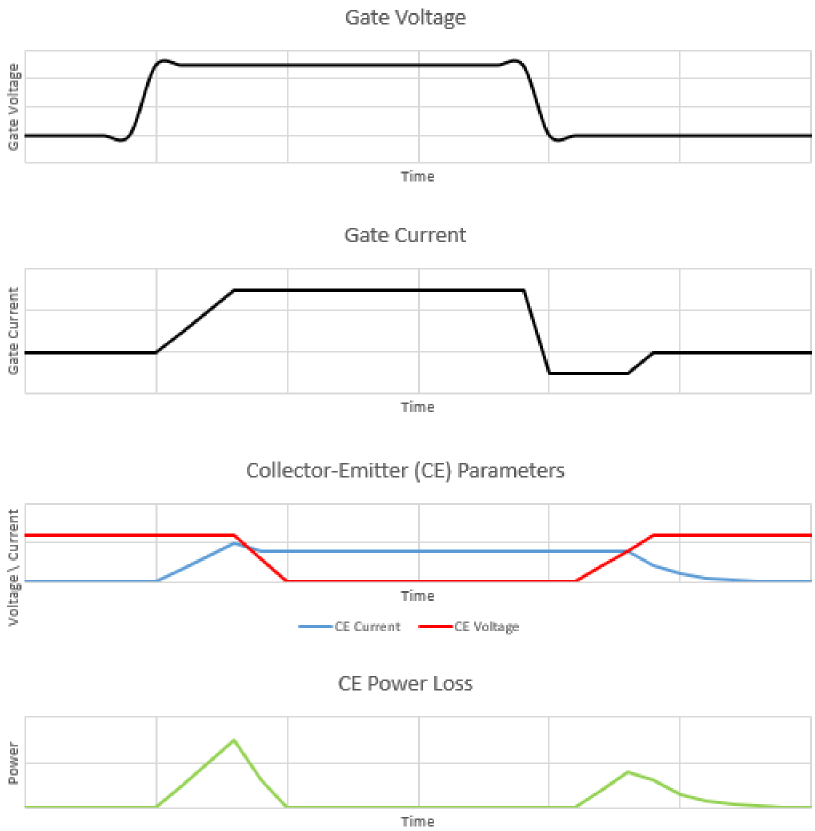


FIGURE 2.8: Switching Losses for an IGBT (Not to scale).

doing by increasing the size of component, this increases the capacitance and relative switching losses. A balance must be struck between these loss modes in the design of the inverter to minimise conduction losses at low operating frequencies and switching losses at high operating frequencies. Adopting a new material would need research and development of more exotic semiconductor material, which requires is a more costly route to follow.

2.3.3 Future Inverters

Future power electronic switches for vehicle electrification look to expand into the use of Silicon Carbide based MOSFETs. These state of the art transistors look to replace existing Silicon based, by outperforming predecessors through improved operating voltages, efficiency, operating frequencies, and consistent thermal behaviour [52, 53, 54]. However, poor quality and volume of existing production methods incur higher relative costs that prevent their mainstream utilisation. Developments in production quality and scale would improve the economics of these components and provide further energy saving in electric vehicles.

2.4 Electric Machine Developments

Electric machines provide mechanical tractive power for vehicle propulsion. Electromagnets within this propulsion method follow principles of Lorentz' law to carry out the conversion of electrical to mechanical power with no harmful byproducts (e.g emissions). Electromagnets and permanent magnets arranged in different configurations within the rotor and stator, can vary output power and methods of commutation (control). This form of power conversion is significantly more efficient with $> 80\%$ of supplied power being converted to useful work compared to combustion engines that are $< 40\%$.

Input of electrical power are used to control electric machines. Manipulation of the power AC waveform is executed with reference to the position and speed of the electric machine rotor. Precise control of the waveform frequency and amplitude are essential for consistent and smooth application of torque.

Additionally, control of this waveform has to take into account the back electromotive force (EMF) of the electric machine. Feedback current is sent through the phase signal, as non-energised coils cross the magnetic fields of other energised coils or permanent magnets. This occurrence alters the waveform affecting the control of the motor and its efficiency. The effect of back E.M.F is typically characterised by current and voltage instrumentation of the 3 phase signals.

2.4.1 Types of Electric Machines

Notably, various topologies of electric machine exist with variation in their efficiency, durability and cost. DC brushed, DC brushless (BLDC), Induction (IM), AC Permanent Magnet Synchronous Machines (PMSM) are all noted types of motors used for automotive tractive applications. Poor overall performance of the DC brushed machines and limited constant torque of the BLDC restrict the adoption of these types of motors (Table. 2.4) [55, 56]. PMSM provide a balanced solution of performance and cost for manufacturer adoption, with its primary shortfall caused by its cost and

Type	Efficiency	Cost	Service	Regeneration
Brushed DC	Moderate	Low	Brushes & Bearings	Difficult
BLDC	High	High	Bearings	Yes
PMSM	High	Low	Bearings	Yes
Induction	Moderate	Low	Bearing	Yes
SR	High		Bearings	Yes

TABLE 2.4: Key characteristics of electric machine technologies.

availability of rare earth metal magnets (Neodymium). The specific motor used is highly dependent on both technical and economical merits with PMSMs and BLDCs performing highly at a technical standpoint, but are also supplemented through the uptake of low cost and robust IMs.

2.4.2 Performance Characteristics

Importantly, key differences are recognisable of electric machine tractive power methods; the deployment of torque contrasts that of combustion alternatives. Electric machines have the ability to provide high initial torque values at low speeds controlled by the current rating of the inverter, this continues into the constant power region of the motor where flux-weakening needs to be employed due to voltage & current limits, and at higher speeds increased back-EMF results in reduced torque capability of the motor (Figure. 2.9) [57]. This performance profile is beneficial for automotive applications where city or high performance track driving profiles reflect transient behaviour of speed. Performance of electric machines are dependent the ability to provide magnetomotive force (MMF) between the stator and rotor across the air gap where high magnetic reluctance occurs. Thus, it is important to select appropriate materials and efficient designs that minimise occurrences of high reluctance, back-EMF, demagnetisation and excess currents that all contribute to losses.

2.4.3 Efficiency

Critically, electric machines suffer from both electrical and mechanical power loss modes. The modes are identified as:

- Conduction losses
- Eddy currents

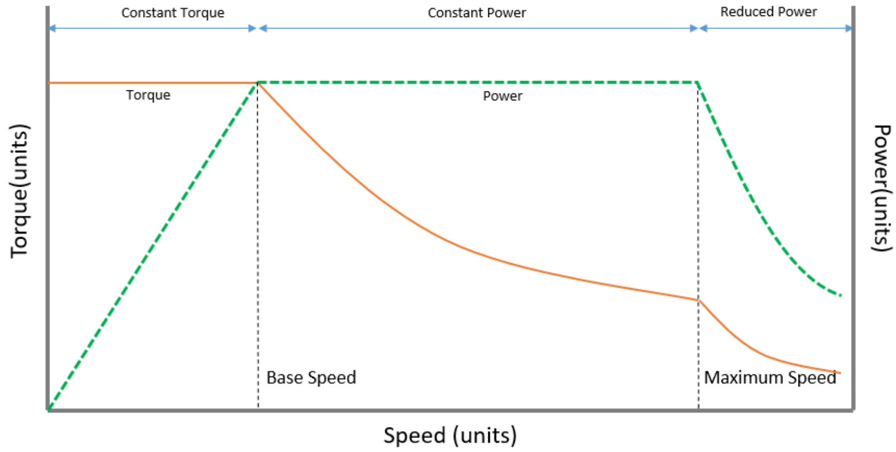


FIGURE 2.9: Power regions across the speed profile of a general electric machine.

- Bearing friction losses
- Windage losses

Conduction (Ohmic) losses occur as current travels through the motor's conductors and is calculated in a similar way as both seen with battery and inverter Ohmic losses. As current passes conductors in an electric machine, internal resistances in key sub-components (terminals and windings, typically copper) result in a voltage drop. This leads to a loss of power relative to the internal resistances of the component and the current that passes through the material. Eddy currents are the formation of counter magnetic fields within the rotor/stator cores as coils are energised; they oppose the motor's torque and dissipate the lost power as heat. This form of loss can be effectively controlled through lamination of ferrite cores to prevent eddy occurrences in planes opposing machine rotation. Due to the moving mechanical parts, friction and viscous losses are expected at the bearing and the rotor interacting with the internal aerodynamic environment of the motor casing. The majority of these losses result in heat generation, while a minuscule amount is converted to acoustic noise. The proportion of losses, however, varies between motor types, with induction motors having a high proportion of iron losses compared to those permanent magnet types [57].

Critically, the determination of this component's performance are possible through various methods. Virtual modelling tools such as numerical models and specialist simulation tools can provide rudimentary estimates of the performance during design stages, while physical tests require the use of dynamometers and high precision power analysers used to examine AC waveforms and harmonics of the electric machine [58]. The methodology of these techniques are well understood, but large investment are required by OEMs to transition to more capable testing tools that are state of the art and in high demand.

2.4.4 Future Electric Machine Technology

Gap

Limitations of the current electric machine technology for automotive applications centre on maximising durability and improving the economic sustainability of electric machine production. Surges in demand and manufacturers' supply control efforts (due to uncertainty with the long-term availability of natural resources) have increased the price of rare earth magnets by at least ten-fold in some cases. With neither of these critical drivers close to being resolved, automotive manufacturers must investigate other opportunities to de-risk long-term issues around electric machine components.

Resolution

Switch reluctance motors (SRM) provide an opportunity to reduce the dependency on scarce/costly rare earth metals. This subset of electric machines supplies 3-phase power to a wound stator that rotates a passive ferrite rotor. The electric machine negates the need for costly rare earth magnets while simplifying commutation through a fixed winding. Thus reducing the overall material costs of the motor, the need for complex electric machine designs and improving durability.

SRMs are also expected to offer similar levels of energy efficiency as with PMSMs. A recent study highlighted that SRMs perform slightly better at vehicle cruising profiles, whereas PMSMs have an advantage in transient conditions [59]. Due to the net similarities in efficiency, both types are plausible technologies for future vehicles.

Technology challenges

However, SRMs are disadvantaged by the necessity of utilising more advanced motor controllers. An inverter required for such a motor must account for torque and current ripple. An increased cost for materials and components could offset the cost benefits drawn from switching to SR-type motors.

2.5 Auxiliary Component Developments

2.5.1 Component Cooling

Importantly, even though powertrain electrification components outperform other powertrain technologies in efficiency, they are subject to an increased sensitivity to variations in thermal conditions. Component research has demonstrated the potential consequences of reduction in performance or degradation of the component itself [31, 60, 61, 62].Due to the increased sensitivity, thermal management of these components are a critical feature of these vehicles.

Batteries

Notably, there is a raised important to thermal management with the introduction of vehicle energy storage through electro-chemical cells. Battery properties such as internal resistances and solid electrolyte growth have been proven to link to power and capacity loss at cold and warm temperature respectively. These occur at both driving and stationary state when batteries are charged – even more so, with the introduction of fast-charging where high continuous currents are put through the battery. Henceforth, it is critical to have a high degree of control to manage the heat rejection/accumulation from the battery, but as importantly prevent thermal runaway of packs. This problem is exacerbated with the current trajectory of minimising the volumetric footprint of battery pack design, placing cells closer together, and limiting heat rejection to the environment. Battery pack design and development must account for these behaviours to ensure that vehicles perform consistently through varying environments with minimal loss to AER, but also satisfying durability requirements to meet product guarantee agreement with customers.

Importantly, battery cooling is also a critical safety requirement for a consumer vehicle. Liquid lithium electrolytes can be put under thermal/electrical stresses or experience internal shorts, which has the possibility of initiating oxidisation of the cathode. This reaction can lead to a cell rupturing. If this occurs, other cells in its vicinity could also be put under thermal stress and lead to a chain reaction of oxidising cells placing the battery and, ultimately any vehicle occupants at risk. Cooling systems ensure the batteries are kept within a safe thermal operating window; therefore, it is a necessity where battery power draw and the cell characteristics expose a vehicle to this occurrence.

Power Electronics

Thermal considerations towards traction inverters are centred on cooling of power transistors to minimise loses and prevent overheating. The current generation of Silicon IGBTs and MOSFETs are physically limited to peak temperatures 150-175°C [62]. A balanced approach to efficiency and cooling are achieved through appropriate sizing of the physical transistor to dissipate heat, and implementing necessary cooling system to transport heat away. This is a far greater concern for HEVs where packaging of the inverter near the combustion engine could raise the local ambient temperature, limiting thermal rejection from this power conversion device. Henceforth, additional motivation arises for the adoption of Silicon Carbide transistor where they have a theoretically thermal limit of 700°C, which in turn provides a greater temperature differential to reject heat to its surroundings [63]. It is also necessary requirement to cool these switches as they susceptible to thermal runaway with loses growing more than linear and thermal rejection being strictly linear with rises temperature. This would also require cooling to protect other critical components of the inverter [64]. Studies have provided concepts to cool these devices, but as advancement outside of traditional low pressure coolant circuits and liquid thermal jackets, require further work to ensure they are packaged properly and providing cooling efficiently.

Electric Machines

Electric machine cooling requirements are motivated through optimisation of efficiency and durability characteristics. As temperature increases both globally and locally within key sub-components of the electric machine, an increase in losses occur due to a rise in copper resistances, irreversible de-magnetisation of permanent magnets, and breakdown of the winding insulation material [65, 66, 67]. Permanent magnet selection plays a critical role in the durability sensitivity of the motor, with Neodymium magnets subject to degradation at 140°C, and Samarium-Cobalt magnets at 250°C [68]. Ferrite based magnets with a positive temperature co-efficient permit high operational temperatures, but are as susceptible to degradation at lower temperatures and are less powerful [69, 70]. As a general rule of thumb, a 10°C increase in operating temperature results in an expected loss of half the electric machines operational life expectancy, the severity of de-magnetisation through loss of flux-density and coercivity is related to the both the temperature and duration to which it occurs [71, 72]. Henceforth, it is critical to implement appropriate cooling methods with regards to the construction of the electric machine, packaging constraints, typical use profile (load, speed, and steady-state vs. transient), and accessibility for maintenance. In reference to the previously discussed section of electric machines types and their present/future applications to the automotive market, liquid cooling system would see continued use for motors containing permanent magnets (IM, PMSM, etc), while SRM (without permanent magnets) could rely on smaller liquid or air-cooling solutions without critical concern for degradation of the machines durability. Both types will still need sufficient cooling to prevent significant thermal damage to winding insulation as they are considered one of the weakest thermal points of traction electric machines.

Cooling Requirements

Thermal management technologies such as air-cooling, liquid-cooling, positive temperature co-efficient heaters, and Peltier devices are transferable from prior generation of consumer vehicles. It is vital for the development of vehicle electrification that component thermal management systems correctly balance the thermal conditions for components and minimise power consumption used to achieve that capability. A dynamic of efficient thermal management is preferred so that energy consumed to cool/heat these components do not surpass the energy saving made or compromise degradation of the targeted components.

The need to optimise thermal performance electrification components, results in the utilisation of complex thermal management systems. These system use complex logic, adaptable configurations and opportunities to collectively maintain desired temperatures of integrated components before, during and after journeys have been completed [73, 74]. The importance of these control system provide the ability to scavenge and recycle losses to further efficiency of the vehicle and maximise the durability of sensitive components.

2.5.2 Heating, Ventilation, and Air Conditioning

HVAC systems provide climatic control for the cabin of the vehicle. Most modern-day vehicles as standard provide some variation of thermal control to improve the cabin habitability for human occupancy [75, 76]. Adequate thermal control is pivotal in providing a positive consumer experience that potentially increases the sales of the vehicle.

HAVC Energy Consumption

Consumption of energy through HVAC systems are a critical consideration for optimisation of vehicle efficiency. With the change in component contributions to relative load, energy consumed for cabin HVAC have a greater impact on the overall efficiency and AER of a vehicle. The increased influence of this system opens up opportunities to improve vehicle electrification efficiency. The real-world expectations on energy saving by this system is dependent on the geographical deployment of the vehicle. Operation in extreme cold and hot climates would see noticeable energy differences with high efficiency HVAC systems, while energy saving in moderate climates would be less reliant on HVAC systems. For JLR, satisfactory product performance in extreme environments and conditions are necessary requirement for their customer segment, and as a result raises the significance of wideband performance over hot and cold temperatures.

HVAC Evaluation

Fundamentally, the performance, energy consumption and efficiency evaluation of these systems can be determined through a mix of modelling and testing methods. Numerical energy, physic and computational fluid dynamic models are virtual methods used to help design and estimate the performance of HVAC systems, while in a similar approach to other components, physical models and tests are reserved for validation means. Even more so with HVAC systems, full physical tests are costly due to the complexity of system integration into prototype vehicles.

Importantly, key metrics to evaluate HVAC systems have grown with the transition to vehicle electrification. Under combustion vehicle requirements, the performance of HVAC system prioritised aspects of comfort, quickness, and noise over efficiency [77, 78]. This is evident through the transition of key metrics used in research studies. With the energy constraints of BEVs, there is a raised importance to optimise HVAC energy consumption, and utilise recovered waste heat to improve efficiency of other components to minimise deterioration of AER, battery pack size and cell degradation [79, 80, 81].

2.6 Energy management

Importantly, vehicle hybridisation allows the full dexterity of energy management systems. These systems are designed to maximise the overall vehicle efficiency by optimising the power generation method to extend the range from the given onboard energy storage. For present hybrid vehicles, this is typically seen with the optimisation of the combustion power generation method that operates at an average efficiency of 20-40% in comparison to that of the electric machine's 80-90%. Assistance from vehicle electrification enables the selective operation of combustion powertrains at points, lines or regions of optimal performance where the powertrain is most efficient. This can be visually represented through a brake-specific fuel consumption map, which outlines the efficiency concerning operating parameters of the prime mover (typically torque, rotational speed, intake manifold pressure).

Various computational decision making strategies are employed to improve vehicle efficiency through vehicle energy management. Techniques such as Rule Based

Controller (RBC), Fuzzy Logic (FL) and Equivalent Consumption Minimisation Strategy (ECMS) have been demonstrated for local optimisation methods where system decision making is made with immediate parameters [82]. Stochastic, Dynamic Programming and Neural Network methods are collectively described as global optimisation methods. Historic and wider data sets are used by these techniques to improve the understanding of the problem at hand. These methods rely on providing holistic problem solving to come up with the optimal strategy to employing the different operating modes of a hybrid powertrain.

2.7 Physical Technology Summary

The introduction of tractive electrification methods has greatly improved the energy consumption characteristics of vehicles. These state of the art systems provide improved efficiency of Tank-to-wheel energy consumption and reduce direct harmful emission. The tank-to-wheel establishes a comparative framing where we analyse the energy consumption from the point at which energy is on-boarded onto the vehicle until it expends power through its wheels. By comparing electric and combustion vehicles in such a way, we can establish and demonstrate the beneficial higher energy-efficient conversion (and no direct emissions) of an electric vehicle through an equitable perspective. As a product, this advancement in powertrain technology closely aligns and helps the industry and society in reaching environmental goals.

2.7.1 Technology Maturity

Overall, the critical components for vehicle electrification are at various stages of technology maturity. AC electric machines were first developed in the 19th century and have seen investment in other sectors' development. IGBTs and power MOSFETs were invented in the 1950s and then commercialised in the 1980s for applications such as large audio amplifiers and as part of mobile networks in the 1990s. Rechargeable lithium-ion batteries were first achieved in the early 1990s. The former two components are relatively mature in comparison to the battery hardware. Primary motivations for battery research of the latter hardware are focused directly on improvement in component performance, while power conversion technology research has shifted to manufacturing quality and production sustainability. With this consideration towards test methods, individual test rigs and testing strategies will focus on alleviating pressing component performance issues such as battery power density/longevity and evaluating SR electric machine technology. In contrast, problems manufacturing SiC power electronic switches would not directly benefit from improvements in testing capability.

2.8 Vehicle Modelling & Testing

Modelling of components, subsystems and systems are a fundamental step in the development of vehicle engineering. These activities are critical to provide explicit results of the performance characteristics of state of the art technologies. Neglecting such steps would increase the risks of missed product requirements and elevated development costs that reduce income and profitability of the industry.

2.8.1 Vehicle Development Process

Importantly, both virtual modelling and physical testing activities have varied importance to the contribution of the vehicle development process. Virtual models are used as a cost-effective method to estimate component, system and vehicle performance, while physical tests calibrate/validate estimations from virtual models, and are used to certify the final production vehicle (Figure. 2.10). This representation is a abstraction of multiple Vee development cycles interacting with each-other. This combination draws the benefits of each method to address the deficiencies of their counterpart, creating a thorough solution to development of vehicles.

Development Process

Product development processes are needed to ensure that technologies under development are achieved within planned constraints. Implementation of these processes formalise a structure that projects and products sequentially move through themed states that correspond to critical activities needed to maximise their success. The adoption of these methodologies create a streamlined development path that clearly

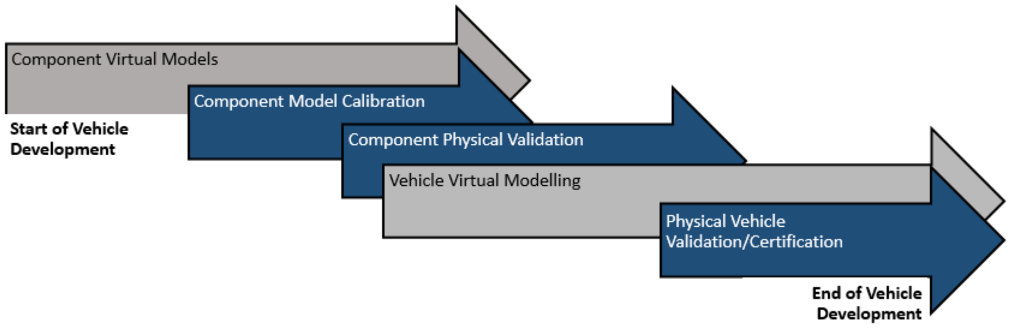


FIGURE 2.10: The involvement of virtual models and physical tests used to develop vehicle before production.

defines objectives/requirements/actions to be completed within time and resource constraints [83].

Review of Processes

Structure and Variations

Notably, these processes can take various forms dependent on their application and activity requirements. Waterfall, Vee, DoD, W-shaped and spiral models are all examples of implemented engineering processes that are utilised to maximise the development of technologies [84, 85, 86]. TThese models are either specifically tailored for its intended application, or adopted in a generalised form. The determination of appropriate frameworks need to account for existing deficiencies, opportunities and priorities that would provide the greatest benefit.

Importantly, these processes' primary purpose is to plan activities and transitions concerning resources, costs and risk management. With clear separated steps within the processes, activities at each stage are connoted as value adding steps, and each transition stage can be scheduled to minimise idle times. While in parallel the appropriation of resources and transference of responsibilities are linked to milestones within the process. The division of the project in this form ensures that the sub-objectives of each step align with those surrounding it but also fulfil the overall project objectives. Without this approach, a lack of control is induced in the development process that can ultimately lead to excessive costs, poor usage of resources and poor insight to risks that would make a project uneconomical.

Deficiencies

Critically, the product development process can also pertain negative influences on projects and organisations. Research into its application have noted that [87][88]:

- Structured nature of the processes can restrict creativity and agility.
- The sequential methodology can restrict communication.
- Universal adoption of a single process structure, may be inefficient with a diverse project portfolio
- Interactions between organisational structure could lead to communication barriers
- Poor demonstration and communication of the process can be met with resistance to change from within the organisation.

These negative factors could compound existent issues that are driving factors for the implementation of the process. A strong understanding and balance of these processes are needed to ensure that they are integrated effectively and their interactions with the organisation are best managed.

2.8.2 Modelling Standards

To ensure uniformity in the measurement of vehicle efficiency and energy consumption, regulations have been set out by legislative bodies that are followed by automotive manufacturers in the development of automobiles. These regulations provide a standardised reference to evaluate the performance of vehicles among both virtual and physical tests. Determined by the point of sale, vehicles sold in the majority of United Nations (U.N) countries follow the WLTP standards, while other regulations are supplemented by other countries (United States Environmental Protection Agency Five cycles) [89, 90]. These regulations set out key parameters such as the drive cycle, test conditions, instrumentation requirements. Variation in how tests are conducted can influence the relevant accuracy of these energy consumption tests [91]. The ratification of these regulations by government bodies are there to ensure that a representative test of consumer vehicle use are followed among all manufacturers without an unfair advantage to mislead consumers.

Current Regulations

Current generation of test standards (notably WLTP) have made steps to improve representative consumer driving behaviour, but now are challenged by limitations of the testing process. The transition to WLTP corrected the low relative acceleration that was experienced with its predecessor, the NEDC. This previously accepted behaviour was unrealistic of actual driver control [92, 93, 94, 95]. This change has however created complication with the increased concern of tire slip on rolling road dynamometers [96]. The recognised hardware limitations and path for legislative development need to be aligned to ensure that drive cycles are developed to achieve realistic driving behaviour, but essential hardware are also amended in parallel to carry out test objectives.

Gaps in Regulations

Critically, the blanket homologation of drive cycles continues to struggle in providing precise representation of vehicle energy consumption and efficiency for consumers. The implementation of singular drive cycle profiles for vehicle efficiency certification fails to account for differences in climate, regional driver behaviour and traffic that heavily influence the relevance of certification values to various geographic regions [97, 98, 99, 96]. This highlights the limited ability of certification regulations, and draws motivation for manufacturers to develop vehicle technologies that are beneficial for certification and that are directly visible to consumer use.

2.8.3 Virtual Modelling

Fundamentally, computational vehicle virtual modelling has revolutionised the process of component/system design and evaluation. This methodology automates and streamlines the execution of large mathematical, logical and scientific models that would otherwise require significant time and resources to calculate manually. Coupled with the growing access to computational power, present models can be created to represent the behaviours of components and the parameters around them.

Vehicle Energy Consumption

Crucially, backward-facing (BWF) and forward-facing (FWF) models are the most commonly used tools to evaluate vehicle performance. Each tool focuses on providing a perspective of energy consumption by pulling the necessary velocity requirements to match a velocity trace or by a driver model pushing vehicle forces to attain the desired speed output of a vehicle along a drive trace, respectively [100]. BWF models utilise zero-order equations and steady-state look-up tables to evaluate a vehicle over time through larger time steps. On the other hand, FWF models use higher-order equations that incorporate transient modelling behaviour through execution at a smaller time step, but to do so requires more computational power to match the computational time of BWFs. This is demonstrated through the evaluation of the two methods for powertrain component sizing, where FWFs performed better across drive cycles that were considered more transient and allowed to test the drivability of the vehicle[101]. The two approaches are used to a different degree throughout the component or vehicle development process, with BWFs being favoured at initial development for their crude estimations and cheap characteristics while, FWF at the opposite end of the spectrum provides detailed and accurate representations of systems that are more defined and closer to implementation/production phases.

Physics Based Modelling

The use of physics based virtual models are reserved for unique applications within automotive development. This speciality tool uses advanced mathematics and techniques such as bond graph methods to map out complex systems [102]. These tools are advantageous for modelling extreme conditions over numeric alternatives. However, they require experienced operators to build, update and maintain these state-of-the-art models.

2.8.4 Physical Testing

In contrast, physical testing provides a highly accurate representation of complex systems and products. The use of physical tests either require a prototype or completed unit to be tested under controlled conditions. This method captures the near complete behaviour of the System Under Test (SUT), without the sometime simplified models used by virtual alternatives.

Fundamentally, the majority of physical based methods use a similar framework. Key features of these tests can be listed as:

- A form of SUT input and output energy measurement
- A test environment where key parameters can be controlled.
- An instrumentation set to measure independent performance parameters.

These set of features are shared among the testing of electro-chemical cells in cycler chambers, electric machines with engine dynamometers and complete vehicles on rolling road dynamometers.

However, physical testing are the most costly form of component and system evaluation. The prototypes, final products, test equipment and resources required to conduct this form of evaluation, increases the capital costs required to carry out this activity. These costs are a key contributor to the reason why this form of testing are reserved for minimal use and the reliance on virtual methods that are increasingly flexible and cost efficient are gaining traction.

RDE offers an alternative form of testing that captures the complexities usually omitted from laboratory-based tests. RDEs, as a result, are expected to improve the accuracy of measuring vehicle emissions and energy consumption. In an RDE test, the test vehicles are typically instrumented with a PEMs device and other sensors, after which they are tested on existing public roads. Comparison between laboratory results and RDE tests have demonstrated that under RDE conditions, both HEV and ICE vehicles had higher energy consumption emissions. This suggests factors/assumptions overlooked in standard laboratory lead to a significant variation where OEM-reported emissions are lower than consumer-experienced emissions. RDEs enable testers to evaluate the vehicle performance under realistic driving conditions such as traffic, road, driver behaviour and weather. For electric vehicles, this would likely impact the overall range estimation of the vehicles, with OEMs overestimating achievable ranges through laboratory tests. RDEs offer an alternative that would provide a reflective range estimation of what consumers would experience.

2.8.5 Hybrid Methods

Hybrid methodologies also exist that use both virtual and physical models. X-in-the-loop concepts allow the development of test setups where virtual component, controllers and environments can be simulated via real-time computers and co-currently interact with real hardware. The test process has been pioneered for the evaluation of high safety critical devices that operate in or around high value assets in the transportation industry such as avionics and other vehicle controllers such as ECUs [100]. Derivations have led to the creation of Software-in-the-loop (SIL), Model-in-the-loop (Loop) and Hardware-in-the-loop (HIL) tools, that all look to capture the accuracy of complex systems in hardware and use virtual environments over cost intensive physical test environments.

Hybrid methods are typically represented through a structured format. This is represented where a complete test loop (structure) is split with one substructure facilitating a portion of the test loop in physical/software/other forms. In contrast, another substructure is conducted in a virtual environment. These substructures are operated in unison to represent a complete test loop. This structured format is taken so that the virtual substructure can supplement physical equivalents that are either impossible to fit into typically finite test spaces, uneconomical to test at full scale, or unsafe to test in absolute reality.

Challenges with hybrid testing

Consequently, the combination of two sub-structures from different domains poses challenges to the stability and fidelity of the complete systems. Introduction of lag, delays and unintended physical dynamics have the ability to compromise the stability of the test system. It is important that these issues are first addressed across any physical test subject, apparatus and emulated virtual test environment before deployment as hybrid test method.

Importantly improved fidelity mitigates issues towards system stability. A real-time system with smaller time-steps can capture, process and react at a resolution that overcomes the adverse dynamics created by the lag, delays and physical properties. However, real-time technologies typically use fixed time-steps and has limitations to their size that time-step can be reduced. This is primarily down to scheduled nature adopted to ensure robustness of the such a system.

In addition, ODE integration steps used to carry out calculation between time-steps and their integration with RT systems can lead to a source of error. Limitation to RT time-step downsizing forces these calculation to be carried at larger intervals resulting in inaccuracies as a result of generalising a systems behaviour. This is compounded with lag, delays and the process using present time-step data to determine future actions leading to inaccuracies. This can be improved through either using higher resolution time-steps. As time-step resolution increases to improve accuracy, this expands the number of calculations needed to be solved for a given period of time and therefore demands more processing capability which have their own limitation.

Influence of hybrid testing

Importantly, hybrid test methods offer an opportunity to reduce the costs of electric vehicle testing. The sub-structured nature of hybrid tests allows test methodologies to supplement parts of EV testing that are too expensive or dangerous to undertake.

In addition, it is essential to understand the impact of future technology changes on hybrid test technologies. As computer processing technologies improve, this opens the possibility of further reducing limitations imposed by time-step resolutions. As these technologies are open-ended, any development in processor and FPGA technologies would be expected to trickle down to RT hardware as they gain maturity.

2.8.6 Modelling Summary

The development of vehicles will continue to rely on both virtual and physical methods. As highlighted virtual models are heavily used in the early development of components and technologies due to their flexibility, control and costs, but are surpassed by physical tests that are capable of encompassing complex behaviours and interactions relevant to the final production performance and are overlook in virtual alternatives. Each evaluative method complements each other by providing strength in an aspect that the other cannot. Both test accuracy and cost are valued by manufacturers and therefore are still relevant for future vehicle development.

However, with the transition to vehicle electrification, an increase in physical test demands are expected – at least in the near term as we understand component and system behaviours sufficiently well to build reliable models. The demands for vehicle electrification efficiency require high tolerances on energy auditing methods, to ensure that electrical interactions and complex thermal behaviours are sufficiently captured to build awareness to potential strategies of system optimisation. As far from present research and industrial experience, the overall mixture of method used are likely to shift towards a greater dependence on physical hybrid test resources, where accuracy and precision benefits are drawn from both ends of the vehicle development methodology spectrum.

To minimise the economical impact of this change, the overall cost and flexibility of modelling should be targeted. The reduction deficiencies of physical test methods would expand opportunities to use physical and hybrid methods earlier within the development process that could positively affect the value of the vehicle development process.

2.9 Review

In conclusion, vehicle electrification has identified itself to be the best solution towards overcoming harmful pollutants from global transportation. This technology advancement overcomes the shortfalls of conventional combustion engines that are highly inefficient and release CO_2 and other gases as part of their power conversion. By switching to these advanced powertrain technologies, a reduction in global emissions and reliance on fossil fuels can be made.

However, the research and development costs of electric and hybrid vehicle need to be reduced to aid mass adoption. The main barriers to their adoption lie with increased costs driven by immaturity of the technology. This dynamic prevents the dominance of powertrain electrification over combustion technologies that benefit from a century of maturation.

Crucially, the flexibility, sensitivity and the altered proportions of vehicle energy consumption drive the increased development costs. The limited accuracy of virtual models prevent sufficient estimating capability that was available with combustion technologies. This places an increased reliance on physical tests that have a higher overall cost for physical prototypes, facilities and operations.

Chapter 3

Aims and Objectives

3.1 Insight from literature review

3.2 Aims

The present state of vehicle electrification indicated a necessity to produce and sell a cost-competitive electric vehicle. Electric vehicles are known for better performance, efficiency and environmental characteristics than the latest generation of combustion-engine automobiles [103]. However, the capital costs of the vehicle play a significant role in the consumer decision-making process when purchasing mobility solutions [104, 105]. This dynamic favours combustion engine vehicles with an edge in technology maturity and, therefore, lower development and material costs. Reducing product costs needs to be undertaken to overcome the financial barrier that hinders the mass uptake of vehicle electrification and future advanced powertrains. Material, production, Research & Development (R&D), and operational costs are areas where this can occur. For this innovation report, the focus was on the last two aspects.

3.2.1 Research gaps

Component maturity

Firstly, the literature review highlighted the variation in maturity for electric powertrain components. This was exhibited through each component area where battery research is focused on exploring the present functional performance, efficiency and durability; durability and sustainability of components being the primary focus for electric motors; researchers fine-tuning the efficiency and expanding the thermal limits of inverters. Additional research on evaluating the thermal performance of individual components and their joint operations contributes to this. The varying degrees of maturity highlight the different sensitivities and influences each component and the joint system have on the vehicle's overall performance.

Necessity of virtual models and physical testing

The literature review highlighted the costs and complexities of physical testing. Physical testing of components/vehicle prototypes in laboratory and real-world environments requires significant efforts in replicating suitable test environments, sufficient instrumentation and high asset costs. As such, research studies are increasingly being conducted more often in virtual form or similar (sub-structured testing).

However, virtual models have limitations and must be appropriately balanced with physical testing. Published research on the development of virtual models and their uses highlights that these evaluation techniques fundamentally simplify real-world equivalents. These are driven by the computational techniques used and the data quality used to build the models and are typically valid to specific conditions. As a result, this limits virtual models where physical testing must remain to complete the necessary evaluation of electric vehicles.

Moreover, physical tests are necessary to help characterise initial component virtual models in the early development stages of a vehicle. These virtual models typically use data produced from physical tests to populate n-dimensional maps to estimate an output value and an input variable. As such, there is a reliance on physical testing to not just fulfil gaps in virtual modelling but also build them.

These cases emphasise the existing demand for physical testing and are likely to increase as industry competitiveness rises between automotive manufacturers. As emission tolerances grow tighter, the cost of components fluctuates, and utilisation of the latest state-of-art technologies emerges, it can be expected that manufacturers will have a greater demand to gain these advances to deliver attractive products to consumers. As a result, overall R&D costs will likely grow through physical testing and establish an incentive to implement control measures.

Applied distributed technologies

Notably, the literature assessment establishes the limited demonstration of applying distributed and coordinated test resources to reduce the cost of vehicle testing and development. Examining the available literature discloses some critical factors that affect sub-structured testing and ID-HILs for haptic control of physical test apparatus. As a result, there is an opportunity to investigate the plausibility of using ID-HIL systems to explore the feasibility of reducing the costs of physical testing for the development of electric vehicles.

3.2.2 Development Aims

From the knowledge reported in *Chapter* 2 and the conclusions drawn from them, a number of key routes were identified for optimisation of R&D and operational costs. These were:

- Improvement to the feasibility of physical test methods.
- Improvement in virtual modelling capability of electrification technologies.
- Refinement of product use cases/technology by reducing charging times.

Targeting of these deficiencies would provide holistic opportunities to improve the practicality of electric vehicle development and encouraging mass uptake by consumers in line with current legislative objectives.

Technical Aims

Improvements in virtual modelling techniques would allow for increased productivity in the development process, minimise development overhead costs, and assist directly in optimising component sizing (battery capacity and system efficiency), all of which bridge both technical and costs gaps between EVs and combustion engine vehicles. Currently, virtual modelling for electrification components heavily relies on empirical models that require physical tests to extract component behaviours for quick, cheap and accessible in-silicon development. The lack of knowledge maturity and fast-paced developing nature of advanced propulsion systems restricts the development of equivalent physics models that reduce the dependency on physical test reference data. Decades of product developments for combustion engines provide a strong foundation upon which engineers can rely to develop high quality multi-physics models for the requirement of consumer vehicles. The equivalent level of knowledge to create these models for electrification technology needs time, effort and resources [106, 107, 108]. A passive approach to developing electrification knowledge maturity through decades of growth, competence and expertise as was the case for combustion engines, opposes the industrial objective for immediate action on transportation emissions. An active approach would require accelerated research in the field to mature the market and industry knowledge to reduce overall costs of the technologies themselves. This requires an expansion in R&D capacity that incurs additional short-term costs to development overheads.

In contrast, improvements to the feasibility of physical test methods was selected as the most favourable technical strategy in offering opportunities for immediate cost reduction in the development process. Through the development of physical evaluation methods, JLR could invest in the current test infrastructure to optimise the required research and development overheads, gain a competitive advantage by getting products out to market faster than competitors, and de-risk product development by improving quality of work conducted. By achieving these outcomes, JLR would gain opportunities to improve profitability of their product, gain additional revenue and reduce the cash cycle conversion period/boost product agility. All of which directly benefit JLR as an automotive manufacturer in producing the next generation of vehicles sustainably.

Henceforth, the aim of this study is best suited to the pursuit of optimising physical test methods due to the holistic benefits that they would provide. Innovations from this strategy would help reduce costs required to develop technologies, but also provide a robust foundation to efficiently develop component knowledge necessary to implement higher fidelity virtual models. This provides for long-term sustainable growth, over a more riskier short-term investments into technology maturity.

3.3 Objectives

A set of objectives were created to bound the necessary requirements for solutions that would improve the feasibility of accelerated physical test methods for electrification technologies. The review of existent literature and first-hand experience in the vehicle development process, state of the art technologies, and modelling techniques assisted in identifying opportunities to develop knowledge and apply solutions. This approach ensured an informed rationale was followed to deliver against key requirements for an innovative solution.

3.3.1 Optimisation of R&D Costs

A strategic path to close the financial gap between the development costs of different powertrain types should focus on the reduction of overheads and lost costs amounted in the physical testing stage. Costs within this critical portion can be categorised into:

- Human Resource costs.
- Physical asset costs.
- Facility costs.

Each of these costs identified have varying contributions to value creation and time. Facility costs are a semi-fixed cost that are recognised as efficient when they are utilised effectively, and variable costs expressed through human effort depend on the duration and scale of the task [109]. As part of this study, the physical technologies being innovated should look to reduce/optimise costs associated with each identified contributor in the form of physical testing used to develop electric vehicles. For JLR this would reduce the overheads provided by research and development tasks, and therefore offer opportunities to improve profitability after product costs.

Optimisation of Human resource costs

Overall objective This study will investigate the opportunities to reduce human resource costs through implementing greater automation of a hub-dynamometer with simulated real-world effects.

Measurable The performance of the changes will be evaluated by the total time saved. A measurement of person-hours provides the ability to measure time saved concerning human contribution to the task. This metric ensures that the time measured also accounts for the influence of the human capacity needed to carry out a task.

Achievability There is strong confidence that the chosen methodology to evaluate the saving capability of automation is achievable. The chosen methodology utilises existing facilities/hardware with additional resources and guidance to help develop the solutions. These measures ensure that challenges brought about by the implementation can be effectively resolved.

Relevance The study will reduce the demand for human resources required for electric machine testing to align with the overall objectives of developing vehicles economically and sustainably. Automation will be used to supplement actions conducted by human resources. By doing so, digital technology will reduce the variable costs caused by the need to resource engineers and technical staff for such tests.

In addition, the developments produced by this section of the study act as a critical apparatus for the development of ID-HILs explored in the other section of the EngD. Automating the relevant test resources will enable the refined control of local and distributed nodes as part of a network. As a result, the outcomes of the section enable and complement other elements of this report in meeting objectives to improve the sustainable development of electric vehicles.

Importantly, the study will distinguish itself from other studies to evaluate the quality of its application for safe transient operation in the WLTP cycle. Other studies have predominately utilised automation for emission and NVH evaluation of combustion powertrains[110, 111], engine-in-the-loop testing[112], combustion powertrain calibration[113], as well as utilisation of BEV and HEV architectures on low transient cycles such as the NEDC[114, 115], or application away from consumer road vehicles[116]. By doing so, this study will explore the development of hub-dynamometer automation relevant to state-of-the-art test requirements needed for research and development of electric vehicles.

Time-bound The actions necessary to carry out this task can be met within the time frame of the EngD. Virtual and physical methods enable parallel development of the technical elements. Virtual prototypes permit initial development with no dependency on resources, while physical testing overcomes long simulation times with the necessity of proof of capability; however, the scheduling of physical tests could be influenced by the availability of test resources, materials, and external issues.

Optimisation of Physical Asset Costs

Overall objective This section of the report will investigate the impact of network conditions (such as latency) on testing electric vehicle powertrains over a two-node ID-HIL system as it conducts a test cycle to evaluate its energy consumption.

Measurable In this case, this objective's accomplishment will be determined qualitatively through the feasibility of the proposed system to supplement existing testing frameworks. The proposed system will be evaluated against essential functional requirements met by the solution it aims to replace. Meeting these qualities and demonstrating the cost benefits of such a system should provide confidence in the industrial application of the solution.

In addition, the quality of such a system should be evaluated quantitatively through the impact of the system on a test subject's state-of-charge error. The proposed system should be evaluated across several test scenarios and bench-marked against standard conditions to identify a suitable operating window. Doing so should determine the system's suitability and offer opportunities for further refinement to improve the system and the knowledge around it.

Achievability Notably, the availability of vehicle component models enables the undertaking of the study in a virtual form. With the collaboration with Jaguar Land Rover, calibrated component models are available to provide a representative estimation of the impact of the study's objectives. Access to these models provides the opportunity to avoid physical tests that require larger considerations but also minimises the time needed to develop component models needed to conduct an equivalent simulation.

Relevance The study to be carried out aims to provide insight into the capabilities of ID-HILs for EV testing in industrial applications. ID-HILs offer a supplementary stage in the vehicle development process where the cost to update or amend components increases as they transition from virtual to physical prototypes. By demonstrating the feasibility of the systems, the study should establish the fundamental ability of the system to supplement and decrease the demand for physical testing assets that increase the cost of EV research and development.

Time-bound Notably, the chosen methodology allowed for an evaluation of the system without dependencies that could lengthen the project's time frame. Using physical resources such as different laboratories and specific hardware would have imposed additional organisational requirements and constraints depending on the availability demand of each asset. Choosing a virtual approach negates these constraints and minimises the risks of delays in the project.

Furthermore, pursuing the study through a single body streamlines the implementation of the project to investigate the critical objective. Incorporating multiple organisations requires cooperative working and agreements in establishing a functional joint venture to carry out the outlined research. Establishing a joint venture to carry out a physical proof-of-concept would not be feasible within the standard duration of an EngD.

Optimisation of Facility Costs

Overall objective The primary focus of this section of the report is to investigate opportunities to optimise facility costs through the use of data and connected resources to accelerate technology developments.

Measurable Aligned with the EngD's objectives, this report section focuses on the direct drivers of resource costs towards testing individual components. The study will evaluate the advances of the proposed solution through the time a test subject occupies a resource and how well it utilises that time. The results could provide a resilient benefit with minimal sensitivity to technology changes by aiming to optimise this cost driver.

Achieveabilty The evaluation of ATMS is mostly achievable, but limitations require investigation to be carried out by virtual means. Likewise, though assets and resources exist for physical testing, restriction posed by COVID-19 limit safe access test facilities necessary to deliver a physical proof of concept. A virtual study of the system would verify the digital elements and estimations of the system performance.

Relevance Notably, the study provides a separate study into utilising ID-HIL technology in a collectively exhaustive way. The study focuses on the application of ID-HIL in an asynchronous form with different requirements than those explored with synchronous ID-HILs (Chapter 5). By establishing the research to explore this path, the overall research topic provides an exhaustive exploration into the complete innovation of ID-HILs.

In contrast, the following research topic covers a niche but important aspect of cost optimisation for automotive manufacturers. The subsequent research would focus on component development not necessarily carried out by automotive manufacturers and more on OEMs and ESPs. As a result, the benefits from the research are expected to provide an indirect benefit to automotive manufacturers such as Jaguar Land Rover through reduced prices of components.

Time-bound Similarly, there are opportunities to evaluate a proof of concept without the dependency on physical assets. This study can follow a virtual approach to demonstrate the benefits of such a system. By undertaking the research in such a way, the study de-risks delays and obstructions that could prevent the work from being conducted on time.

Moreover, the study faces challenges in implementing the solution into an industrial situation for its complete evaluation within the time frame of the EngD. The solution would be required to meet a stage of maturity to be tested safely before being evaluated in an industrial context. Due to its novelty and the limited knowledge of the minimum requirements for its safe implementation, it is difficult to determine if the entire solution development is plausible within the length of an EngD study.

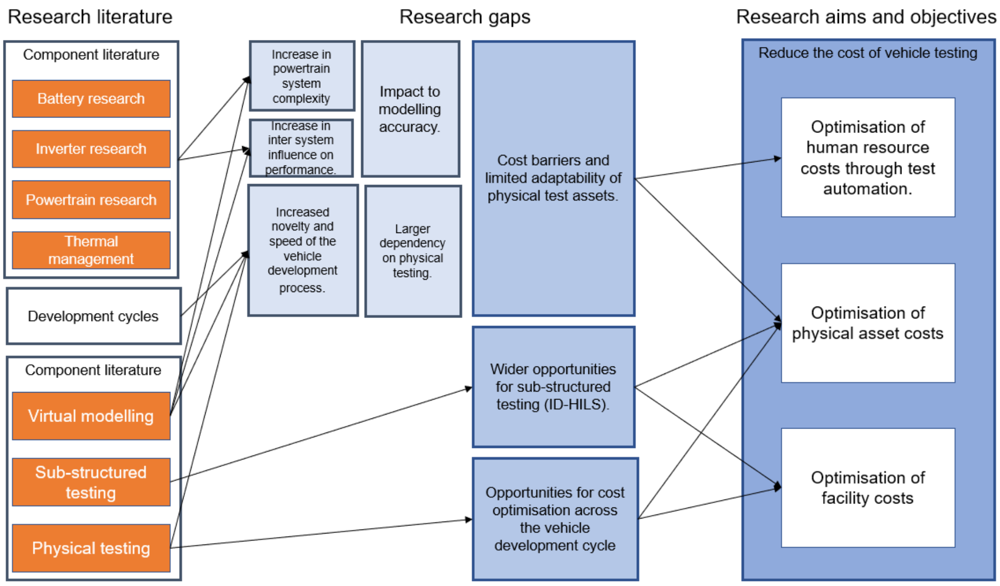


FIGURE 3.1: Illustrative map of research gaps, aim and objectives drawn from literature reviewed.

3.3.2 Research gap and outcome structure

Importantly, the aims and objectives were derived from gaps identified from the literature review. This is illustrated in Figure. 3.1. The literature review was partitioned into three sections that included evaluating the current state and future trends in key EV components; the development processes employed manufacturers to develop vehicles; and the current and futures states of modelling and testing techniques. These identified gaps as outlined in Figure. **??**, which in turn informed and assist on generating relevant aims and objectives.

3.3.3 Productivity and Development Cycle Impact

Importantly, the combined benefits of optimising R&D and operational costs through improvements of human effort, improvement in development quality (identifying issues earlier) and time consumed through physical test stages, provide additional advantages in market competitiveness and agile development for automotive stakeholders. A reduction in physical test duration creates opportunities to shorten the overall development period required for products [117]. As a result, this benefits stakeholders as products released on-time or earlier than planned enable manufacturers to preserve/gain revenue as well as minimise capital tied in assets and incomplete processes to de-risk liquidity and adaption to changes consumer requirements in the automotive market.

3.4 Innovation Through Technology

3.4.1 Automation

The objectives of this investigation, to further accelerate vehicle electrification development, align with the typical benefits of digital automation. Manufacturing automation as a general technology has already been used within specific settings of the automotive industry. Famously, the benefits of automation - improved productivity and consistent quality are recognised now as a necessity for the modern mass production of vehicles [118, 119]. Automation technologies continuously grow and offer opportune application to improve productivity and quality of vehicle technology R&D.

Moreover, successful examples of automation need to consider secondary factors to ensure benefits outweigh its cons. High product and installation costs can make industrial applications of automation cost ineffective in comparison to manual alternatives [120]. The design and implementation of modern systems should consider the life-cycle costs of automation and include considerations to ensure adaptions can be made when the application changes.

Test automation has grown predominantly with the addition of increased digital automation of systems provided by ECU on-board vehicles. Automation for automotive software development is motivated by the necessity to produce high quality code and the need to recognise errors at the development stage where they are cheaper to resolve [121, 122].The use of test automation is still at a stage of infancy as surveys and examples highlight that manual testing remain the most common form of evaluation (59.1%), followed by automated test execution (32.3%), automated test case generation for software development (8.6%) [121, 123]. The little presence of automated test execution and case generations sets a wide scope towards opportunities to innovate the vehicle development processes through automation. It has also been recognised that the next focus of automation should be targeted towards coordination of activities [124].

3.4.2 Connected Systems

Communication based technologies have created opportunities to connect various systems, stakeholders and resources that are physically separated. Introduction of this technology has enabled advancement in control system and test coordination capability in the automotive industry [125, 126]. With increasing availability of high bandwidth network connections for both domestic and industrial applications delivering new business models and services, similar benefits and opportunities can be applied to the physical vehicle development process.

The use of connected systems (also known as distributed systems) has been proposed and used with specific functionality for physical testing. Haptic based distributed automotive tests have been conducted that looked at the interactions from a driver-in-the-loop perspective [127, 128, 129, 130]. The study demonstrated the plausibility and key considerations for its deployment.

Studies into distributed test systems have also suggested improvements that should be addressed by future research. Refinement of communication methods to improve reliability and consistency of data, as well as development of algorithms to manage error handling were recognised as important future developments towards this stream of advanced testing [131]. The objectives and proposed solutions of this study looks to provide alternative/substitute methods that address concern brought from these studies.

The importance of data communication for automotive product development has also previously been highlighted for operational management of test activities. Webservices and virtual repositories were used to collect, and increase accessibility of models and knowledge to stakeholders in the organisation, while masking complexities that prevent their wider coverage [132]. The study summarised that there are significant opportunities to maximise productivity, reduce duplicated work, and improve learning from previous mistakes. Opportunities for further application were conceptualised within this EngD and recommended by the author, towards indirect optimisation of physical testing costs.

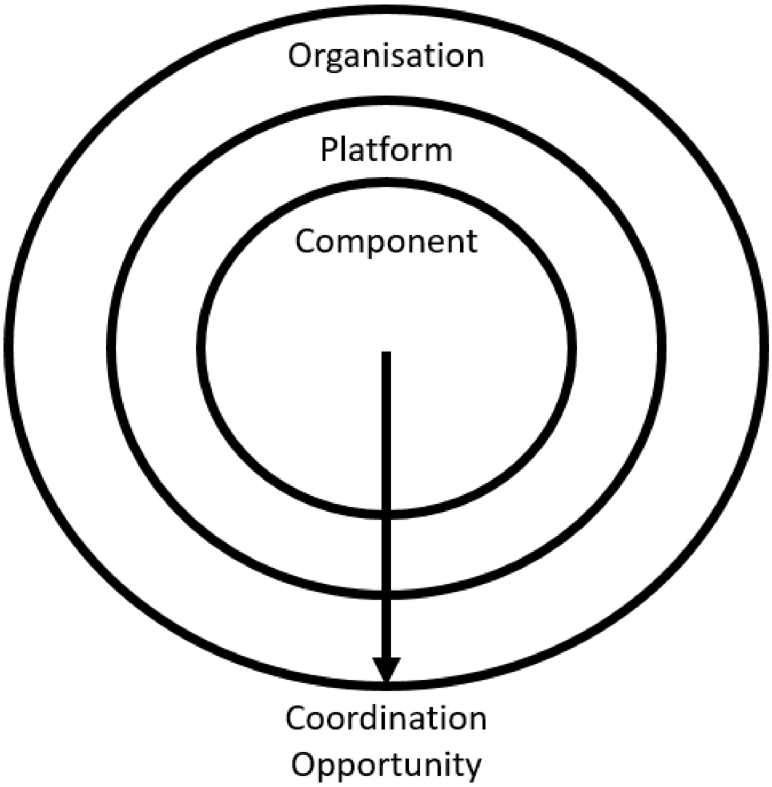


FIGURE 3.2: The visual representation of automaton and coordination within automotive technology process development.

3.5 Development Approach

A strategy of holistic technology innovation through the various levels of the organisation was planned. Three distinct levels where targeted at which to apply innovative concepts to raise productivity of individuals, empowerment of knowledge throughout organisation and maximising success by improving process quality. Optimisation of these aspects generates value across the physical test groups in ways that minimise resistance to change improving the relationship between individuals, their activities and the organisation [133]. These change principles argue that to maximise success and adoption requires the inclusion and investment of all stakeholders at various levels within the organisation.

Opportunities to apply automation and knowledge communication tools vary through automotive organisations relative to the perspective taken. While automation has the strongest influence at individual components and activities, the benefits of linking knowledge grows outwards as additional stakeholders are included and organisations grow in size (Figure. 3.2). This relationship guided the conceivable solutions and benefits at each level for automotive entities.

Chapter 4

Component Level Case Study

4.1 Foundation

Component testing is used at the early stages of the vehicle development process to understand and validate early estimations of vehicle performance models. Component prototypes and mock-ups are physically evaluated under controlled conditions as part of this process. The outcomes of which are used to benchmark component technology and validate virtual models that are intended to further the development of complete vehicle performance estimations.

4.1.1 Bench-marking

Component and system bench-marking is necessary to understand the competitor and industrial strategy. Testing existing components builds an understanding of the relationships between design, operating parameters, and their performance. By building awareness of present components, analytics can determine the current state, internal weaknesses and opportunities to evolve future components attributes such as cost, performance, efficiency, production methods and design choices.

4.1.2 Model Calibration and Validation.

Models of components, subsystems and systems require calibration as part of the vehicle development process. Modern-day virtual tools are highly accurate, but when produced into a physical form, their performance output may differ due to interactions with other components/subsystems/systems and physical behaviours that are unrepresented in the theoretical model. Thus, data collected from physical tests can be used to update parameters or assumptions made within the model to improve accuracy. This sub-process can be further used to develop empirical models of systems that we struggle to model with current virtual technologies. These activities typically feature in the intermediate stage of the vehicle development process when physical prototypes of components and systems become are available.

In addition, the performance of components and systems can be validated through physical tests. This form of product evaluation allows OEMs, ESPs, and manufacturers to verify that design elements meet the requirements set out for the component/system. For the automotive industry and in the perspective of powertrain performance, this is necessary and sometimes a mandatory requirement to detect development issues and certify energy consumption and emission of vehicles. This activity occurs in the final stages of the vehicle development process once the production version of the components and systems is available for testing.

This activity ensures the accuracy of assumptions made for component models at the initial stage of the vehicle development process. Early tests of component prototypes and predecessor parts ensure complex physical behaviours are understood and reflected in virtual vehicle level simulations. The improvement in virtual model accuracy reduces development risks associated with integration issues and failed objectives. Failure to address these issues introduces a growth in risk that is increasingly more expensive to correct further down the development process, where there are more significant dependencies between components in the vehicle.

4.1.3 Technology Development Process

Optimisation of component tests activities are desired to effectively manage R&D overhead costs. Direct expenditure of developing prototype components and physical testing activities are a significant contributor towards this value. Tasks such as benchmarking and iterative testing to characterise components as well as empirical models, consume a large volume of test resources (facilities, equipment, and employees) to ensure these are conducted to an accepted accuracy and precision. With the shift to vehicle powertrain electrification, R&D overhead costs are expected to rise. The immaturity and complexity of these next generation components places an increased reliance on physical component tests to capture the sensitive energy behaviours required to calibrate and improve empirical models. As a result, the additional volume demand and required precision, increases the total number of tests and resources needed to carry out this development activity.

4.1.4 Component Level Testing

With a focus drawn to advancement of individual tests rigs as part of optimising EV development, a study was conducted to investigate the automation of component test resources. At this level, the technological improvement focused on the application of test automation towards quality and productivity of a closed system. By improving operational capacity of these resources, it was hoped that the turn-around time for physical testing could be reduced, resulting in an increased number of separate projects to be conducted at reduced cost and duration as part of the vehicle development time.

Electric Machine testing

A test case was established to demonstrate the technical feasibility around a physical test resource relevant to EV development. In this case study, a hub dynamometer used to test electric machines and their corresponding power electronic components was selected to become the target platform. This specific rig was chosen due to attributes of high investment costs and industrial demand to validate powertrain configurations (Figure. 4.1). This new dynamometer test system proposed within this study looks to improve quality and productivity of the original layout by outsourcing the electric machine, dynamometer control and partial safety monitoring to an external controller (Figure. 4.2). Automation through such a ways allows the safe operation of the test cell to conduct transient test cycles under dynamic load, necessary for validation of electric machine, and inverters, as well as reduction in the number of test staff needed to conduct tests.

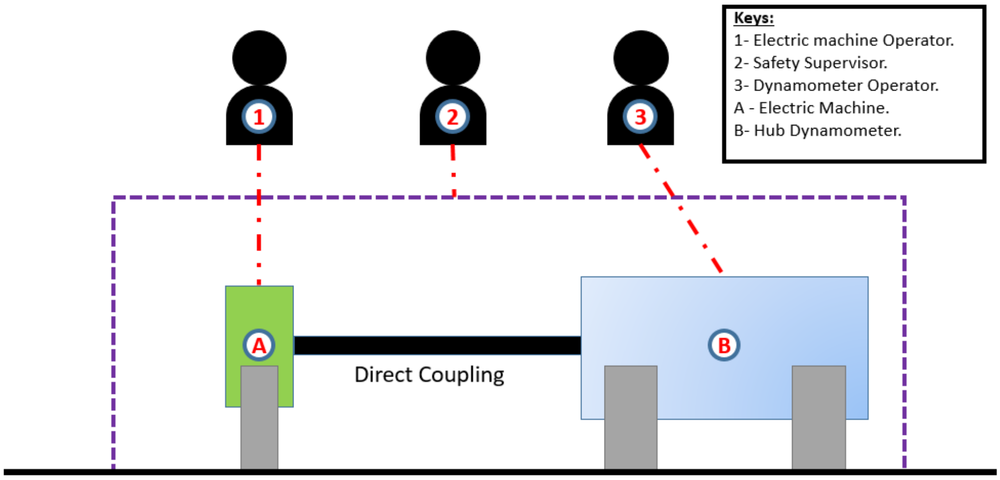


FIGURE 4.1: The current operation of transient testing upon a standard dynamometer.

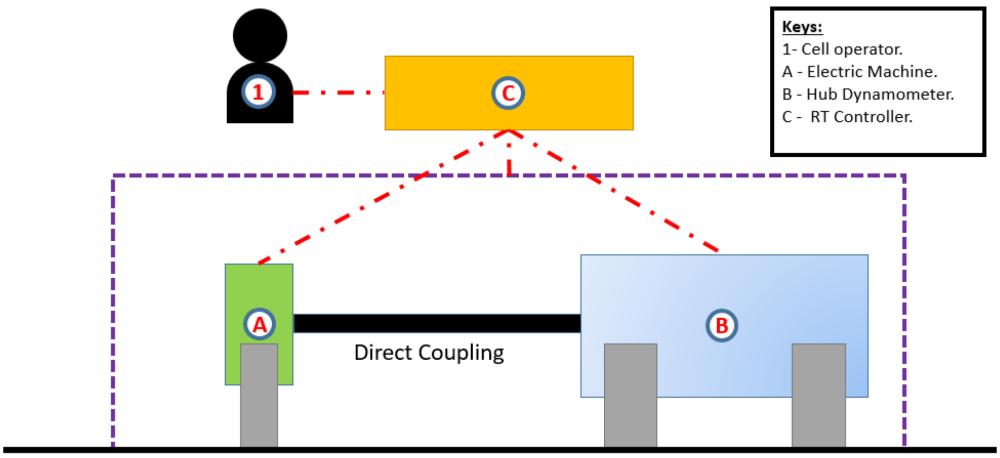


FIGURE 4.2: The proposed upgrade to an existing hub dynamometer to enable transient testing.

4.2 Requirements

4.2.1 Quality

The implementation of automation should look to improve the quality of physical test results. Quality as a concept is made up of experimental accuracy and precision attributes. Accuracy in respect to physical testing, represents the correctness of a model's results in relation to real-world performance, while precision denotes the consistency and confidence of achieved results. Physical test methods are noted for their high accuracy due to the ability to capture complete physical behaviours of the test target, improvements in accuracy are typically achieved by enhancing the test environment to be more representative of the test case. Precision of tests results are however highly variable, and are dependent on instrumentation and test control. Error caused by instrumentation offsets and noise are subjected to the quality of the chosen sensors and data collection methods. Test control variation is subjected to the method of operation. Control methods can be split into human and machine automation elements. The performance of these control methods are dependent on their ability to perceive, process, and act upon information. With respects to this study's aims and objectives, machine automation provides an opportunity to out-perform human control, by reducing the variation in test-bed control. This would improve the precision of the executed test, and enables fewer test iterations needed to build confidence in results.

4.2.2 Productivity

As part of the application of automation towards individual test control, a host system had to be developed to control the key aspects of the test set-up. This system had to include the ability to simultaneously communicate relevant data, monitor device conditions, and carry out actions that regulate the System Under Test (SUT). These characteristics were necessary to execute a planned schedule of sub-tasks and ensure that the system operated safely without harm to physical hardware or operators.

4.2.3 Objectives

Automated Control

Essentially, as part of the application of automation towards individual test control, a host system had to be developed to control the key aspects of the test set-up. This system had to include the ability to co-currently communicate relevant data, monitor device conditions, and carryout actions that regulate the SUT. These characteristics were necessary to execute a planned schedule of sub-tasks and ensure that the system operated safely with out harm to physical hardware or operators.

Transient Control

The ability to replicate test conditions of final product certification and end-user duty cycle was also desired. A feature enabling the simulation of transient control of common and custom drive cycles would provide valuable data towards improving and validating virtual models closer to that of the final product. The resultant capacity to carry out such tests increases the accuracy of the associated models, reducing the risk of integration issues, errors and delays of the final product.

Simulating Road Load at a Component Level

The ability to carry out realistic transient tests requires the capability to apply non-linear loads, and conditions as experienced within a completed road-going vehicle. Forces and effects such as vehicle speed, acceleration, mass, and parameters such as aerodynamic, tire and transmission drag are all significant enough to generate variations in conditions that influence the performance of the SUT. An automated system from transient test capability would need to account for such changes with different vehicle parameters and transform it into a representative feedback response at the point of connection between the electric machine, environment and the dynamometer.

4.3 Background

4.3.1 Dynamometers

Dynamometers are a valuable tool that facilitate the physical testing of powertrain units. Kinetic power of a combustion engine/electric machine is absorbed through a mechanical connection while output properties of speed and torque are controlled or monitored. Modern day dynamometers utilise large electric machines to carry out this absorption function due to refined capability of control and power handling. Other mechanical methods of power absorption have been used before, but most are less capable and flexible than those of electric machine dynamometers. The use of these test tools provide a safe environment where mechanical power produced by physical components can be measured.

Types of Dynamometers

Importantly, there are several form of dynamometers used to evaluate the properties of vehicle powertrains dependent on the progress of development. These include (Figure. 4.3):

- Hub-type dynamometers
- Hub-axle dynamometers
- Chassis Rolling road dynamometers

Hub-type dynamometers are used at the component level development where only individual components are available, while Hub-axle and Chassis rolling road are utilised when complete prototype or production vehicles are accessible. The former of which has ability to be used in the earlier portions of vehicle development, while the latter though restricted to the advanced stages of development, better capture the realistic physical interaction of other components [134, 135]. The current state results in limited capability of hub-type dynamometers in providing details regarding final completed system behaviour.

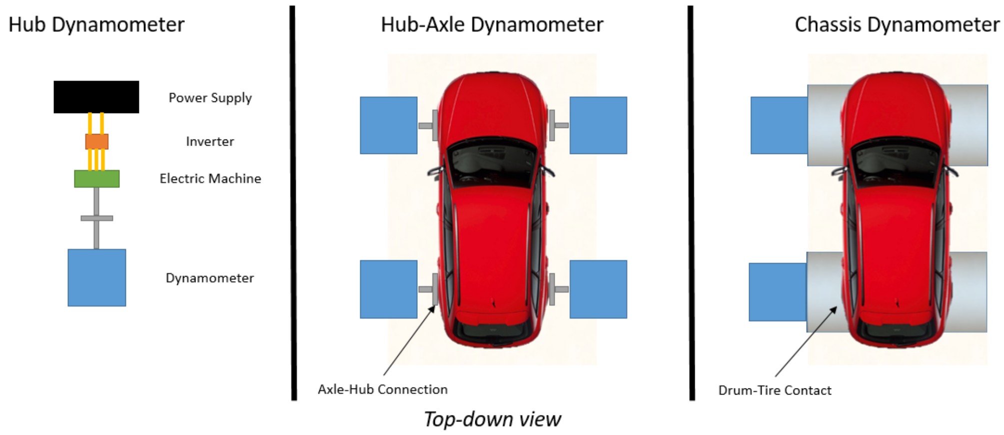


FIGURE 4.3: Physical layout of hub, hub-axle and chassis dynamometers.

Dynamometer Principle of Operation

Vehicle powertrain electric machines and dynamometers share the same principle of operations, but are handled oppositely in test cases. This principle are detailed in a power quadrant matrix where the resultant behaviours of each influence the vehicle state [136]. With an example vehicle exclusively moving forwards in a journey, the vehicle tractive powertrain operates in state one, while the dynamometer must operate in state two to absorb power. This mid-point between these states is the resultant behaviour of the vehicle. To achieve this in a controlled manner each unit must control both the shared speed and overall torque. In the standpoint of combustion power-trains that are restricted to state one, torque is controlled by the combustion engines through the throttle as per typical operation, while the joint shaft speed is controlled by the dynamometer (Figure. 4.4). With the transition to vehicle electrification, future dynamometers control needs to consider the variability in electric DUT (The combined elements of the physical drivetrain components being tested) control (speed/torque modes) and switching of states required to accommodate regenerative braking.

4.3.2 Automated Drivers

Automation of drive cycle testing upon chassis dynamometers has been previously established. Robotic control of actuators have successfully demonstrated the operation of vehicle throttle and brake pedals with the purpose of attaining the target drive

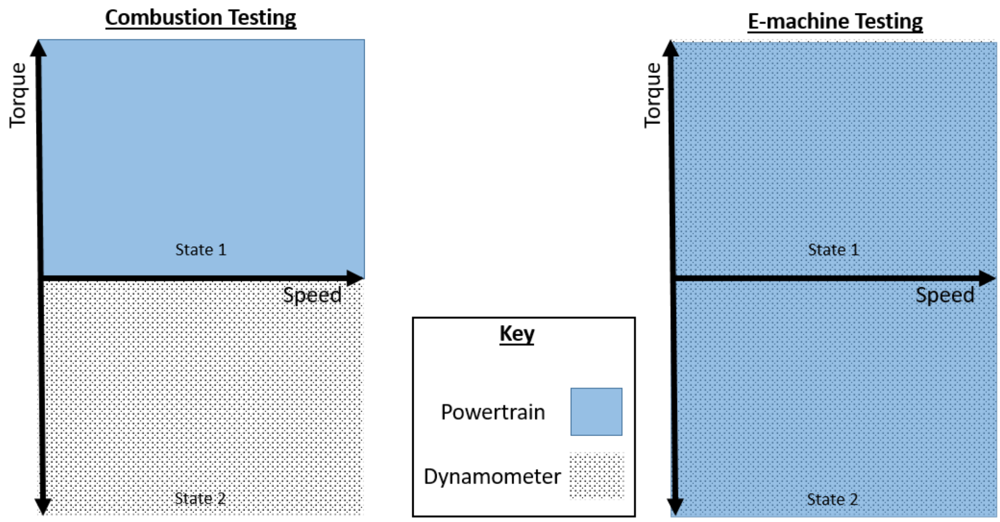


FIGURE 4.4: Operational states of the dynamometer and powertrain between Combustion and EVs.

cycle speed. The use as such allows consistent control without the operator error or variability.

Control Method

Notably, various control methods are utilised to provide optimal decision-making capability in operating vehicle forces on the chassis dynamometer. These include methods such as PID, Fuzzy Logic, stochastic methods, with differing success. The choice of which for vehicle electrification is determined to that providing the lowest energy consumption and therefore highest efficiency. For combustion vehicles, additional driver behaviours such as pedal busyness influenced secondary output parameters like NOx that are caused by transient variation of the combustion Air-Fuel ratio [91, 137, 138]. With reference to hub-type dynamometer testing for the evaluation of electrification components, conventional automated driver methods (i.e PID and Fuzzy Logic) were identified as the most optimal solution to carry out this function [114].

However, automated drivers have been noted to under-perform in comparison to human operated test set-ups. Experimental means have highlighted a slight advantage to human drivers in achieving higher powertrain efficiency results [139]. This occurrence is caused by the wider perception of human drivers unlike that of Proportional Integral-Differential (PID) and FL systems that restricted to immediate perception and focus to operating in reference to a single point rather than a human driver

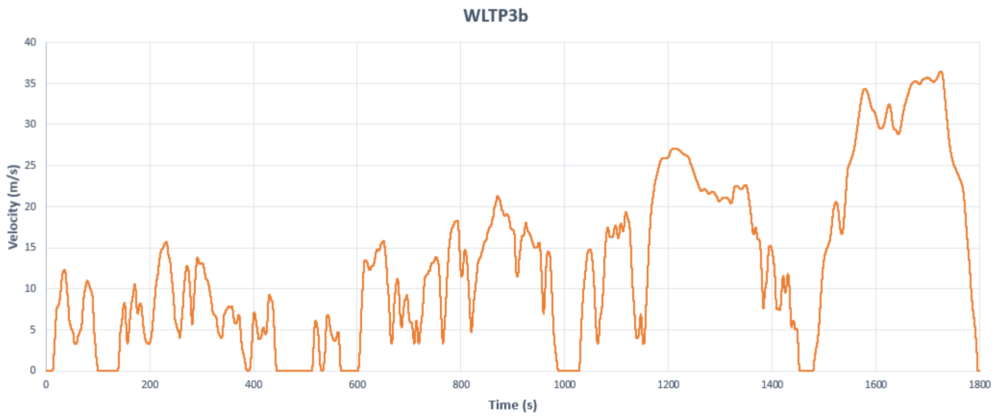


FIGURE 4.5: WLTP 3b drive cycle.

that would be instructed to be kept within tolerances. Consequently, it could be argued that results produced by an automated hub-dynamometer are likely to deviate from full certification. The difference is barely enough to eliminate the use of automated drivers but is worth recognising when interpreting results.

4.3.3 Vehicle Test Standards

WLTP

Certification documents such as WLTP establish key insights to the requirements for transient test capability [140]. As mentioned prior, these standards are ratified and followed by the majority of United Nation members and regulate vehicle energy certification testing to ensure an unbiased representation is met among all manufacturers. With this being the de facto guide to vehicle certification, it was decided that the initial development of an automated test system should also follow these considerations to provide an effective benchmark to chassis dynamometer tests and further methods. As a result of this the WLTP set of drive cycles will be used as part of this investigation (Figure. 4.5).

These guidelines also set out test tolerances that are be used to determine the validity of tests. Under Annex 6, subsection 2.6.8.3.1 of the Global Test Regulations 15, an error tolerance of $2km/h$ with a 1 second advance/delay is acceptable as part of the test (Figure. 4.6)[140]. This account for test methodology variability, and therefore applied to this study, act as an accuracy baseline to which we could determine the suitability/validity of the electric machine control through transient tests. It is important

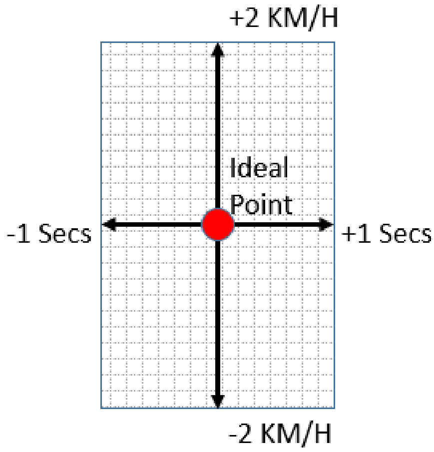


FIGURE 4.6: Accepted speed error as part of the WLTP regulations.

to note that the 1 second advance/delay allows the SUT to exceed the overall $2km/h$ tolerance through transient portions of the test cycle.

Road Load

As part of a complete system the relevance of road loads were also analysed. Research into vehicle drag modelling and the requirements outlined in energy certification regulations defined a minimum standard for the numerical methods used to replicate forces through the hub-dynamometer [141]. The widely accepted models provide plausible representation of road loads components such as tyre, transmission and aerodynamic drag that are implementable through computational control of dynamometer systems.

4.4 Design

4.4.1 Overall Layout

For the automation of component level testing, a generalised map was conceived to understand the layout SUT (The combined elements of the DUT and virtual vehicle) and apparatus. Individual parts were grouped according to their purpose in the test-step (Power Supply: battery; SUT: Electric Machine & Inverter; and Load: Dynamometer & Control unit) (Figure. 4.7). This structured approach outlined the

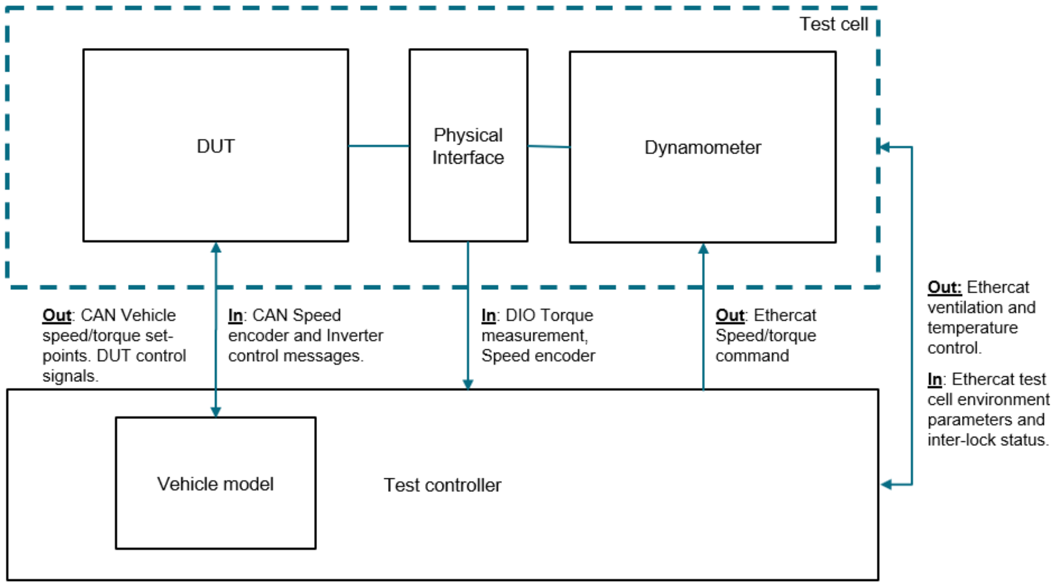


FIGURE 4.7: Generalised test layout of a SUT.

required control, communication and interactions between each segment, as well as providing a robust guide to planning automation for other component tests.

Hardware Layout

This was populated in detail to capture the specific interactions and control of Drivetrain Under Test (DUT) systems. The detailed map recognised the key input parameters provided by power supply and coolant chillers, the inverter and electric machine comprising the DUT and the dynamometer acting as a load. This aided understanding the precise communication methods and specific controls that the overall control system and automated driver interactions.

4.4.2 System Control

A real-time (RT) HIL system facilitated the control of the test set-ups. A National Instruments Veristand controller collected, processed and distributed commands through a real-time operating system. To accommodate variations in processing and instrumentation speeds of the test devices, the HIL system operated in its own control loop known as the primary control loop (PCL), while the other devices operated within their own loops (Figure. 4.8). This solution ensured that the HIL platform consistently reacted to device events, if when a dangerous state occurred; the whole system could

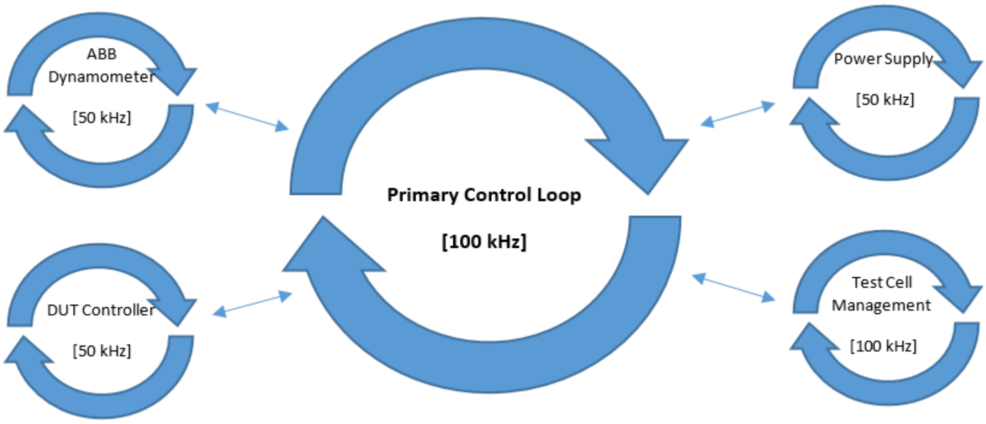


FIGURE 4.8: Primary and device control loops.

be brought safely to idle. This requirement dictated that communication between devices should be based on a push principle, where the latest signal frame is passed onto the PCL without disrupting or delaying the RT constant cycle rate. This structure ensure that safety critical PCL controller runs continuously without waiting for devices and builds flexibility in the system to allow interfaces that operate at slower cycle rate than the PCL.

The RT HIL components and the associated devices were all operated at specific executions rates to maintain safe environment. The PCL and the test cell management system operated at 100kHz, while other devices operated at the maximum rates possible. The main RT HIL components operated at this rate to ensure the test apparatus reacted as soon as possible to any unsafe condition. In addition, this was balanced with the necessity to operate the RT processor a consistent rate plus sufficient resolution to capture harmonic behaviour of the electric motors (as specified in the laboratory's overall requirements).

4.4.3 Vehicle Model

Inertia

The difference in dynamometer and vehicle inertia had to be compensated within the HIL model. Inertia of dynamometer's rotor, and prop shaft was significantly smaller than that of the combined inertia of the vehicle differential, axles, hubs, tires and chassis. The known inertial parameters of main components allowed the implementation of a virtual interface to model the vehicle's inertia. The modelling of dynamometer-vehicle inertia interface can be expressed through Equations 4.1 - 4.5. This feature ensured that an accurate estimation of the vehicle speed was possible for the driver model and drag models to function.

$$F_{vehicle} = M.\frac{dV}{dt} \tag{4.1}$$

where, $F_{vehicle}$ = vehicle force, Newtons; M = mass, kilograms; V = velocity, metres per second; t = time, seconds.

$$F_{vehicle} = F_{propulsion} - F_{drag} \tag{4.2}$$

where, $F_{propulsion}$ = propulsion force, Newton; F_{drag} = propulsion force, Newton.

$$F_{propulsion} = N_{wheels}\frac{T_{prop}.Gear_{Ratio}.EDU_{split}}{R_{Tire}} \tag{4.3}$$

where, N_{wheels} = number of wheels, integer; T_{prop} = torque at prop-shaft, Newton-metres; G_{ratio} =gear ratio; EDU_{split} = drive unit layout split, 1/ number of drive units; R_{Tire} = radius of tires, metres.

$$Mass = VehicleCurbWeight + RotationalInertiaMassEquivalent \tag{4.4}$$

$$T_{prop} = In_{prop}.\frac{d\omega_{prop}}{dt} \tag{4.5}$$

and, In_{prop} = prop-shaft inertia, kilograms-metres squared; ω_{prop} = prop-shaft rotational speed, radians per second

Vehicle Drag

Real world drag models determined the forces required at the SUT shaft based off the desired vehicle speed and current forces upon the SUT shaft. The model uses a quadratic equation to represent a combination of tire, transmission and aerodynamic forces that oppose vehicle forward motion [142]. This equation can either be sourced through the regression analysis of virtual models or physical coast-down tests (Figure.

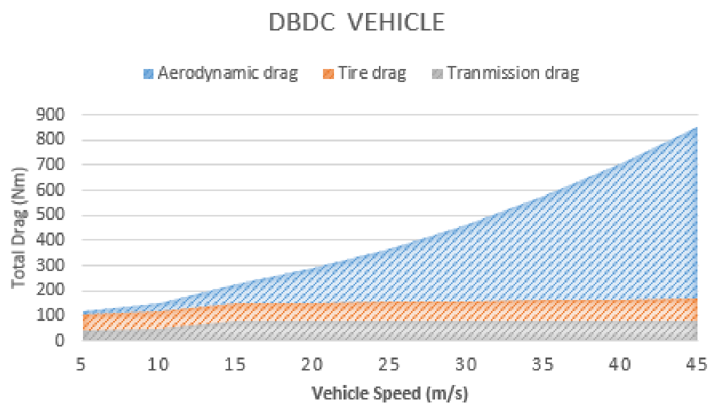


FIGURE 4.9: The decomposition of road load drag.

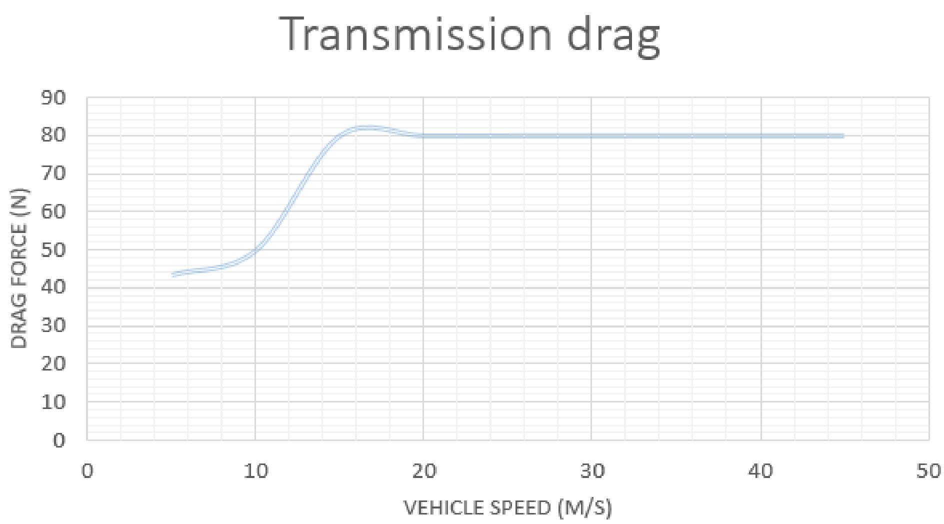


FIGURE 4.10: Transmission Drag for the DBDC vehicle.

4.9). In adaptation for the automation of the hub-dynamometer, virtual models where used as it allowed flexibility of using various components to create a hypothetical vehicle.

A combination of component drag models derived the specific vehicle drag models. Theses included the SAE J2452 equations that emulated tire drag (Equation 4.6), a one-dimensional look-up table characterised by the efficiency of an existing manufactured drive-train unit (Figure 4.10), and an aerodynamic co-efficient of a similar profile of an existing vehicle (Equation 4.7). Combining these models calibrated from physical tests ensured a reflective profile of road load forces.

$$F_{tire} = P^{\alpha}.F_R^{\beta}.(A + BV + CV^2) \tag{4.6}$$

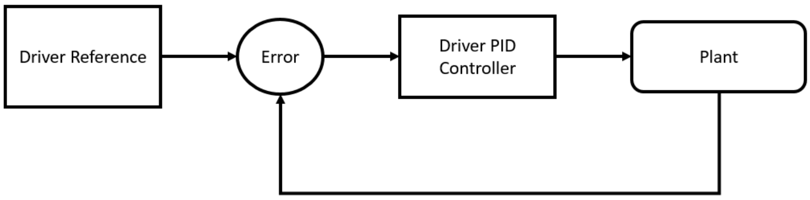


FIGURE 4.11: Layout of a PID controller used for the automated driver.

$$F_{aero} = \frac{1}{2}\rho a C_d V^2 \tag{4.7}$$

Mechanical Brakes

In addition, mechanical disc brakes where emulated as part of the vehicle model. A mathematical model was implemented that took into account key parameters regarding the design attributes of discs and calipers (Equation 4.8) [143]. This model was chosen as it reflected an accurate working of mechanical brake behaviour, while also being adaptable to variation in component design parameters.

$$T_{brake} = \frac{\mu_k Pr \pi D_b^2 R_m . N}{4} \tag{4.8}$$

,where μ_k = co-efficient of kinematic friction, dimensionless; Pr = brake pressure, Pascals; D_b = caliper bore diameter, metres; R_m = mean brake pad radius, metres; and N = number of brake pads, integer.

4.4.4 Driver Model

Automated Driver

Because of the literature review, a PID controller carried out the driver function within the HIL platform. A basic PID controller, analysed the error between the virtual vehicle's current speed and desired speed of the drive cycle at that instance, through proportion, integral and derivative errors and formulated an appropriate output (Figure. 4.11). The PID as demonstrated by its other application and ease of development became the optimal solution for this test case.

Drive Trace Input

The journey control and drive cycle were inputted via a python script. A 'For' loop script was created that updated the virtual vehicle's target speed between fixed time intervals of one second. This method was ultimately chosen as it facilitated various options of drive cycles without re-deployment of the HIL as well as the provision to start, pause, stop, or switch to manual override for operator control. This would have otherwise been restricted through embedding the drive cycle in the driver/vehicle HIL model.

Pedal Box

A virtual pedal box mapped the PID output into torque commands for the DUT and dynamometer. Positive values of the PID were treated as acceleration commands, and as a result, an acceleration request was sent to an electric machine torque map, which referred the appropriate torque in accordance to the vehicle speed. Negative outputs where treated as coast and braking commands, which in turn resulted in a deceleration request through a brake pedal map to the dynamometer and a regenerative braking strategy function passed to electric-machine (Figure. 4.12). This design layout enabled tuning of the pedal inputs for the vehicle commands and modification of the regenerative braking strategy as seen on production vehicles.

The PID controller and its settings were initially tuned offline using virtual simulation tools, while further refinement would occur on the test apparatus. Using a combination of the Zeigler-Nichol approach, in-built PID tuning tools in Simulink and manual corrections, tuned the PID controller to an approximate model of the test system created on Simulink. The PID was refined to minimise errors on a similar WLTP cycle. Once suitable PID values were achieved with the simulation model, these were used as a starting point for the actual system.

The Zeigler-Nichol approach to tuning the PID controller was adopted as it allowed a structured and straightforward approach to estimating the PID parameters. The method is well defined and known. Though this approach can produce an aggressive response, it produced an estimated starting point to work from.

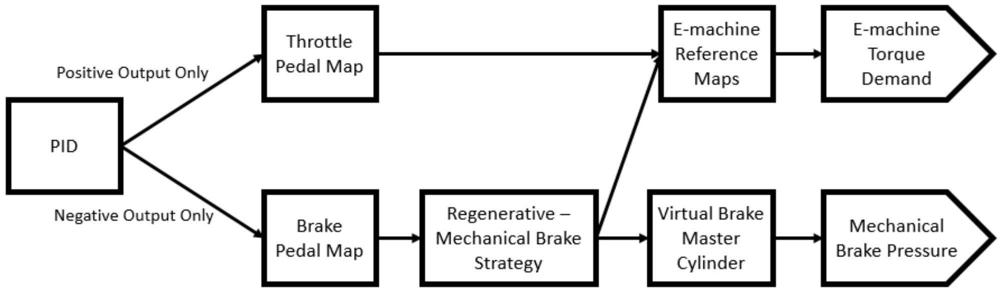


FIGURE 4.12: Automated dynamometer pedal box.

Limitation of the driver model

One of the noticeable limits of the proposed driver model is the inability to replicate the look-ahead capability of a human driver. PID controllers only account for the immediate error between the plant (vehicle) and the stimulus. In contrast, a human driver can adjust their control inputs to correct future velocity changes. As a result, the automated driver in this study could behave differently from that expected of a real-world alternative.

One way to remedy this would be to adopt a feed-forward system as part of the PIDs design. This feature would be implemented by adding a delay to lead the plant or implementing a causal model into the controller to account for future changes. This adds complexities to the system when trying to communicate with external systems (such as distributed test systems) when adopting a delay. At the same time, a predictive casual model would need to be validated to estimate the feed-forward signal for the vehicle appropriately and accurately.

4.5 Application

4.5.1 Apparatus and implementations

Test hardware

The test hardware consisted of fixed elements available to to the specific test cell used. These included:

- 320kw 10,000rpm ABB electric machine dynamometers with Froude inverter controllers.

- FTF 500-900 Bitrode battery pack cycler capable of 900V and 250kW.
- Two Lauda chillers in separate cooling loops for the inverter and electric machine set to ambient temperature at a fixed cooling rate (10L/min).

The hardware used represented the minimal necessary test-bed equipment needed to conduct an electric machine-dynamometer test.

HIL system

The combined controller for the SUT, test hardware and test cell management was housed in an Evolution rack produced by Austin Consultants. The Evolution racked consisted of a National Instruments Veristand real-time controller with additional input and output units for CAN, Flex-ray, Ethercat and analogue/digital inputs-outputs. The Veristand unit allowed the real-time control of all critical elements through custom plugins to manage communication between devices and the primary control loop. The Veristand unit also could import Simulink models through exported c-code (This feature was used to implement the virtual vehicle model).

4.5.2 Test case parameters

In particular, a set of parameters were created to emulate a virtual vehicle around a DUT. Key outputs of the DUT (i.e torque and speed) determined these parameters for a vehicle model (Table. 4.1). These parameters were used due to the hardware chosen, accessibility to validated data sources, or calculated to ensure a working test case. The combined conceptualisation of these parameters ensured that the DUT could undergo a transient drive cycle test under conditions that were representative of a real-world vehicle.

4.5.3 Tested Configurations

Two of four possible test control configurations between the electric machine and dynamometer were tested. Configurations 1 and 2 were chosen as the most suitable formats to test a DUT under transient load (Table. 4.2). These specific modes were chosen as they allowed precise control of the road load forces to be deployed onto the DUT, while ensuring the system operated in a safe state.

Parameter	Variable (units)
Traction Inverter	Sevcon Gen4 Size 8
Electric machine	HVEMs
Bus Voltage	120(Volts)
Vehicles Layout	4WD (Dual motor)
Curb Weight	1000(kg)
Power-to-weight ratio (W/kg)	32
Tires	Continental 235/65R17
Gear ratio	5:1
Aerodynamic Drag Co-efficient	0.28
Test Cycle	WLTC2

TABLE 4.1: List of key parameters for the virtual vehicle and test.

Configuration	DUT	Dynamometer
1	Speed Mode	Torque Mode
2	Torque Mode	Torque Mode
3	Speed Mode	Speed Mode
4	Torque Mode	Speed Mode

TABLE 4.2: Various configurations modes for the DUT and Dynamometer.

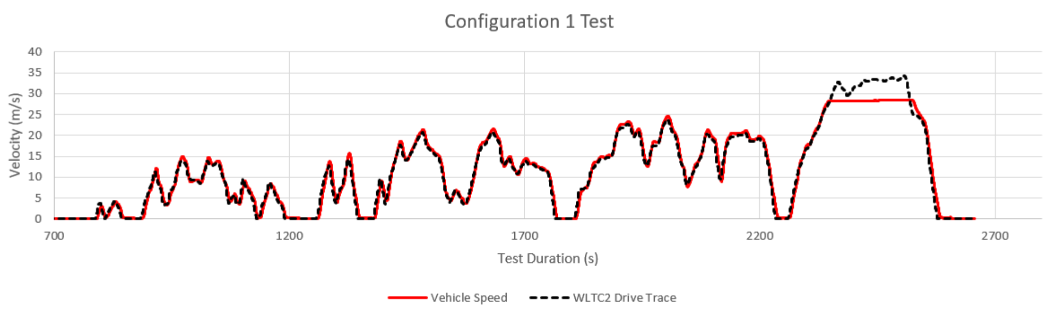


FIGURE 4.13: Velocity trace of WLTP test in configuration 1.

4.5.4 Configuration 1

Firstly, the deployment of configuration one confirmed the plausibility of the functionality of the transient loading and control of the hub-dynamometer testing. Through several iterations of system parameters refinement, a drive cycle test was carried out that replicated the vehicle journey as prescribed by the WLTC 2 drive cycle. The principle analysis of the test showed that the automated system approximately followed the drive trace with only significant deviation when the DUT reached its maximum speed (Figure. 4.13).

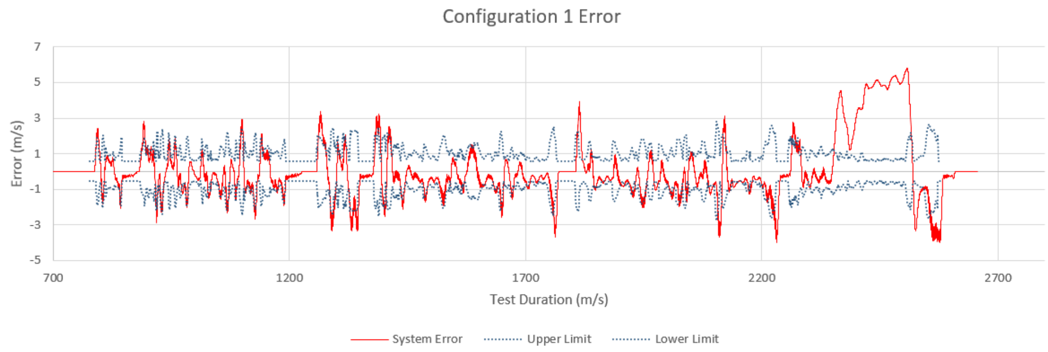


FIGURE 4.14: Observed error with speed tolerances configuration 1.

Performance

The real system required additional tuning for the PID controller to effectively control the virtual vehicles braking behaviour. The initial PID parameters were defined with a computational model of the test system, however when deployed to the system performed inadequately with a large propagation of errors exceeding the defined tolerances of the test standards. In the end a Ziegler Nicholas PID tuning method was used with a PD controller. It was determined that a combination of poor input data from the prop-shaft encoder and the inaccuracies for the virtual dynamometer model distorted the initial deployment of the PID parameters.

The test system requires additional refinement to meet the required tolerances of the WLTP regulations. Through the final tests there were occurrences where the test system exceeded the $2km/h$ (with a one second delay) limits (Figure. 4.14). These occurred during acceleration events where the internal speed control of the inverter limited torque output and caused an unexpected delay, as well as issues with the DUT applying positive torque under braking (Figure. 4.15). Though the system followed the drive trace, the results of the system are recognised to have notable qualitative deviations that differ from the expectations of chassis dynamometers and other advanced forms of vehicle testing.

4.5.5 Configuration 2

Unlike configuration one, configuration two encountered DUT technical issues that prevented safe completion of the drive trace. Through the tests attempted, the DUT frequently stalled after points of zero velocity, this stall occurrence placed the DUT

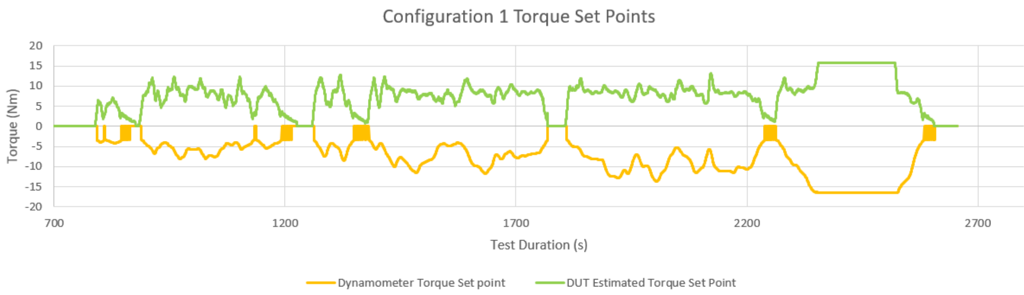


FIGURE 4.15: DUT and Dynamometer torque set-points configuration 1.

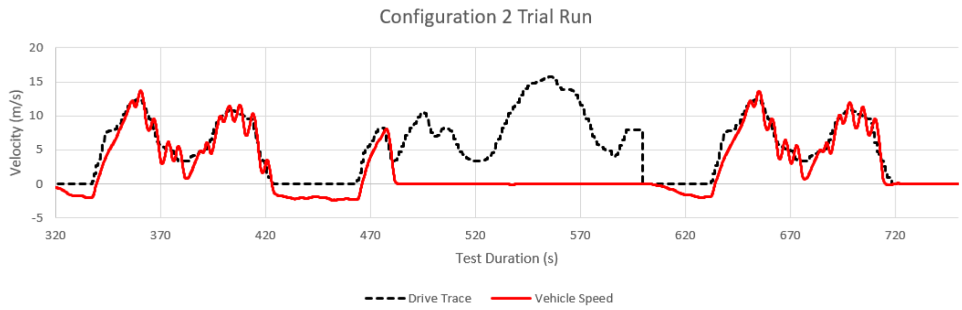


FIGURE 4.16: Velocity trace of WLTP test in configuration 2.

under strain and increased hardware risk from the potential for excessive heat production within the electric machine (Figure. 4.16). Due to this limitation of the DUT and no immediate fix available at the time of testing, a full drive cycle test was not possible. Only a limited capture of qualitative data was possible to evaluate the system capability in this configuration.

Notably, testing both configurations concluded that configuration one was the most appropriate for further development. Configuration two's torque stalling occurrence, as witnessed from the tests, and over-loading the prop-shaft between the dynamometer and the powertrain being tested increases the overall risk to the test equipment and environment. As a result, the study advises not to operate in configuration two until a control system is implemented to overcome these issues.

In summary, configuration one should be pursued for further development. Improvements should include an improved driver model with a feed-forward element and a refined PID tuning process. These changes would provide the best opportunity for delivering a functional system for electric powertrain testing while preserving the safety of the test system.

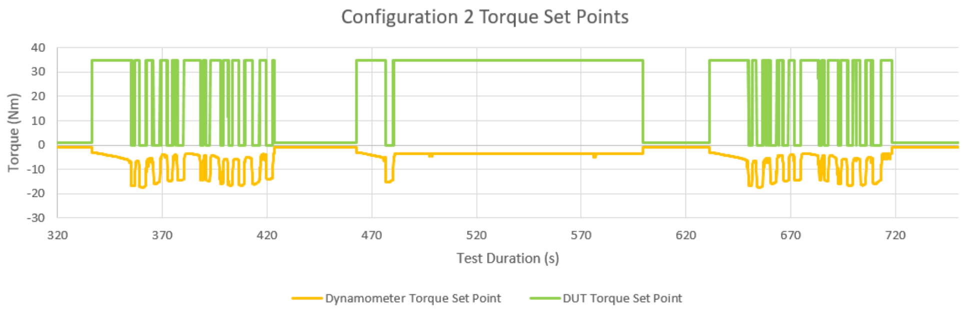


FIGURE 4.17: DUT and Dynamometer torque outputs configuration 2.

Performance

Crucially, the observed control behaviour within this configuration was more representative of driver behaviour. It was evident through the analysis of the DUT and dynamometer torque that the system conversely applied torque from the DUT and the dynamometer load through the vehicle acceleration and deceleration (Figure. 4.17). This behaviour emulated the realistic control of the vehicle by a human driver, where vehicle throttle and brake are operated mutually exclusive from each other.

However, poor tracking of the vehicle speed was also noted as part of this configuration's results. Through the data captured through the driven portion, the DUT and correspondingly the virtual vehicle failed to follow the drive trace precisely. The poor execution of this drive trace highlights both the limited capability of the prototype DUT, as well as the necessity for additional PID tuning to improve the fidelity of this system.

4.6 Evaluation

4.6.1 Technical Behaviour

PID Tuning

The use of a PID controller for the driver model requires additional development and calibration to maximise the productivity of DUT tests. Changes required as part of the system implementation and its performance from the configuration tests have demonstrated the necessity for, the improvements of the virtual environment used to pre-tune the PID controller, and the inclusion of several physical PID tuning sub-tests to verify the suitability of the PID parameters. The suggested approach would look to minimise the test duration required to tune the PID driver per project, by out-sourcing the majority of the PID development onto the low-cost virtual methods, avoiding the need for additional time upon the physical test-bed.

Controller Coordination

The results from configuration one highlighted the importance of the DUT and dynamometer coordination. The comparison of deployed torque between the DUT and dynamometer showed significant overlap of each that would be representative of a real-world driver applying throttle and brakes simultaneously (Figure. 4.15). This behaviour was caused by the independent and uncoordinated operation of the automated driver's control over the vehicle mechanical brake and the internal electric machine control. The overlap caused by co-action of driver control increases the overall energy consumption of the vehicle. The system's purposes of producing accurately certifiable drive traces, minimise excess energy consumption to complete a test cycle, and being representative of human driving condition, currently sees this control overlap as an unwanted behaviour for certification testing but may have some benefit for extreme driving situations that could see the benefit of control overlap for techniques such as toe-heel.

This overlap of throttle and brake could be beneficial for replicating the toe-heel technique used by some drivers. Real-world divers use this technique for additional control of the vehicle approaching a turn. ICE-powered vehicles with manual gearboxes benefit from this technique to set the drivetrain in optimal RPM conditions for accelerating after a decelerating phase and preventing loss of traction caused by potential mismatched speeds while changing down gears. As a result, the system's ability to overlap controls has some benefit for the additional control of the vehicle along with transient test conditions like a drive cycle.

However, electric vehicles being tested may not benefit as much from the deployment of the heel-toe technique as part of a future test system. Electric machines have differing high torque-low rpm characteristics that reduce the need for such a technique. This limits the techniques use to hybrid powertrain with poor low rpm performances that utilises gearbox-clutch systems.

4.6.2 DUT requirements

The study recognised the importance of the DUT maturity to the effective use of automated test resources. The prototype nature of the DUT demonstrated the cost of integration issues and limitations that occupied large portions of the assigned system development time. These instances should equally be considered and accepted as part of the DUT development process. The intended placement of this test solution would be susceptible to prototype component issues and therefore future developments should look to streamline and/or add flexibility into the interface to better handle this occurrence.

In contrast, the advanced maturity of developed electric electric machine and inverter components should reduce the occurrence of limitations experienced as part of this case study. The prototype DUT used was still in the stages of early development and required additional characterisation to be effectively controlled. Realistic application of the automated component test system would require physical components to ascertain a minimum level of functionality before being conducted under automated transient load tests.

Statistical significance

The test system has only been tested as a proof of concept and needs additional validation to support its findings. The test system requires multiple iterations of the test to be verified through statistical techniques such as ANOVA on whether the observation seen are consistent and not caused by unaccounted variability of the test systems set-up. The test system validated through statistical tests would provide necessary confidence towards the system's precision while also establishing a benchmark of performance that could be used to evaluate the benefit of future modifications.

4.6.3 Operational Impact

Test duration

Limited availability of the test-bed, restricted full evaluation of the automated test systems consistency. It was hoped that from a set of tests to measure consistency between test iterations, the system would have demonstrated the capability to reduce

Task	Manual Duration (Days)	Automated Duration (Days)
Test Set-up	10	10
Test Checks	2	2
Steady State	10	6
WLTP	9	4
FTP-75	7.5	2.5
Spare	3	3
Test Set-down	5	5
Total	**46.5**	**32.5**

TABLE 4.3: Total duration required to evaluate a DUT under steady-state tests as well as two drive cycles (including tests at 0,10,14,23,30 Centigrade).

	Active Duration	Facility Cost	Worker Cost	Total Cost
Manual	26.5	£29,150	£14,572	£43,722
Automated	12.5	£13,750	£3,229	£16,979

TABLE 4.4: The estimated portion of research overhead cost attributed for the active duration of testing DUTs (Costs data Appendix A).

the number of test iterations required to statistically verify the precision of its results, in comparison to a manual operator where variance from human error would require additional iteration to build confidence in results. A benchmark for manual duration was derived from discussions and experience from internal projects, while the duraiton saved was estimated from an ideal test case. It was calculated that with the adoption of automation a reduction in 14 days was possible (Table. 4.3). The ideal test system from these calculations would impact the specific test portions of the process rather than the test set-up, checks and decommissioning.

From a project perspective, the full capability of the automated system for transient electric machine testing introduces a reduction in overhead costs in this aspect of development for powertrain technology. With its introduction, a 61% of costs are saved from manual operated tests (Table. 4.4). This notable difference is attributed to the reduction in the cost of the number of operators where additional qualified engineers cost per hour can have a significant contribution in manual testing operations.

Productivity

Significantly, a forecast on test cell capacity highlighted the opportunities for improved productivity through test cell automation. With this technology advancement, the test

	Capacity	Efficiency	Facility Cost	Work Cost	Total Cost
Manual	7 DUTs	51.9%	£258,500	£205,553	£464,053
Automated	8 DUTs	46.2%	£258,500	£126,342	£384,842

TABLE 4.5: Projected impact on productivity and operational costs from individual facility perspective (Costs data Appendix A).

cell was projected to accommodate an additional DUT, while from a financial standpoint the overall impact of flexible resource costs (human resources) drastically reduced the overall operational costs (Table. 4.5). These outcomes where driven by the combined effect of the shortened test duration and resourced man-hours.

4.7 Conclusion

The proposed automation of a component test cell aligns with the objectives set out as a part of this component level study. The application of automation technology at this level partially met the criteria of expanding component test capability and capacity for electrification technologies. The investigation demonstrated the plausibility and required improvements proposed for the introduction of an automated test system. Deficiencies in the chosen SUT test, however limited full exploration of the technology within the study.

Importantly, the implementation of this test resource provided evaluation features in the component testing phase that would have otherwise required other costly test-beds and facilities. Using a hub-dynamometer implemented with a real-time controller, virtual vehicle model and automated driver, the tests conducted as part of this study demonstrated a safe operation of a transient drive cycles, with changeable loads while reducing the number of required personnel needed to verify and understand transient behaviours of electric-machines and their associated power electronics. The features enabled on this test-bed could help evaluate the performance of existing, new, or alternative electric machine components rapidly at an earlier stage of the vehicle development process, where testing costs are cheaper in comparison to advanced stages of product development upon hub-axle and chassis dynamometers, that require expensive prototype, or near-completed vehicles.

4.7.1 Recommendations and Further Evaluation

Due to limited availability of the test platform preventing completion of some desired objectives and assessment of the investigation's outcomes, a set of recommendations were created to identify future paths of development that could expand the capability of this test solution and further component level testing for powertrain electrification. These included:

- Statistical verification of the systems.
- Investigation in the efficiency of the driver model on hub-dynamometers and alternative driver models.
- Multi-axis automation to conduct hybrid powertrain tests.
- Qualitative verification of system precision
- Improved thermal interface for climatic and dynamic cooling loads [116].

These priorities were identified as they addressed the present issues with the current system and required expanded capability of the system. Outcomes such as the precision of the automated driver, reiterate the necessary refinement in chosen control structures for highly transient drive cycles such as the WLTP and FTP-75 [112, 114].

4.7.2 Operation Optimisation

The improvements from this study suggested that inactive and changeover periods of the DUT testing process have a greater significance to productivity after test cell automation. Results from the operation forecast noted a reduction in process efficiency. This reduction in efficiency was attributed to the almost equal proportion of the changeover period and active test duration. Further improvements to operation capability should aim to reduce changeover of DUTs and apparatus.

4.7.3 Application to other component

Ultimately, the automation of component testing should be expanded to other key electrification technologies. For components such as the battery, inverter and H.V.A.C system, the generalised layout in addition to the control system facilitated through

HIL technology opens up the transient test capability. The advancement of this capability in such a manner across all key components would collectively have a significant impact on reducing the research and development overheads that drive the high product costs of these components in vehicle electrification.

Chapter 5

Platform Level Process Optimisation

With the expansion of perspective in the vehicle development process, coordination and communication of test resources create opportunities to benefit the development of vehicular systems at a platform level. Communication networks that share information between component test resources could emulate physical interactions that would otherwise require the creation and integration of full vehicle systems. Through implementing an appropriate test solution, opportunities arise to:

- Decrease the need for full physical vehicle prototypes
- Add precursor steps to identify development issues earlier in the development process.
- Increase opportunities for system level testing at the initial stage of the platforms development.

Providing these features reduce the development costs associated in designing a vehicle, improve the quality of components developed and reduce the overall engineering time required to realise the performance of a vehicle.

5.1 Foundation

5.1.1 Distributed Test Systems

The term DTS defines a group of test resources that are interconnected to overcome shortfalls of singular physical test systems. The benefits of DTS are dependent on the capability of the communication network chosen, its structure, and the collective control method of the resources enabled by the network. These characteristics aid in development of test alternatives where information shared between the individual test resources, supplements the product of larger full vehicle test resources.

5.1.2 Sychronous DTS

The synchronous form of DTSs look to use a network of subsystem/component test resources to supplement completed systems or full vehicle alternatives. This type of DTS relies on the real-time (RT) calculation and transmission of data and its execution at each test node to emulate the physical interactions that would be present in completed system or vehicle prototype. By using subsystem and component test resources, significant savings can be made by avoiding the use of completed systems that require expensive prototypes and milestones to become available, flexible test facilities, and could result in costly fixes to rectify issues occurred.

5.2 Objectives

A set of objectives were established to ensure that the system design met the requirements of an operational system. Each requirement was analysed to determine an appropriate set of criteria that the design needed to satisfy. The successful fulfilment of these objectives would ensure that the proposed synchronous DTS solution would aid the development of quality and productivity aspects of vehicle physical testing.

5.2.1 Suitable Network

A suitable communication network had to be created to connect and operate test resources in RT. The network had to transmit data regarding the behaviour of each node within a specified duration so that other nodes could receive and act upon information to improve their own local test environment. It was critical that characteristics such as latency were minimal in duration to allow representative sampling of test nodes' behaviours in an adequate resolution, while volume of data was achievable within bandwidth constraints.

Furthermore, network topology was highlighted as an attribute that influenced the performance of communication networks and methods of control. A communication network had to be developed so that data would be channelled appropriately to necessary test resources, provide consistent performance, ensure cyber-security and failure of infrastructure would be handled safely by the network and nodes. Inadequate understanding and application of appropriate network structures could result in failures to acquire the desired performance of the network, but also incur secondary issues that could risk the safety of the physical systems.

5.2.2 Hardware Interface

An interface had to be developed to emulate the behaviours at nodes and respond back with the node's current state. As a concept, this would see that physical behaviours at the node are captured through instrumentation, while incoming signals would be converted to an appropriate physical form to emulate physical interactions from other parts of the system. This was a necessary consideration as poor representation of important component behaviours could propagate errors throughout the system and reduce the effectiveness of synchronous DTSs to supplement physical test systems.

5.2.3 System Control

Control of isolated nodes must be specified to ensure that all tests operate in time with each other, and failures at any node can be handled safely. The hosting location, structure and actions of the control system need to be technically determined to ensure that they achieve sufficient control to run the tests, but also retain individual authority of rigs to manage safety systems. The chosen control architecture attributes and ability would be a significant consideration for the alignment with the tools purpose and functionality.

	Bandwidth	Latency (ms)	Data Security	Range (Meters Est.)
LAN	1 Gbit/s	< 1	Secure	Unlimited
Wi-Fi	54-600 Mbit/s	151	Req. encryption	90
3G-4G	2-20 Mbit/s	98-212	Req. encryption	3000-30000
CAN	1 Mbit/s	n/a [1]	Secure	250

TABLE 5.1: Outline of the network characteristics to link research facilities together.

5.3 Background

5.3.1 Communication Networks

A set of benchmarking metric were collated to judge the appropriateness of various network technologies per the requirements of a synchronous DTS. These were identified to be latency, bandwidth, data security and range. The selected metrics would help identify a network that could operate with a reduced latency for RT communications; the necessary scalability to extend the system between building and to external partners, and satisfactory network security required for automotive research.

Communication Mediums

Research into communication media identified the suitability of Ethernet Local Area Network (LAN) technologies for the purpose of synchronous DTSs. Various forms of network technologies were compared for attributes such as bandwidth, latency, data security and range. Ethernet LANs surpassed subsets of wireless telecommunication networks that incurred greater latency and poor data security (Table. 5.1). CAN networks were also noted for their communication performance and current application within vehicle technologies but were severely limited by scalability for DTSs operating at ranges over a few hundred meters.

Latency

Latency, the measurement of time taken between the transmission and recipient of data between nodes, was acknowledged as the most significant aspect of a RT communication network. Studies have produced models that identify and quantify the causes of latency in Ethernet applications [144, 145]. Outside of the physical wire transmission of the data, application interrupts at the nodes were recognised as major causes of network latency, followed by the coding of data. Thus to minimise latency, the time of flight and application method were of key importance for the development of synchronous DTSs.

Protocols

Within Ethernet network technology, additional configuration features affect the performance and characteristics of the designed communication solution. These attributes are recognised and represented by IEEE and ISO standards for the Open Systems Interconnection (OSI) model [146, 147]. Research around the Transmission Control Protocol/Internet Protocol (TCP/IP) model highlights the challenges of network communication as seen by TCP's development. Features such as buffers for input/output data handling, device acknowledgement for flow control, and strict packet sequencing to allow data-point splitting and re-joining provide the necessary capability to undertake challenges with digital communication to ensure transmission speeds, availability and accessibility of data [148]. It is critical to understand how these protocols and their attributes interface with each network model.[149]. The two concepts highlighted the in-depth consideration needed to supply a functioning communication system. Conceptually, both models contain the same functions but are visualised differently. The TCP/IP model collapses the application, presentation and session layer into a single application layer and the combination of the physical and network layer of the OSI model into another singular link layer. Each layer corresponded to details in how data would be packed, addressed, managed and communicated.

Three developed transmission protocols were identified as applicable solutions for the purpose of DTS. These were the Transmission Control Protocol (TCP), User Datagram Protocol (UDP) and EtherCAT. Of all the network specification, the transport layer was identified as the most influential towards the management of communicated data. The three protocols varied by:

- UDP's reliance on a single trip of data transmission to minimise overall latency. Without recognition of the recipient in this protocol, the network exposes itself to data loss or receipt of the data out of order [150].

- TCP requires a message receipt before sending a new data packet. This ensures that data is sent and received in order (structured), but requires a sequenced two-way transmission of data between nodes for each message [151].

- EtherCAT a UDP subset, uses single trip data in a master/slave ring-format to send data in a structured form for RT purposes. The ring-format enables the master a data verification capability, and avoids data collisions of a shared network bus [152].

Critically, other forms of sub-set Ethernet networks designed for RT were considered, but were ultimately disregarded in the analysis for an appropriate communication network the due to inherent limitations. Application of Voice-Over-Internet Protocol have demonstrated the ability to provide RT communication of data between multiple nodes [153]. This form of Ethernet data transmission was deemed irrelevant due to unclear integration to DTSs and inconsistencies in low-latency data transmission.

5.3.2 Real-Time Control

The requirement for concurrent operation of test resources and communication networks necessitated the need for a RT system. To handle this operation, a RT Operating System (RTOS) would dictate joint sub-system sampling, transmission and interaction of data at uniform discrete intervals. By doing so, concurrent coordination of subsystems could be attempted with a unified time reference shared across all nodes.

Real-Time Tolerances

The RTOS execution and responses as a collective need to be aligned with the intended operation requirements to ensure that the system is constrained correctly, while maintaining all elements are operated safely. RT tolerances in reference to the way that handle failures can be categorised into [154]:

- Soft - Loss in quality of service(QoS).

- Firm - Limited Error Tolerance.

- Hard - Total failure of the system.

The collective design of synchronise DTSs for automotive application transcends all three of these recognised tolerance classification, with non-critical sub-system signals and nodes being serviceable by soft or firm tolerances as determined by their impact to accurate representation of a non-distributed vehicle, while signals relevant to test resource safety would need to be facilitated by Hard RT.

Real-Time Process Scheduling

Likewise, the scheduling of processes need to be effectively managed for optimal operation of the RT system. Within each time-step, tasks of sampling, transmitting, and execution of received data takes place. This in turn requires strategic planning of what tasks occur when within each time-step [155]. Optimal design of these processes are necessary to reduce the overall time-step duration for improved system resolution, but also error and failure tolerances. In addition, with the potential of multiple nodes interacting with each other, effective management of tasks within the time-step need to account for added time to process the data from other nodes.

Tasking

RT systems can utilise multi-tasking to process tasks that are required to be run in parallel for time-sensitive applications. Multi-tasking systems typically divide up the available time frame and allocate the parts of several tasks to be executed, allowing multiple tasks to be executed in a near-continuous state. This allows a form of pseudo-multitasking to be carried on a single processor. RT systems typically have in-built schedulers and interrupt handlers (as in the case of the NI Veristand equipment used) that ensure prioritised tasks (a task with higher tolerances) are executed as soon as possible.

5.3.3 Application

DTSs

The application of DTS has been explored for driver-in-the-loop applications. A study conducted between the University of Michigan and Tank Automotive Research, Development and Engineering centre (TARDEC) demonstrated the practical application

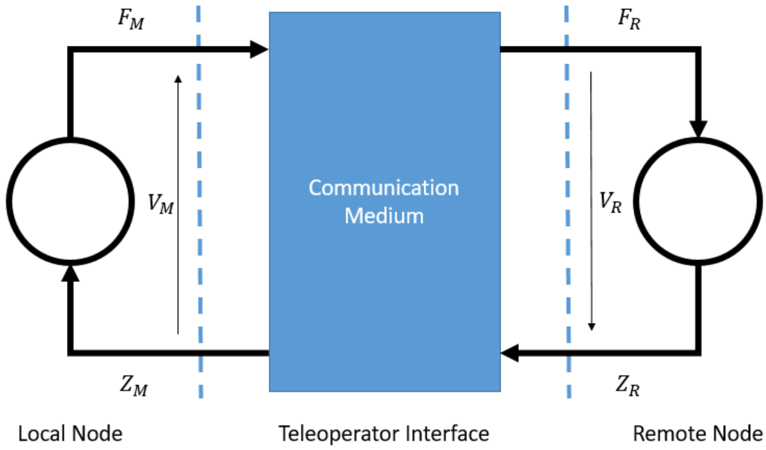


FIGURE 5.1: Illustration of the transparency concept.

with one node containing a driver simulator, and a second holding a diesel combustion engine attached to a dynamometer. The study proved the use of haptic control between nodes over a communication network, in addition to exploring the effect of network latency in the form of a figurative transparency concept (Figure. 5.1)[127, 128, 129, 130]. This research was highly relevant to the theme as it recognised the application of DTSs, their use in a haptic test case, and the significance of system behaviour. However, the TARDEC DTS application had differing requirements than those of the proposed application within this study. Here it was implemented to demonstrate the functionality of haptic control of test resources with significance to human control and perception of the test environment. The requirements for haptic control vary from those of coordinated testing of physical resources, which could necessitate sampling and control resolutions higher than that of human perception.

Tele-operated Systems

Tele-operated systems offered insight into the external application of distributed technologies that were of significance to the development of this systems. Case studies have applied distributed technologies in both the aerospace and medical fields in examples such as satellite orbital control and remote medical operations [156, 157, 158]. Both cases showed the relevance of detailed consideration to ensure stimuli and feedback met product requirements, and selection of appropriate communication networks.

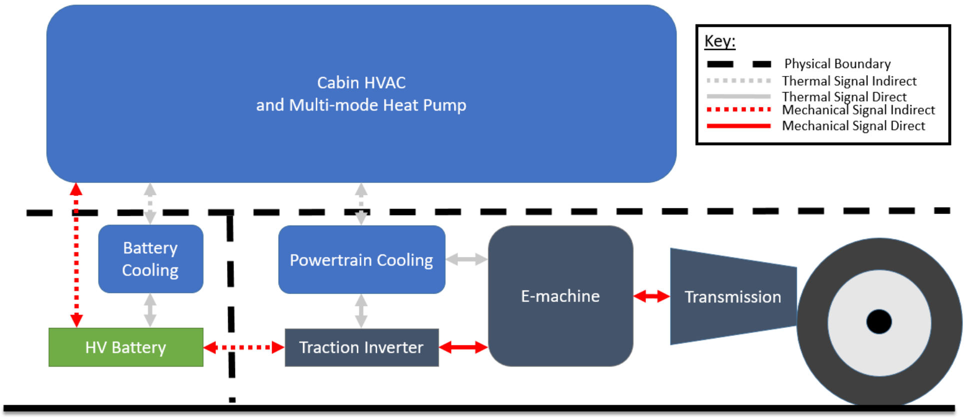


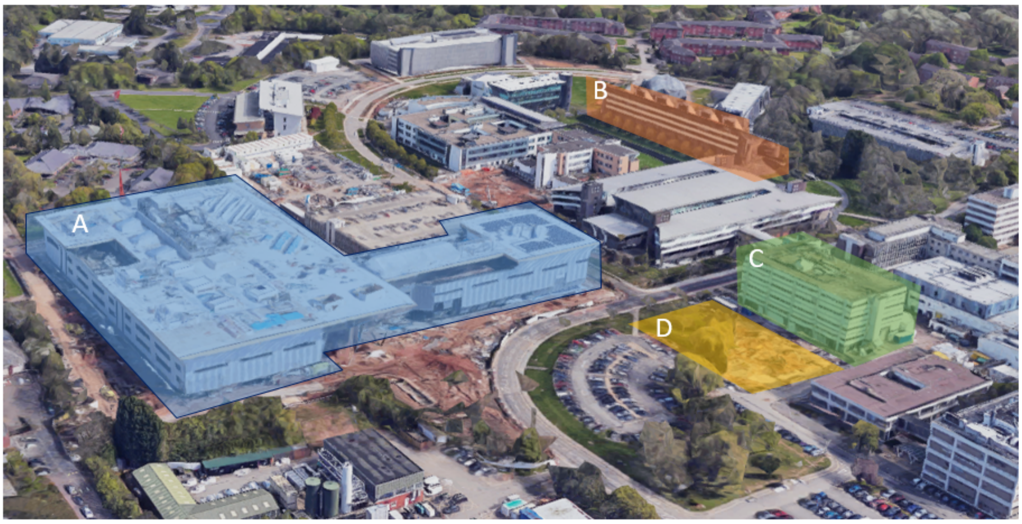
FIGURE 5.2: Segmentation layout of a state of the art EV.

Knowledge derived from this technology stream can be utilised in the design and implementation of distributed test technologies. Signals communicated in real-time can be classified as for compliance (no feedback) or bilateral (feedback) control purposes. Studies have raised the awareness of latency and packet drop as qualities when designing such a system for bilateral control. Poor network qualities such as those mentioned could result in loss of control of the system or destabilisation [159, 160]. Unlike existing research on this topic, this study looks to investigate the impact of a voltage-current feedback structure instead of the commonly adopted position-position or position-force architectures used.

5.4 System Development

5.4.1 Overall Layout

Firstly, an overall physical layout of EV hardware and test resources was determined to aid in the conceptualisation of the system. For a state-of-the-art electric vehicle, this segmentation was made between the energy storage (battery), the tractive components and thermal management system (Figure. 5.2). This specific segmentation was pursued as it strategically split the complete system at subsystem boundaries to maximise stability of connected nodes, while also taking into account the current capability of test resources.



Key	Building	Proposed Function
A	National Automotive Innovation Centre	Chassis/Hub dynamometers and HVAC Thermal Chamber
B	International Digital Laboratory	Simulation Suite
C	Energy Innovation Centre	Battery cell cyclers, Simulation Suite and Hub dynamometers
D	Energy Innovation Centre extension	Battery pack cycler

FIGURE 5.3: Geographical layout of test facilities on campus.

5.4.2 Network

A suitable Ethernet network was created to enable the connectivity of synchronous DTS nodes. The locations of the test resources resulted in the application of a ring-fenced Virtual LAN (VLAN) to connect the test resources located across various campus-wide buildings (Figure. 5.3-5.4). This network solution was chosen as it provided an Ethernet LAN solution emulated over existing Ethernet network hardware of routers and switches. Furthermore, the ring-fenced feature isolated the network from general network traffic across the university network, thus limiting the influence of external network traffic, but also providing a barrier to external intrusion of the network.

5.4.3 Test Resource Interface

Test resources would be interfaced to the network using HIL hardware to handle the instrumentation and control of test models and apparatus. Analogue, digital and common device buses (CAN/LIN/Flex-ray) from the test resource could be directly mapped to HIL hardware (dSpace Scalexio/ MicroAutoBox) connected by synchronous DTS network (Figure. 5.5). This allowed signal route specification for data

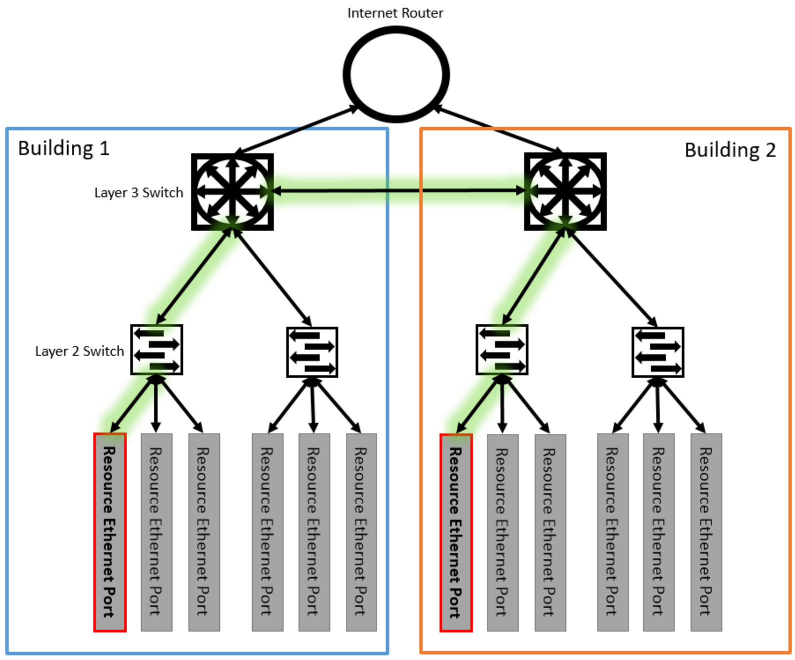


FIGURE 5.4: Physical layout of the network hardware across the campus network infrastructure.

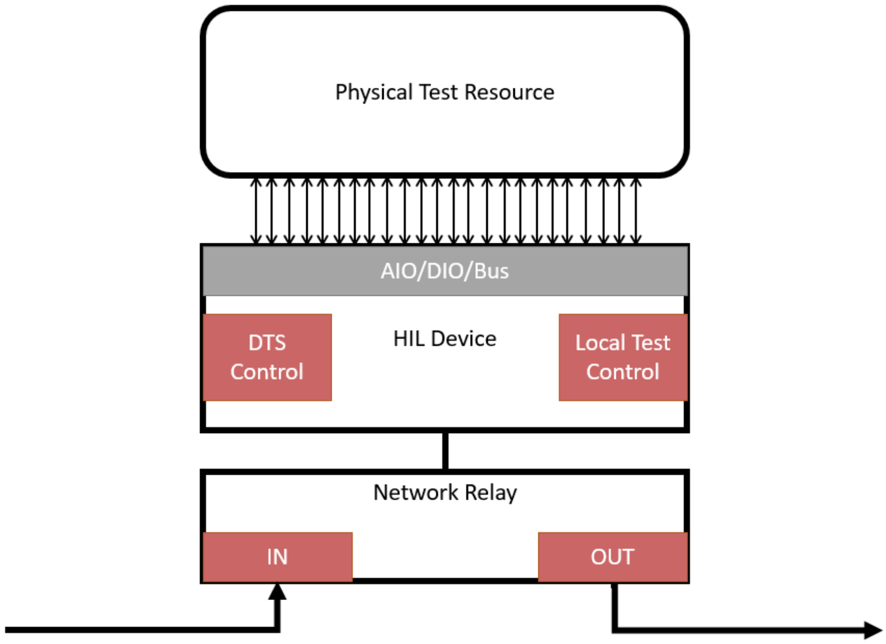


FIGURE 5.5: Node system layout as part of DTS.

by required nodes through a real-time system that additionally had the ability to host automated local control of the test and safety system(as demonstrated in *Chapter 4*).

Virtual Interface

The use of the selected test resource hardware would also allow the integration of virtual components and subsystems to be used within the synchronous DTS. Matlab and Simulink models could be interfaced to the dSpace hardware as MIL platforms alongside the DTS local control structure. The use of widely used virtual modelling tools allow the inclusion of early development components where physical models are unavailable.

5.4.4 Control System

Test Control

A control system was conceptualised to reflect the capability of the underlying DTS infrastructure, the proposed test system, and operational requirement of the test resources. A Master-slave structure was devised where one node would drive the overall test and connected nodes would listen and respond to the master node (Figure. 5.6). The master node was chosen based on the subsystem's ability to provide overall control and potential sensitivity to time-variation imposed in its control feedback loop. Thus, the powertrain was selected as the master node as its drive control was most critical to test driver inputs and implication of delays affecting the safety system.

Safety Control

Safety control of test resources was designed to be hosted locally, and its status to be communicated to all other nodes to ensure appropriate actions could be undertaken by the whole system. This structure mandated that immediate control was available to local automated test resources and users best positioned to govern as well as respond to test safety requirements, while any failures at other rigs or the communication network would be detected and independently handled to bring the distanced test resources to a safe state (Figure. 5.7). This layout was chosen as it ensured that failures across the DTS could be reacted to immediately at the local level, and not create or amplify risks at remote nodes.

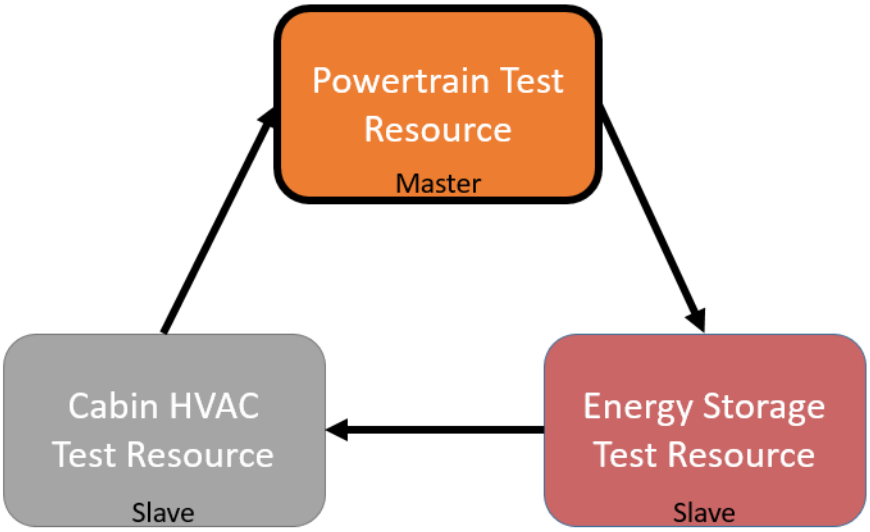


FIGURE 5.6: Figurative ring network emulated by the VLAN, with master-slave designations.

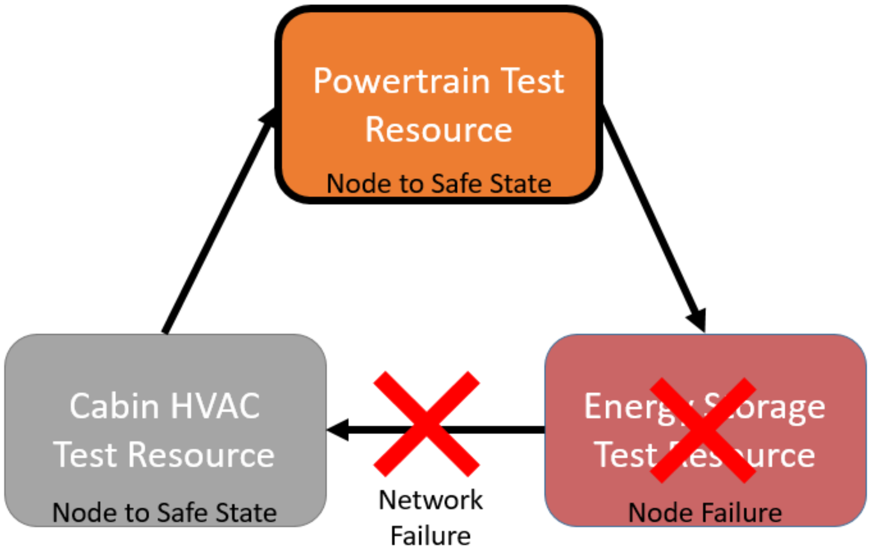


FIGURE 5.7: Failures at any point in the network or nodes would trigger local test controls to bring the test resources to a safe state.

5.5 Evaluation

5.5.1 Network Tests

To explore the functionality of the network proposed as part of the synchronous DTS solution, a latency test was conducted. The test was designed to experimentally capture the time of flight of the data packet between test nodes across the VLAN network set-up. Acquisition of the packet time of flight between the two nodes would help to estimate the performance of the system across various network configurations and provide tolerances for RT frequencies.

Test Objectives

The main priority of this test was to establish key characteristics and behaviours of the network that could affect the performance of DTS. The test had to:

- Provide a value for node-to-node latency
- Identify any inter-daily variations that could adversely affect DTS performance.
- Identify any intra-daily variations that could adversely affect DTS performance.

Test Layout

The test was set-up between two nodes designed into the VLAN to measure its performance. A data packet of 16 bytes was timed as it took a return trip from one node to another. The test was established in this format as it created a representative estimation of the data transmission between nodes to determine its time of flight at an absolute singular point.

Test Properties

The network test was conducted for a week to capture latency data. A ping per second was transmitted at a constant rate to the target node; once the data arrived back it was recorded. The test was conducted during a generic university term week, as it would best reflect the nominal load of the campus network in the case that the external network affected the DTS performance.

Results

Network latency results from an overall perspective established that the VLAN was a suitable communication platform for synchronous DTS applications. The results indicated that a single trip average latency of 0.18-0.19 milliseconds could be expected with an average of 22.75 packets dropped per day, while peaks of 0.22 milliseconds are an infrequent occurrence at midnight (Figure 5.9). With reference to the RT function, the network operating at its current latency would effectively transmit data at 5.2kHz and could adequately represent signals that operate at <2.6KHz in accordance to Nyquist sampling theorem. In respect to battery electric vehicles, this would provide sufficient sampling capability for signals representing the majority of components and systems used, except for CAN baud rates, high frequency AC waveforms, Inverter switching events and electric machine rotor positions through encoders/resolvers (Figure. 5.8) [161, 162, 163, 164, 165, 166, 167].

Notably, the results of this test influence the output of closed-loop distributed control systems. Feedback error used in a closed-loop system with a time delay between the controller and plant would result in actions by the controller being out of sync with the state of the plant. As a result, the system could lose stability and lead to inaccurate behaviour of the vehicle model.

In addition, open-loop systems are susceptible to delays. An open-loop distributed system would be more tolerant towards node to node delays but could be impacted by fluctuating delays. Fluctuating delays could lead to inconsistently receiving actions, which could affect the outputs monitored at each distributed node. Corrective measures could be implemented by introducing data buffers to ensure received data (with a time-stamp) are released consistently to the test equipment at each node.

However, some anomalies were recognised from the latency data capture. A simple moving average of the results with a ten minute period revealed that the network behaved adversely within the first hour of the day, and again roughly around midday (Figure 5.9). To determine if this occurrence was a regular event of the network, a statistical analysis was required to evaluate the results.

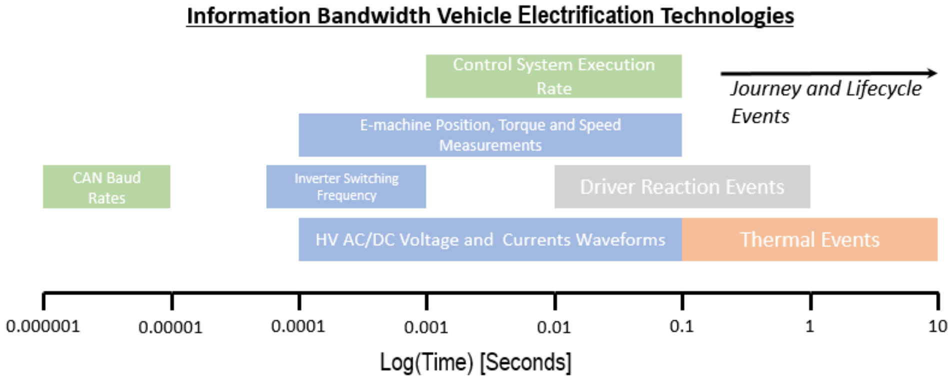


FIGURE 5.8: Information bandwidth of signals across BEVs.

Source of Variation	*SS*	*df*	*MS*	F	P-value	F-crit
Days	0.0220	6	0.00366	1462.689	0	2.117
Time	0.000133	83	1.6E-6	0.639	0.994	1.299
Error	0.00125	498	2.5E-6			
Total	0.0233	587				

TABLE 5.2: Two-Way ANOVA Test of network latency.

Statistical Analysis

A statistical analysis of the network behaviour confirmed daily performance was significantly regular. A two-way Analysis of Variance (ANOVA) test confirmed that the network operated with the smallest latency between 6am and 12pm, and operated at a higher latency during late periods of the day with strong confidence. Henceforth, operation of the DTS would be best advised between the morning period if high network tolerances were necessary (Table. 5.2)(Figure. 5.10). However, the overall performance gain would be minimal (0.1kHz benefit in sampling frequency) in reference to the scale of system operation and the small variance in performance between the two distinguished periods (Figure. 5.11).

In contrast, performance between daily variations was not distinguishable within the available data. The ANOVA test suggested that the daily results were similar to each other, but I could not statistically prove this outcome (Table. 5.2). Extended periods of testing would likely be needed to verify this network occurrence, though it should be noted that to do so would need re-development of the experimental apparatus and methods to appropriately handle the proposed volume of data that would be collected over the suggested test period.

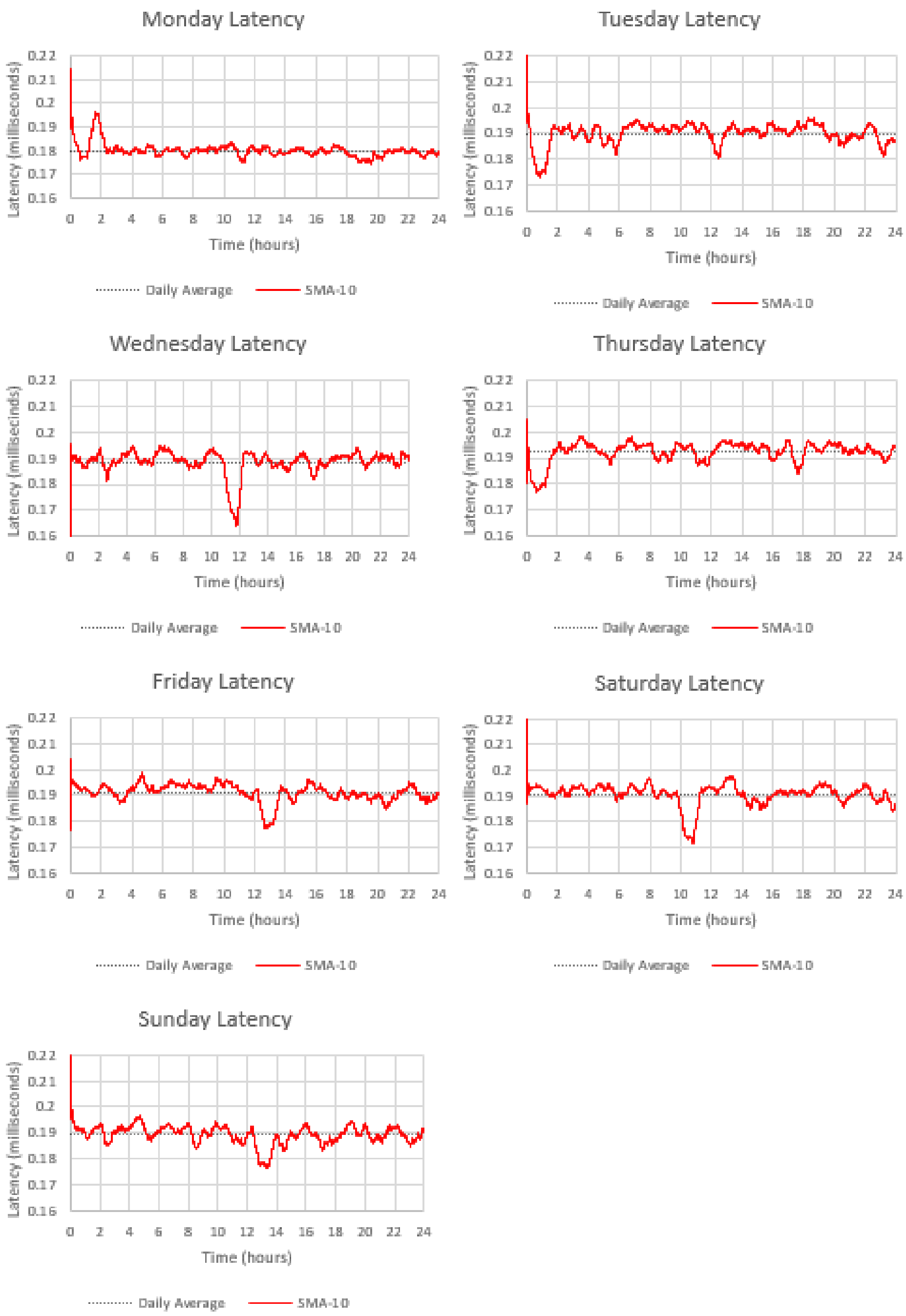


FIGURE 5.9: Results obtained from the network latency test.

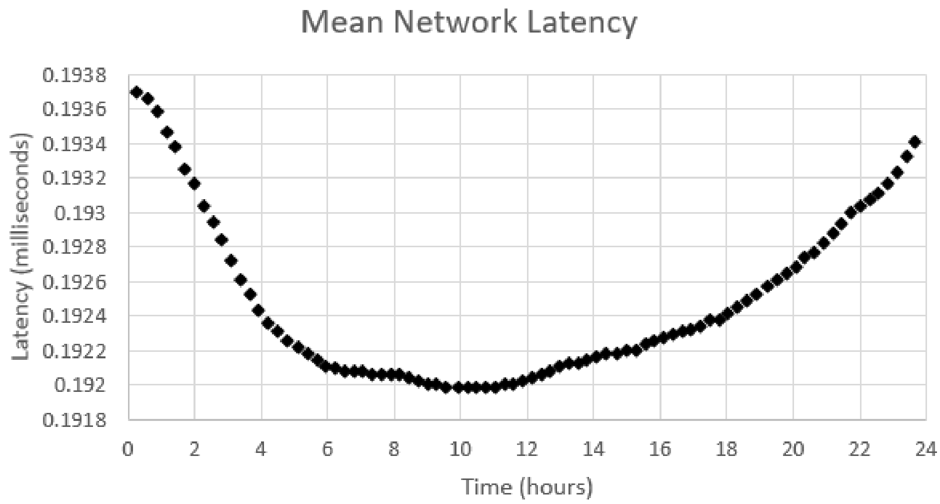


FIGURE 5.10: Daily mean of latency produced as part of the two-way ANOVA between DTS nodes.

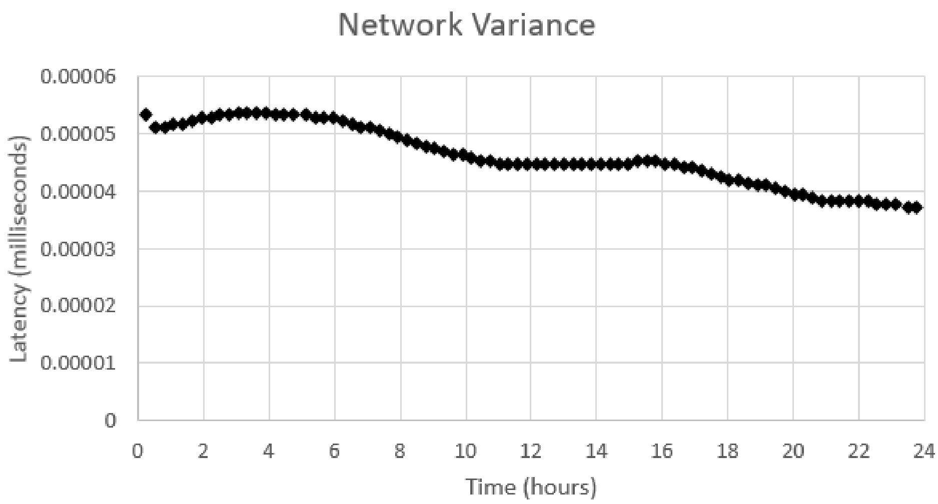


FIGURE 5.11: Daily variance of latency produced as part of the two-way ANOVA between DTS nodes.

Discussion

Ultimately, the investigation into the VLAN performance confirmed the suitability of this solution to provide node-to-node communication. The test results demonstrated that latency performance was sufficient and consistent enough to provide a representation of expected signals needed to simulate a complete electric vehicle segmented across a conceptualised synchronous DTS. Henceforth, the future development of this technology should be plausible with current network technology at a campus-wide scale.

The results produced by this network test can be utilised to estimate the latency expected of a multi-node DTS structure using a ring topology on a campus environment (under a single switch). Total latency is expected to be proportional to the number links between nodes (one link per node). Therefore a reasonable estimation of total latency for multi-node DTS systems can be made. This estimation method may not be as applicable for a DTS networks operating on a wider geographic scale, where data packet routes are not expected to take a similar route between test nodes.

However, the results do not certify the use of this network technology for systems of a larger scale than that tested in the current application or DTSs hosted locally on company sites. VLAN and Ethernet networks over a wider geographic scale would have larger latency characteristics from increased distances travelled by transmissions, the added hardware switching, and shared public bandwidth. Thus, the results produced with a campus VLAN inadequately represent application of this network solution for synchronous DTSs operated at or greater than a national scale. During the period of the network development, establishing a network between two geographic nodes was abandoned due to differing network security procedures between the stakeholders. Scaled DTSs would require collaboration between all stakeholders to ensure a standard of cyber-security is mutually applied.

5.5.2 System Tolerance Simulations

A simulation was created to investigate the impact of high latency networks on synchronous DTSs, where the network latency was higher than the sampling period (execution rate) of the system. The simulation emulated the network latency between a

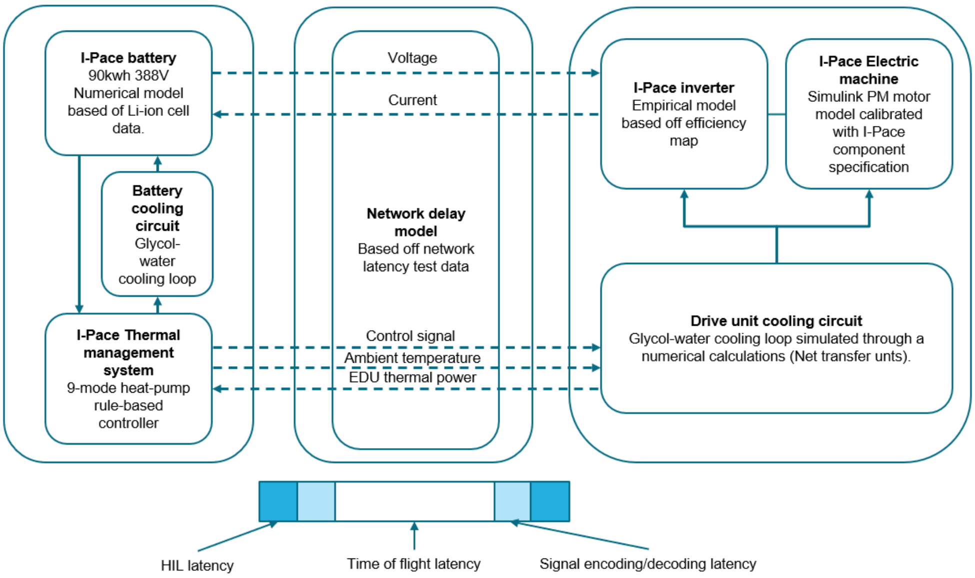


FIGURE 5.12: Layout of network latency impact simulation.

two node DTS representing a BEV architecture (Figure. 5.12). This study was carried out to evaluate the plausibility and QoS of using large scale Ethernet networks that would have higher latencies.

It was hypothesised that systems related to the high voltage bus would be the most sensitive bilateral signal to be affected by latency. Of all the transmitted signals, the vehicle's voltage and current were identified as system properties that had time dependent sensitivities between the battery and powertrain. The closed loop between each of these linked signals and their respective nodes would mean signal delays could have a propagating effect on error and therefore accuracy of the model. Henceforth, the increased latency between the powertrain (inverter and electric machine) and the battery node would likely highlight and uncover any issues that may hinder using DTSs towards energy consumption testing.

Simulation Design

A numerical Simulink model was created to emulate key components of an EV and the network behaviour. The simulation segmented empirical models of a Jaguar I-Pace with the battery and thermal controller in one section, a second section contained the electric machine and inverter, and a third section contained the network delay emulator (Figure. 5.13). These models were built from and calibrated using component data acquired from Jaguar Land Rover's internal virtual model of the I-Pace used for

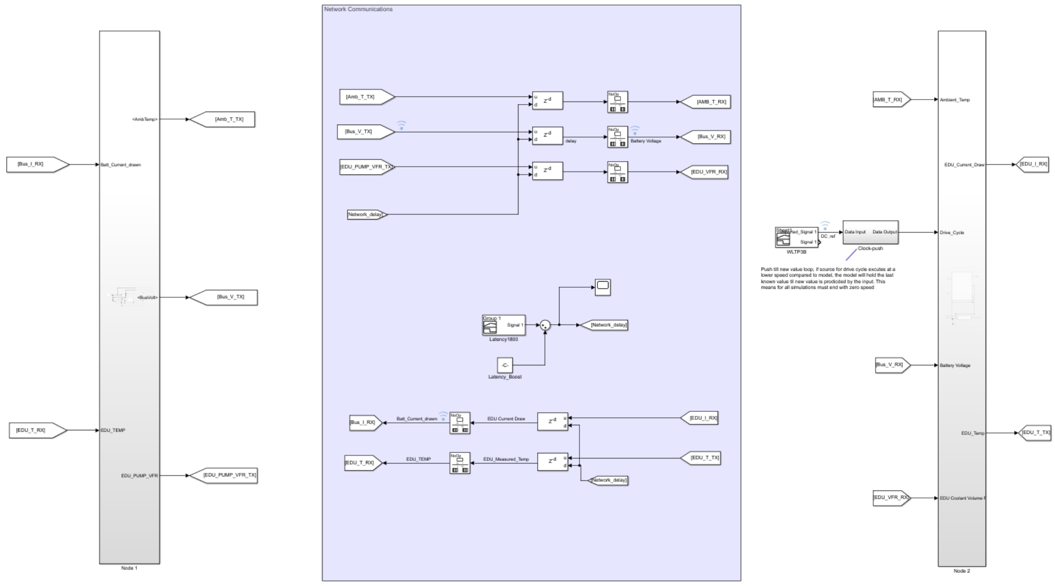


FIGURE 5.13: Simulink model used to evaluate network latency impact upon DTS.

the vehicles development. This overall solution was used due to limited availability of physical test resources, as well as execution through virtual methods allowed greater flexibility to control and modify component/subsystem (including network) parameters used as part of this study.

The simulation developed would use the latency data acquired through the network tests to represent the DTS latencies expected. Delay blocks linked with data acquired from the network emulated network delay between components. This methodology ensured that latency produced from encoding/decoding signals would be included alongside flight delay time. Alternative methodologies such as using Simulink's network toolbox would provide additional capability to modify characteristics of the delay, but this would need additional network tests and calibration of the network model to be entirely representative of the network.

Test Methodology

The DTS I-Pace underwent a WLTP 3b drive cycle as a representation of what would be expected in a physical example of a simple DTS. The DTS model was tested under different latency values and execution rates in a structured EtherCAT protocol configuration that provided insight into its potential performance across varying geographic scales (Figure. 5.14). In addition, the execution/sampling rate of the discrete

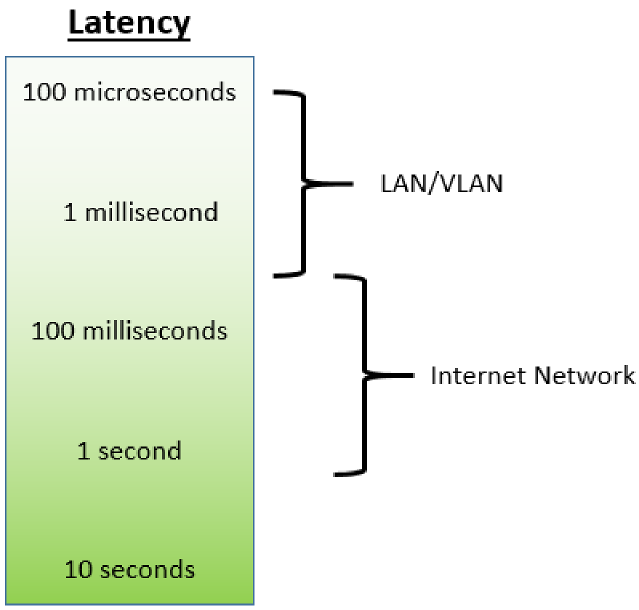


FIGURE 5.14: Latency Bandwidth evaluated and their respective operation cases.

HIL RT communication was also varied. Execution rates of 100Hz, 1kHz and 10kHz were chosen as they reflected sampling rates typically used to instrument continuous systems in automotive testing. A fixed time-step continuous solver (Runge-Kutta 4th order) was used to minimise simulation error as a result of time-step limitations and account for both continuous and discrete behaviour across the model. This solver minimises truncation errors compared to other methods available when larger time-steps are used. The simulation's time-step was set to a tenth of network delay to reduce aliasing. At smaller execution rates this was not possible, the Runge-Kutta method would likely perform better than Euler methods under these conditions.

Results

The results produced from the DTS simulation showed minimal error impact on the vehicle performance as a result of network's latency and system execution rate (See Appendix B, Table. B.1). Differences in energy consumption were noted though (Figure. 5.15-5.16). The deviation experienced by distributed system increased with latency through driven portions of the drive cycle. As the DTS execution rate increased (1kHz and 10kHz), the simulation suggested that the system would begin to overestimate energy consumption. The scales that the error is interpreted in, depict that deviation in energy consumption influenced by the DTS system would be masked by other forms of noise in the physical test environment. Henceforth, it is possible to propose that implementation of a physical DTS should not disadvantage manufacturers in evaluating system energy consumption and efficiency as a substitute of prototype testing.

The influence of latency and DTS execution rate was evaluated further through the average absolute error found across the voltage and current signals. The precise relationship of error through latency can be seen as a linear relationship (Figure. 5.18 & 5.19). The rate at which this error grows is related to the DTS execution rate. A slower execution rate results in a greater exposure to error in proportion to latency. It should also be noted that the magnitude of this error could be accounted for in physical examples. Through appropriate instrumentation methods, this error could be sampled to evaluate the validity of this simulation study on physical implementation of a synchronous DTSs.

Importantly, the SOC, voltage and current error results suggest that the execution rate has a significant affect on the accuracy of the DTS. As the system uses a greater execution rate, the scale of error reduces proportionally. With reference to concepts put forward by Zhang et al [159],the simulation suggest that perception between the test nodes is raised as a result of the execution rate adopted. In practical implementation for electrical vehicle energy auditing through DTS, this would result in the aims to operate the DTS at the highest execution rate possible to minimise test error.

The simulation setup may limit the accuracy of evaluating some aspects of the vehicle model. The simulation used a fixed time-step continuous solver that could compromise model accuracy to maintain suitable computational demands. Model events operating at a similar or higher frequency to the period of the simulation time-step could experience aliasing. Models emulating elements such as switching wave-forms between the electric machine and inverters, DC ripple currents, high transmission rate signals such as CAN buses and even detailed emulation of network data handling could be affected. Variable time-step solvers could alleviate this but increase computational demands to improve the modelling of highly transient models or signals approaching zeros.

Tabulated data can be seen in APPENDIX B

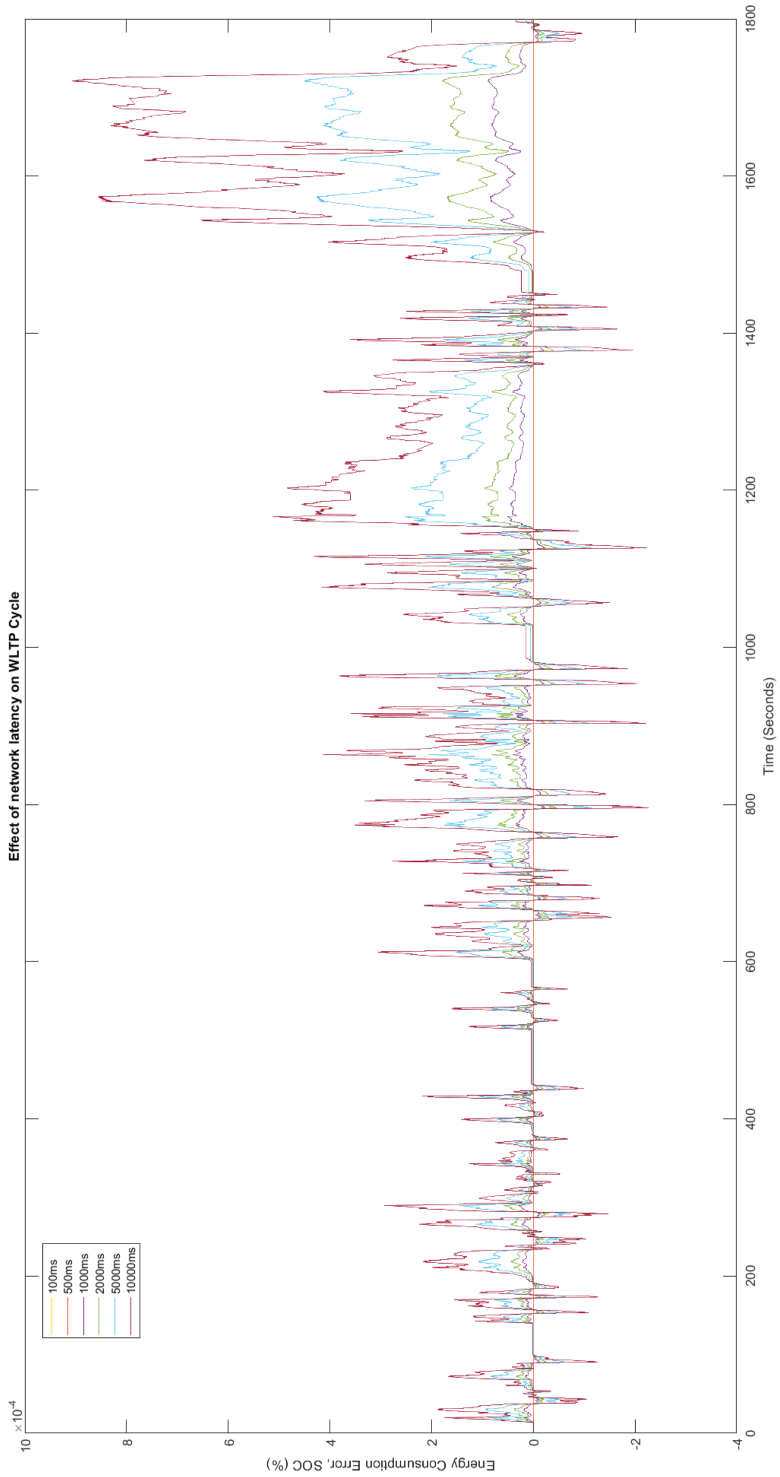


FIGURE 5.15: Energy consumption error as a result of latency on a 100Hz DTS.

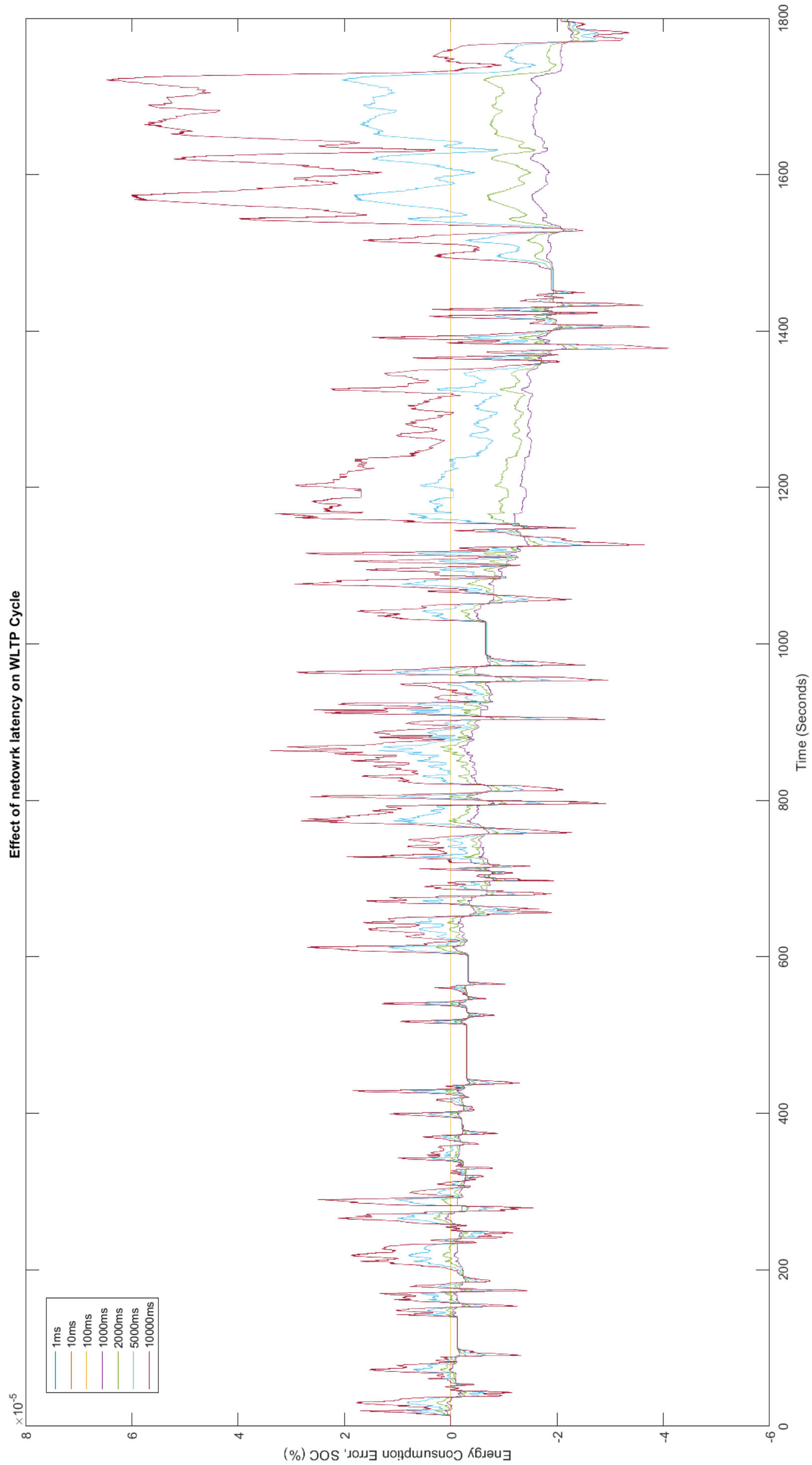


FIGURE 5.16: Energy consumption error as a result of latency on a 1kHz DTS.

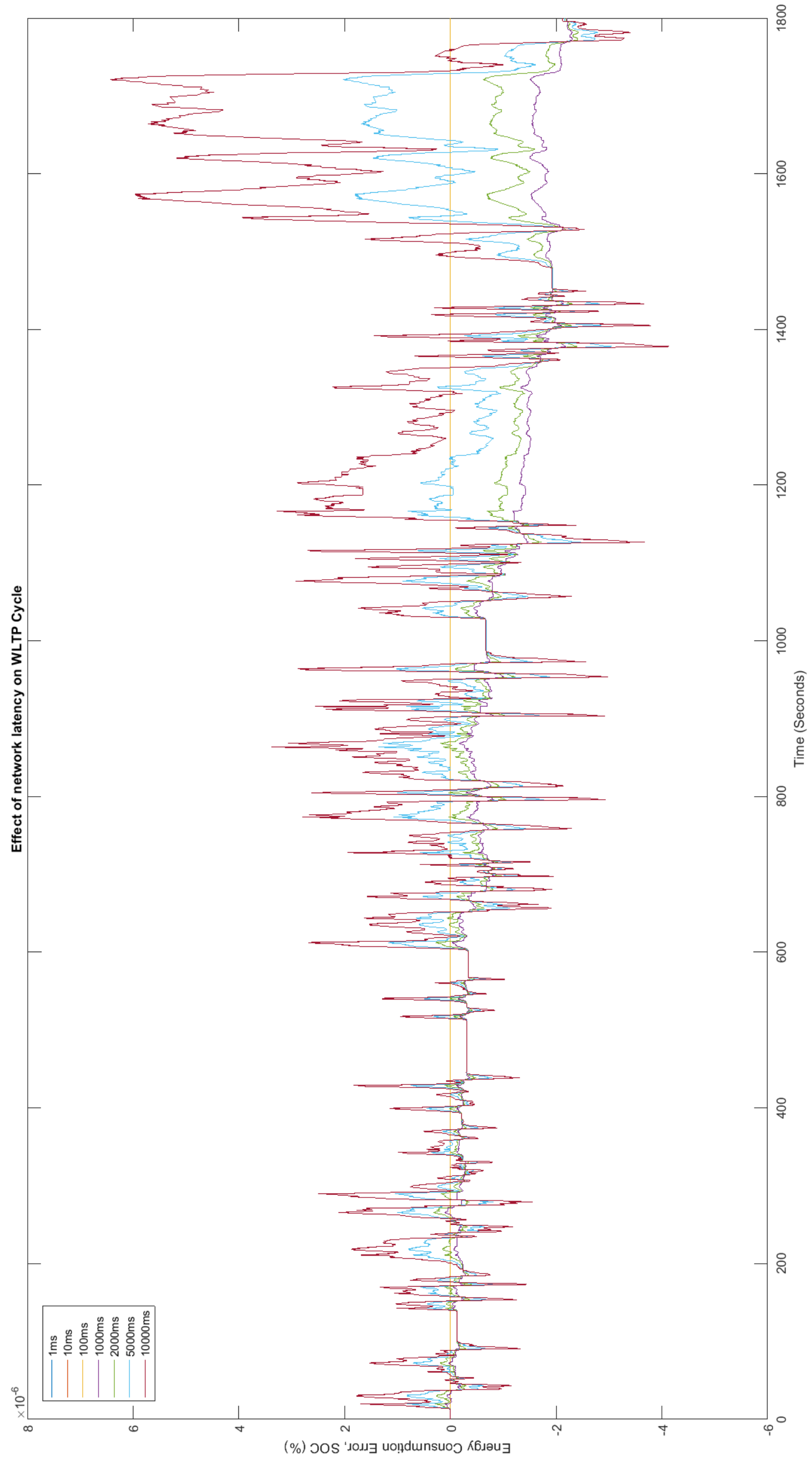


FIGURE 5.17: Energy consumption error as a result of latency on a 10kHz DTS.

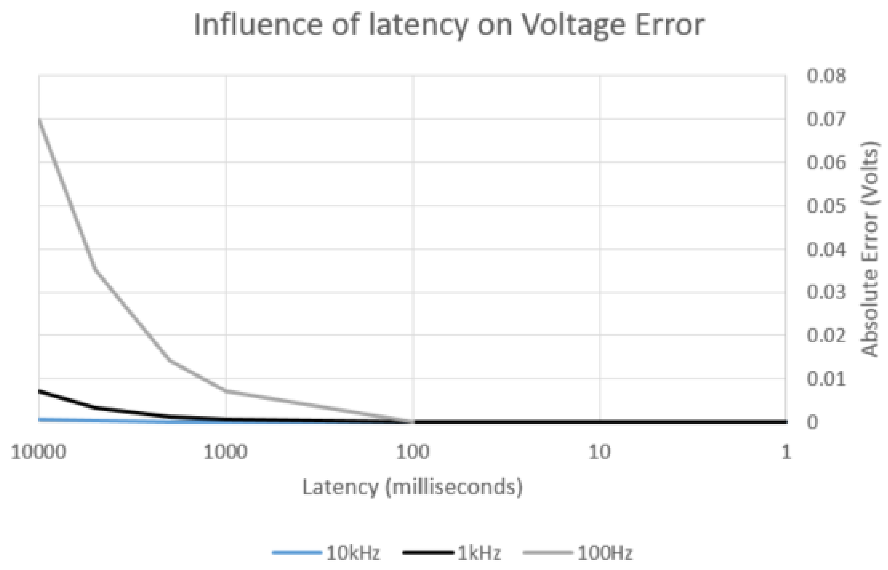


FIGURE 5.18: Average absolute voltage error observed changes in latency and execution rate.

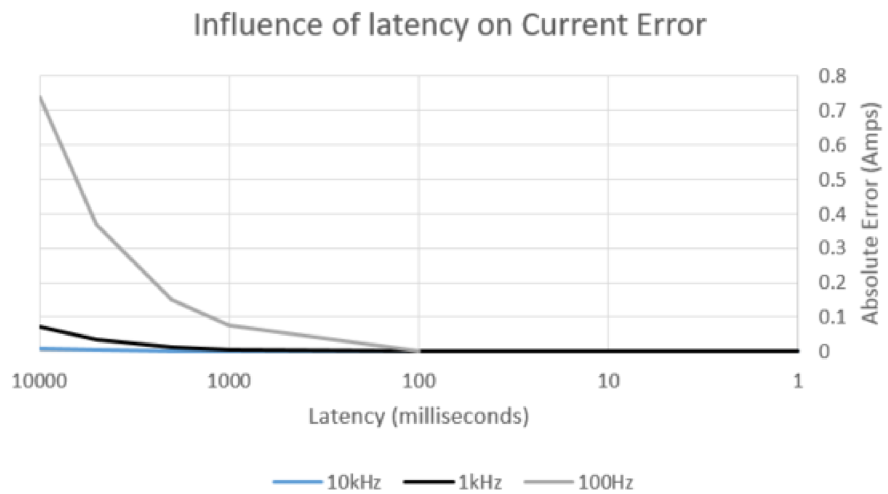


FIGURE 5.19: Average absolute current error observed changes in latency and execution rate.

Bandwidth	10Hz	100 Hz	1kHz	10 kHz	100kHz
1 Gbit/s	12.5 Mbytes	1.2 Mbytes	125 Kbytes	12.5 Kbytes	1.2 Kbytes
100 Mbit/s	1.2Mbytes	125 Kbytes	12.5 Kbytes	1.2 Kbytes	125 bytes
10 Mbit/s	125 Kbytes	12.5 Kbytes	1.2 Kbytes	125 bytes	12.5 bytes

TABLE 5.3: Maximum size of data packets possible per execution step with reference to network bandwidth and execution rate of the DTS.

Discussion

The virtual simulation of the synchronous DTS provided a quick and effective way to estimate the influence of design choices and operating conditions. The design of the virtual model could be quickly modified to alter component attributes and test system parameters to determine the suitability of intended layouts. The virtual model as a tool provided a low cost step to understand the sensitivity of powertrain splitting across DTS layout.

A balance must be struck between the optimal execution rate of the DTS, network bandwidth and the volume of data sent per step. A calculation between the maximum bandwidth and execution rate demonstrates that at a higher execution rates there is a finite limit to how much data (bytes) can be sent per step (Table.5.3). As the execution rate frequency increases, more bandwidth is consumed, thus placing a limit on the transmittable data packet's size. Henceforth, in the application of this study's private VLAN for the campus DTS, the designed system could theoretically operate at 100kHz, however considerations must be made on the limitations of the HIL interface hardware and the sampling rate of the instrumentation techniques used on the continuous physical system. For DTSs operating over a shared network, the execution rate would need to be reduced further, limiting the exact volume of bytes per step.

Importantly, adopters of DTS can estimate the minimum execution rate by calculating the type of size of data packets. For example, the simulated system had five signals to communicate, which would amount to 40 bytes of raw data (using double floating-point precision). DTSs operating with reduced bandwidths would be limited to execution rates <10kHz when coupled with additional control/communication signals (similar data packet structure to CAN protocols would mean another 8 bytes).

Real-world applications of DTSs could use more signals between test nodes adding further limitations. The increased number of signals would scale up the size of a typical data packet being sent over the test network. As a result, signal intensive applications could face further restrictions concerning the test execution rate available.

Error estimated by these simulations only attests to the current DTS layout and its selected components. Simulations were conducted with a BEV architecture with specified component sizes to the test subject vehicle. Different component sizes and the addition of other test nodes could change the stability of the DTS system as the magnitude of responses from nodes and their corresponding signals changes. Thus, modification to initial conditions, battery pack sizes and EDU energy consumption are likely to alter the sensitivity of the system and tolerances of DTS.

Realistically, the application of DTS at a national scale would be susceptible to additional variation in network latency as well as bandwidth. Without the implementation of an isolated Ethernet network for large-scale use, shared network resources (open access internet) would result in interactions with data traffic of public network use. This occurrence and its interaction with network properties would result in data being sent over across multiple steps, increasing the latency experienced during increased traffic periods. Additional measures such as signal correction systems could be applied to ensure stability of highly sensitive DTS applications [168].

In addition, a national scaled DTS with noticeable latency would be restricted by safety considerations. As noted from Chapter 5.4.4, poor performing networks would ultimately increase the risk to physical test systems as safety responses could also be delayed in line with the network latency. This state would be extremely dangerous and would therefore discourage the use of the synchronous DTS system in this configuration.

The outcomes of this study partially resolve issues and recommendations highlighted by previous studies into internet distributed HIL solutions. The recognition and conceptualisation of the EtherCat protocol suite in this study addresses recommendations by Schreiber et al to develop alternate UDP network structures to improve robustness of DTS networks, while development of a simulation tool aligns with Ersal et al's vision to evaluate the stability of test cases before physical implementation [131, 128]. A set of limitations and recommendations were also created from the experience of this study in developing synchronous DTSs for vehicle electrification testing.

Limitations and recommendations

The current simulation tools suggest that that networks operating at a mean latency <1000ms result in no observable error. Observations from the UM-TARDEC investigation would contradict this. Thus, it is recommended that further research is undertaken to determine their influence on the virtual model at lower latencies, or initial physical implementation a local DTS should investigate this property on BEV type architectures.

Currently, the model assumed a highly stable network structure. Unlike the sample taken from the campus DTS network, a higher variation in network latency and an increased occurrences of dropped packets should be taken into account for future versions of the model. Further investigations should look into accurately modelling these two network qualities for the virtual tool.

Finally, the virtual model after improvements in realistic network emulation should be used to investigate complex DTS layouts. The current model examines the performance of a two node DTS as was expected to be implemented on the campus at the University of Warwick. DTS technology has the potential to link other research institution, suppliers and manufacturers for the collaboration of developing new vehicle systems. It is important to understand the impact of DTSs with multiple nodes and segmentation of vehicle systems in different layouts.

5.5.3 Operational Impact

Deployment

Overall, the application of DTNs enables ESPs and OEMs to improve integration with other developing partners and the vertical supply chain. DTNs would allow product and research providers external to manufacturers to gain opportunities to cooperate with end-users and access direct feedback to develop their components/systems. This benefits stakeholders across the development chain as development issues can be identified earlier while also strengthening relationships.

However, DTNs could also face some barriers to adoption by potential stakeholders. ESPs and OEMs could also resist adopting DTNs to limit intellectual property

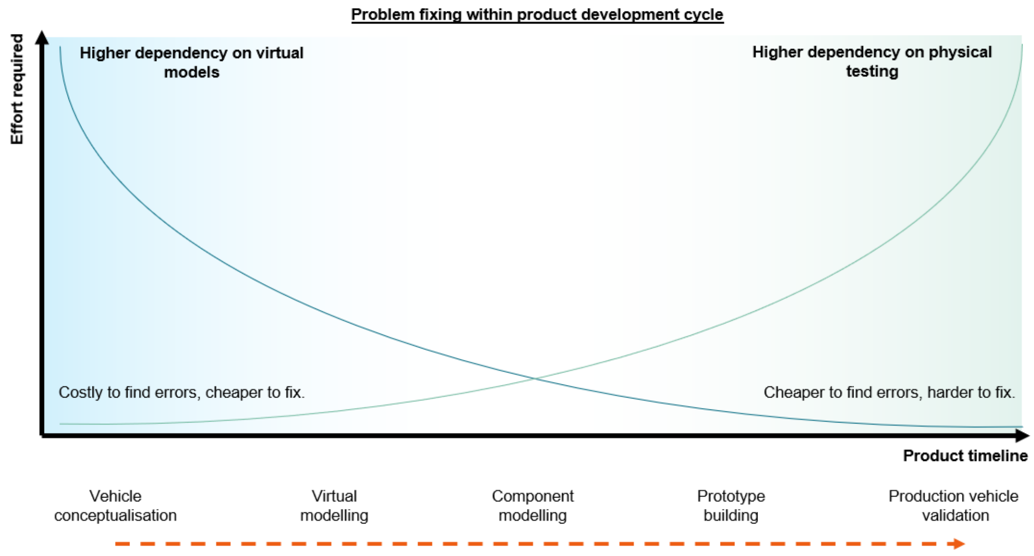


FIGURE 5.20: Perception of product error held within JLR.

exposures to competitors, avoid added effort needed to set up and maintain large partnerships, avoid assimilation by other stakeholders, or prevent restricting themselves to single customers. Implementing DTNs and their roll-out to these stakeholders also needs careful consideration to ensure that agreements are set to mitigate perceived risks.

Quality

Synchronous DTSs provide a platform to improve the quality of system integration, validation and testing. By providing a low-cost alternative to complete physical system builds, errors can be found through DTS at a much earlier development stage than would generally be possible, and can therefore be resolved at a lower cost. By using individually developed components and their respective test resources, issues identified through system functionality and performance tests can be resolved earlier in the product development process where costs associated with changes made to designs are reduced (Figure. 5.20) [169]. Errors found at the fully physically integrated stage of system development are relatively more costly to fix due to the necessary re-production or modification of unique high value parts.

Impact on Development Cost

The largest organisational benefits of adopting a synchronous DTS would be the reduced dependency on physical prototype vehicles. Prototype vehicles are a necessary part of the automotive development process to demonstrate and validate system designs. However, these test assets are sourced at a high cost and cumulatively for a single model programme up to 100 test vehicles may exist until the vehicle goes into mainstream production [170]. Representatives from JLR have claimed that prototype vehicles can vary in cost from £0.5-1m, with heavily modified current/previous generation vehicles representing lower estimates, while engineering and production prototypes produced in lower volumes have higher costs due to bespoke parts and tooling. The high costs for these assets are mainly due to the low production numbers and uncommonness of specific vehicle parts. The use of a synchronous DTS could reduce the need for early prototype vehicles used to test the functionality of EV and hybrid powertrains. With an equivalent transition of all current combustion vehicles (13 JLR models) to electric or hybrid architectures, an estimated cost of £650-£1,300 million will be spent on prototypes by 2030 using traditional methods. Assuming synchronous DTSs supplement early prototypes (10%) this would deliver an investment saving of £13 million a year in R&D spending (3% of overall R&D spending 2020) [171].

Organisational

The applicability of synchronous DTSs needs to also consider the scarcity and availability of test resources. The examined DTS principle relies on the use of existent component test resources to supplement large flexible test facilities and prototypes. This concept heavily relies on the assumption that these component test resources have the existing capacity to undertake this additional operational load, but also coordinate such activities with other component test resources. Thus manufacturers, OEMs, and ESPs with limited capacity would need to optimise operational efficiency of component test resources or invest to expand capacity.

Chapter 6

Process Level Case Study

Following the automation and coordination model outlined in Figure. 3.2, the application of these themes were considered from a holistic perspective of the testing process. This case study explored the integration of a centralised management system to remedy deficiencies of the operational processes that lengthen project duration, increase research costs and risk timely completion of the product. The application of these themes in the automotive framework provides a wider perspective to source valuable information and utilise them to optimise quality and productivity within the business.

Specifically, within this portion of the study the application of the asynchronous distributed system was focused towards optimisation of test-bed resources located throughout an automotive organisation. The system was designed to enhance productivity and increase testing and development throughput to minimise/avoid the additional costs of investing/leasing alternative facilities that increase product overheads. Physical test resources remain to be a high cost activity within R&D departments within automotive industry, with the conclusion drawn from this study's literature review around the expected increase in demand for physical test resource, opportunities to improve R&D overheads align with the objectives to improve feasibility and costs associated to vehicle electrification development.

6.1 Foundation

6.1.1 Asynchronous Distributed Test Systems

Automotive organisations with limited capacity of test resources are likely to incur higher development costs or risk loss in competitiveness by delays. In periods of high demand where resources are fully utilised, users have to commit additional investments to build new facilities to meet demand or outsource testing using third-party facilities. As a result, both solutions require either capital expenditure to acquire new test resources or incur higher resource costs leasing resources that trickle down and increase research and development overheads.

Asynchronous DTSs in this study are defined as collection of test-beds that benefit from the digital communication of data without any adverse influence from transmission speed or latency. Similar to the synchronous form, this SOA test system relies on internet communication infrastructure, but removes the need for RT interactions across the network and adopts a centralised structure where data is sent between a master node (server) and slave nodes (test-beds) in the aim to improve utilisation of test-beds. This diverges from synchronous DTSs as the optimisation of test-bed utilisation has a greater influence from activities conducted directly at each nodes rather than the properties of network.

Asynchronous DTSs act as a process feature that optimises existing test resources' throughput to retain competitiveness and substitute the uptake of costly alternatives during periods of resource high demand. This solution would enable organisations utilising this form of DTS to formulate and execute a combination of component tests to reach an experimental objective through the minimum number of test iterations. By minimising the number of test iterations, a single project can reduce the time it uses a test resource and therefore provide opportunities to accommodate other projects, avoiding the need to delay project or pursue costly alternatives.

Importantly, cost saving brought from asynchronous DTSs are likely to provide a holistic benefits to automotive powertrain businesses over products. The combination of avoiding large capital expenditure on new resources, and additional costs posed by leasing third party resources would lend to improvements of overheads. Improved overheads and associated margin would benefit businesses wider by unlocking capital for re-investment into business. Additional intangible saving could recognised from preserving competitiveness by minimising delays.

In addition, well established businesses are more likely to pursue asynchronous

DTSs for their ability to optimise cost efficiency or component testing and development. Mature businesses past the initial growth stage are more dependent on controlling costs to maintain growth and size. Asynchronous DTSs' capability to improve throughput of testing and maximise the number of projects undertaken aligns with mature businesses' common strategy. Smaller businesses are more like to focus on growth driven by value proposition through volumes and price.

Asynchronous DTSs capitalise on interactions within the individual stages of development process of a vehicle platform as well as value derived from parallel processes of other vehicle platforms within an organisation. Unlike synchronous DTSs, asynchronous variations move away from direct interaction of information between technical assets, and towards indirect interactions that are separated in time but influence operational characteristics of quality and productivity. By establishing a connection between resources, projects and teams, the collective communication and recording of relevant technical knowledge could greatly improve operational activities.

Innovations through this technology development and application were aimed to establish a foundation for a tool/system that would modernise the current processes used to evaluate physical components and systems. The implementation of current processes rely on a complex relationship between manual planning, execution and reporting to provide the desired objectives of the testing portion of the vehicle development process. By integrating a web-service with an automated algorithm to execute test activities, advances can be made to improve scalability component and system testing, as well as increase opportunities for optimisation through the adoption of state of the art control algorithms that could improve the planning and completion of test tasks.

6.1.2 Vehicle Development Process

As previously mentioned, development processes are an important tool for the successful deployment of technologies and products. These processes add structure, gateways and metrics to ensure projects successfully meet their objectives, timelines and budgetary constraints [83]. Failure to do so leads to an increase in project failure risk.

However, the internal view of these frameworks poorly consider the interactions of external factors that work against their internal plans and objectives. Outside of themselves, interactions occur with other projects and the organisation as a whole, where resources and knowledge are shared among stakeholders. Poor awareness between individual projects can result in inefficiencies that increase project costs and generate delays.

This scenario has been explored through research into multi-project planning. These studies highlight the importance of dynamic resource allocation in an R&D environment. Critical points raised, highlight the importance of [172]:

- Uncertainty in project planning due to timing and results.
- Scarcity of knowledge tied to human resource.
- Resource Flexibility.

It is critically important that the application of automation and knowledge communication resolve these existent issues.

The consideration of resource management within technology research and development is particularly significant during testing and validation stages. A study that reviewed testing activities within technical industries highlighted issues with 'Test organisation', 'Time and costs of tests', 'Poor communication of criteria', and 'Process related issue' in context to this critical stage [173]. The feedback and points recognised are reflective of issues faced across numerous technology industries. Within the automotive industry, this phase has raised importance due to the high cost of physical tests, driven by timescales, technical requirements and costs of physical resources [174].With the desire to mature vehicle electrification technologies through increasing throughput, the competition for resources at this level creates a significant barrier that increases the risk of project delays and increased costs.

6.2 Objectives

The primary objective of reducing total testing time per project through test iteration management was pursued as the most appropriate way to achieve additional capacity of existing test resources. Firstly, the approach identified the sub-set of elements that contribute to the overall test time per project. Then the test duration drivers were

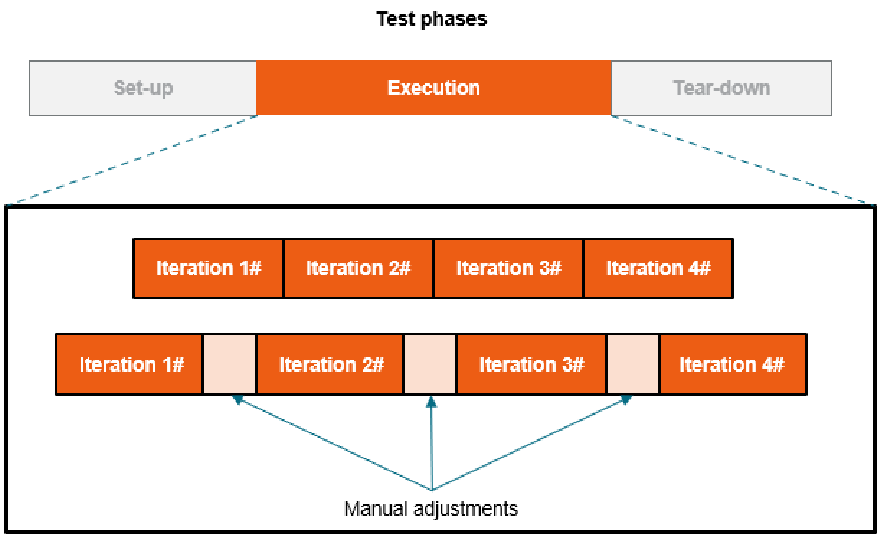


FIGURE 6.1: Test phases per project

explored of the most suitable sub-set element. This approach ensured that a mutually exclusive and collectively exhaustive objective was identified.

6.2.1 Test phases

Total test duration per project can be attributed to three distinct elements of which the test execution phase was identified as the most suitable for optimisation. Test set-up, execution and tear-down were recognised as key phases (Figure. 6.1). Test set-up and tear down duration were likely to be more influenced by complexity of the test apparatus and quality of the staff utilised to execute this phase. The first aspect was heavily influenced by the individual test requirements to a wider applicable solution. In contrast, the second aspect was attributed to operation and project management aspects outside the scope of technical innovation desired. However, the test execution phase provides opportunities by a selection driver where technical innovation is more appropriate to deploy.

6.2.2 Duration drivers

The number of test iterations required to satisfy test resolution objectives presented the best opportunity to innovative using a automated and connected solution for test case generation and execution. A driver tree framework identified individual drivers that allow optimisation of the primary objective (Figure. 6.2). Testing resolution allowed

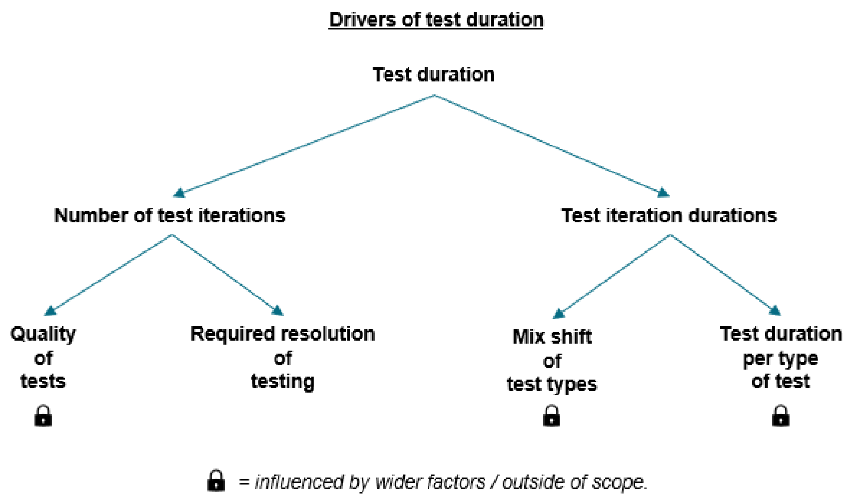


FIGURE 6.2: Drivers for testing duration per project.

partial control of the testing duration where an automated decision making of the process and larger insight could provide opportunities to reduce the number of test iterations. Other drivers such as quality of tests, mix of test types and individual iteration duration of tests are influenced by test apparatus/set-up, general automotive strategy and duration for specific tests.

6.2.3 Resource management

As identified, resource management was selected as a substantial concept in overcoming present issues within the automotive development process. The restrictions imposed by the demand, supply, and availability of physical test resources necessitates that an effective solution enables resource management to overcome these issues. As a result, the proposed tool should be able to plan, coordinate and maximise the availability of resources.

Test case execution and generation

Importantly, automated test case execution and generation could help avoid test iterations that would increase the overall testing duration per project. Test case generation would ultimately allow analysis of present or past data from the existing resources (or even parallel resources) to identify similarities or insights that could identify the most relevant test iterations and discard test iteration that are less significant. Examples of this include the characterisation of efficiencies profiles for components where test case generation could avoid committing test iterations where results are less significant to the overall picture of profile of the component; or using verification results from new/updated components to identify new conditions/re-runs to evaluate the full impact of the newer component. By doing so test case generation could provide some value towards reducing the total number of test iterations conducted.

6.3 Background

6.3.1 Test Resource Automation

Firstly, automation of resources and processes at the organisational level were seen as a key feature that would facilitate the requirements of the objectives set. Automation as a technology development has positively transformed the productivity and quality within subsets of the automotive industry, especially manufacturing [118, 119]. The changes made by this advancement has reduced the costs of vehicle production through betterment of the supply of key components and their assembly.

To successfully maximise its application to other subsets of automotive engineering, the life-cycle impact of automation needs to be considered. The integration of automation needs to account for the reprocessing and end-of-life stages of the technology deployment [120]. Systems constrained for a highly specific roles are at a higher risk of becoming obsolete when industrial changes occur. This, tied with the high costs of automation, suggest that future successful applications adopt flexibility and re-use concepts in their design.

Furthermore, there is a demand (termed as the 4th industrial revolution) for networked enabled automation driven by the accessibility of data provided by state-of-the-art networks and the realisation of value brought by communicated data. Technology companies, and manufacturers have invested in these networks and the automation enabled by them as part of growth strategy [124]. This demand is driven by the holistic growth provided by improved communicating between vertical levels in company delivering smart products and production.

Automotive Resource Automation

The application of resource (facilities/equipment/test-bed) automation has been investigated through various studies. Software developers have applied test automation through the implementation of a digital verification manager that responds to test result results and verifies them to a library of results where other relevant tests could be verified for the development of the software [175]. In addition, Accenture filed a patent on an automated software testing system that effectively used a rule-based controller to queue additional tests to that identified by a user [176]. Automated testing/test case generation has also been explored in automotive settings for vehicle test identification, where a classification fed with vehicle parameters identified necessary tests based on what the type of vehicle was [177]. More aligned to automotive component testing, a test execution tool allowed automated tuning of a combustion engine [178]. These cases demonstrated the various benefits that automation can bring to technical processes through test case generation and execution. Outside of software verification, the majority of these implemented automated tools are focused towards singular aspects of component and product level improvements and are more so focused on verification of performance objectives. In conjunction with the other findings, the creation of an automated test management tool should focus in resolving the gap of holistic automation towards coordinating test activities, but also seek out other test objective which could benefit from optimisation.

Test automation can be classed into test case execution or test case generation. Case execution can be frequently seen in the use of macros and scripts across research, product development and software verification, while case generation focuses on producing test parameters to effectively characterise and verify products. The latter has gained significant interest where it has successfully been used to identify software faults at earlier stages of the development process and improve the robustness to avoid product recalls [175, 177, 179]. Of the two automation paths, case execution has been widely adopted due to it's simplicity, while case generation is used to a smaller degree [121, 123]. To best optimise operational management of the physical testing process both test execution and generation should be used.

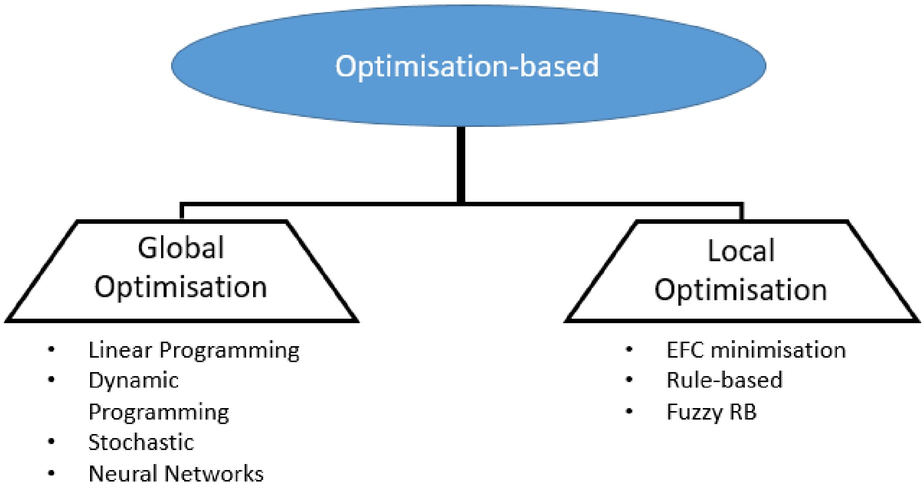


FIGURE 6.3: Global vs. Local optimisation techniques.

6.3.2 Optimisation

Research into optimisation techniques were also considered for use with the asynchronous DTS. Features from these techniques would aid in producing an efficient strategy to conduct tests and allocate appropriate resources in line with the performance of a system. By doing so, a structured and data-based approach, provided by computational means, would effectively carry out with the aim of improved productivity.

Types of Optimisation Techniques

Optimisation techniques are classified according to their capability and influence. Techniques are typically categorised by their overall objective and their application type (Figure. 6.3) [82]. The grouping of these various techniques based between global and local methods, are applicable to optimise a wide array of systems. For the purpose of the asynchronous system, global offline optimisation techniques such as linear, dynamic, stochastic and neural network methods were considered as credible solutions due to their distinct features and previous application.

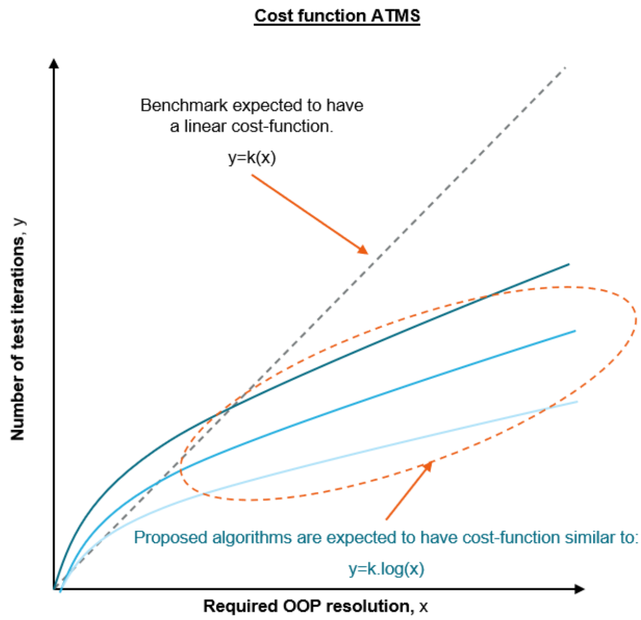


FIGURE 6.4: Expected behaviour of cost function between benchmark and optimised strategies.

Optimisation Objectives

An additional set of sub-objectives were created to guide the optimisation of test-bed utilisation. The sub-objectives centred on the prime requirement of reducing the total duration that tests occupied resources. This strategy was chosen as it aligned with the requirements to accommodate the increased demand brought on from accelerating maturation of electrification technologies without expanding current capacity or creating bias towards specific projects.

Firstly, a cost-function was established to understand how well a proposed strategy performed. Number of test iterations would acts as the cost, while the test strategy performance and required OOP resolution would be key attributes in the cost function. It is expected that best performing algorithms would ultimately have a logarithmic profile as higher testing demands are imposed (Figure. 6.4).

Dynamic Programming

Dynamic programming was identified as an applicable method to carryout the optimisation objectives. This set of techniques uses a methodology that deconstructs a complex problem into sub-problems, and uses recursive steps to reduce overall consumption of resources as a key result [180]. The aforementioned features satisfy the requirements for an automated system that furthers current capacity of test resources.

For the purpose of the automated system for resource management, applications of dynamic programming were explored through research to determine its capability. Two cases were identified that used dynamic programming to minimise energy resource for a vehicle, and its iterative use to identify shapes [181, 182]. Both cases outlined the minimisation capability of dynamic programming for which could be used for the optimisation of test resources.

Stochastic and Neural Networks

Presently, implementation requirements for stochastic methods and neural network techniques such as machine and deep learning prevent adoption of these techniques. These methods require historical data to train algorithms to provide pattern recognition, classification and decision-making. These algorithms were noted for their broad applicability. Markov decision and Bayesian stochastic models have been successfully applied to help predict the behaviour of partially known systems [183, 184]. These align with the research taking place for the development of ATMS, where the testing objective we intend to look at is not entirely defined. These models could be used when surrogate model training is required to supplement physical test iterations. The importance of high-quality data and step in pre-processing data are highlighted through the use of machine learning to forecast the effort and duration needed for project management situations [185]. In particular, the process used to clean data is critical to the accuracy of the model [186]. Using the incorrect techniques for the specific learning model and certain sequences of pre-processing techniques could augment results. The application of machine-learning models to ATMS is limited presently by the availability of training data, preventing practical training of neural network algorithms.

Typically, machine-learning models use optimisation to refine models and decision-making. Optimisation techniques such as gradient descent and error calculations such as mean-squared-error, mean-absolute-error or mean-absolute-percentage-error find an optimal solution. Examples include using these technique to adjust weights and bias for linear/logistic regression, decision-tree (and their sub-sets e.g. random forest) and bespoke neural-net models. Real-world applications include using a machine-learning algorithm to find the optimal power-split between two power sources as part of hybrid vehicle of which the models predicted road types and driving trends with an accuracy >90% [187].

6.4 Design

6.4.1 Principle Solution

Essentially, the application of an asynchronous DTS aligned with the requirements of the objectives created. An Automated Test Management System (ATMS) was envisaged as a form asynchronous DTS, where a centralised controller monitored multiple configured test resources and communicated additional test cases to them to efficiently complete their experimental purpose (Figure. 6.5). In this methodology, the system would tactically deploy new test conditions to satisfy the purpose of the experiment through a reduced number of test iterations (Figure. 6.6). By reducing the total test duration in this way, extra capacity for additional tests could be made to accommodate increases in research demand.

In particular, the system was initially designed to enhance the determination of optimal operation point (OOP) for SUTs. As a representative case, the typical behaviour of an SUT was treated as an unknown uni-modal non-linear curve, which would be investigated by ATMS through requested test iterations at specific points across the test boundary (input conditions) to determine the optimum point in the least number of iterations. The problem case was constrained in this way to prevent over-complication of the optimisation solution. This test objective was chosen as the primary function due to its uniqueness and difference from other optimisation cases such as system verification that had previously been explored as part of other studies [176, 175, 177].

An example application of this tool would be towards evaluating optimum cooling and heating set-points for powertrain temperature management systems. Users of utilising ATMS would configure vehicle energy consumption (or efficiency) as the key metric, which be monitored and used by the automated system to identify the collection of temperature set-point to evaluate for the thermal management system.

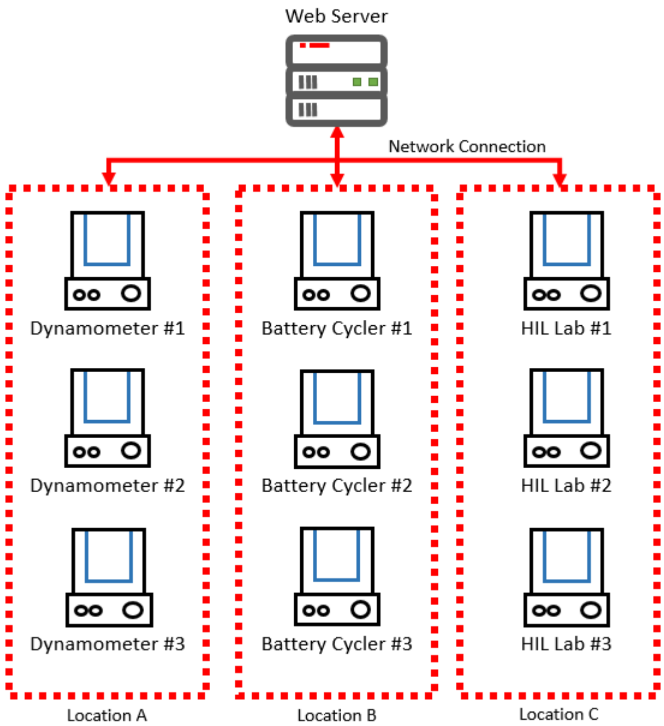


FIGURE 6.5: Generalised layout of ATMS as a asynchronous DTS.

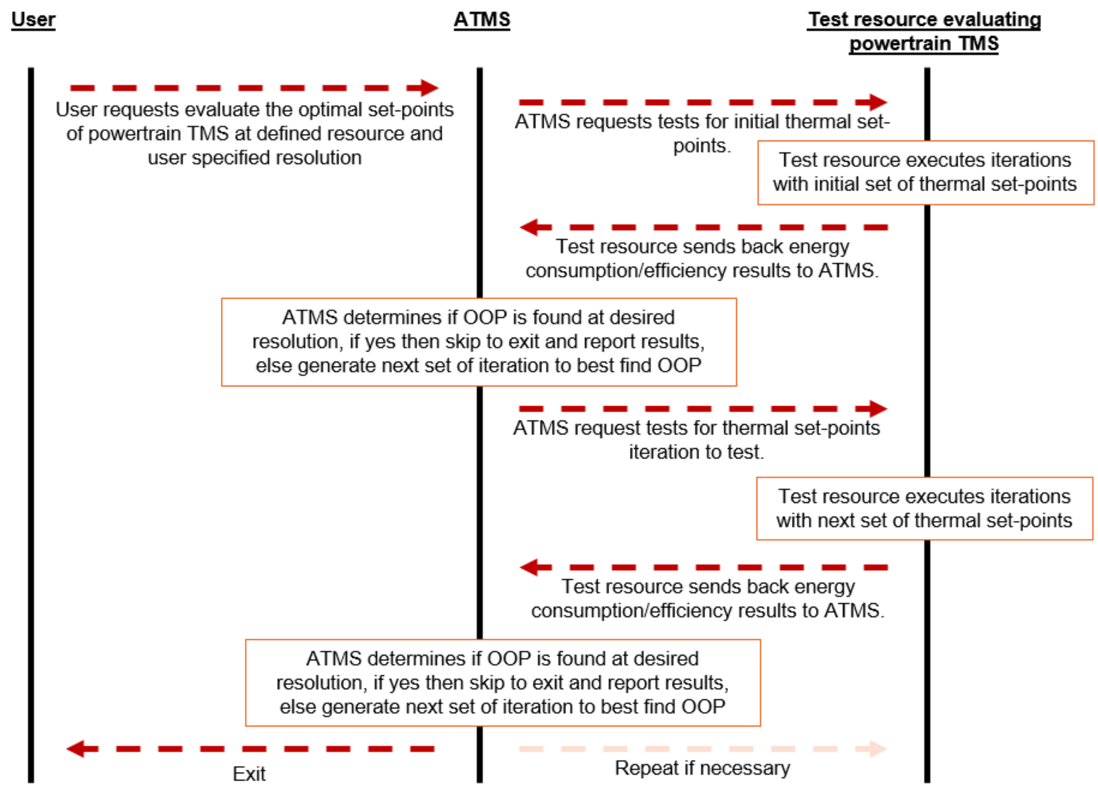


FIGURE 6.6: Test process automation through system interactions.

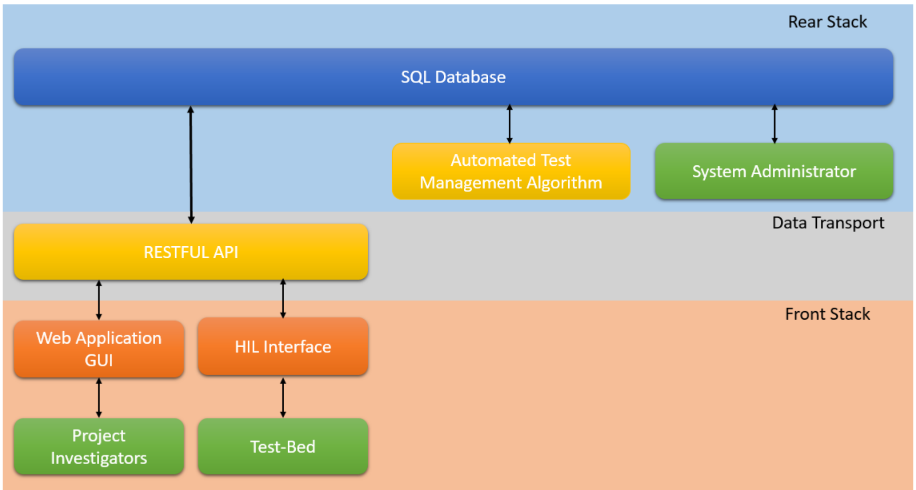


FIGURE 6.7: Visual Representation of the designed stacks.

The application would incremental test the system through a formulated approach of using the minimal number of test iterations and reduce the total duration of the test.

The ambiguous nature of the SUT function limited the potential optimisation methods. Due to the singular source of information regarding the SUT function (from tested points), zero-order methods were the only capable solution to determine the location of the OOP. This naturally restricted the possible methods to which ATMS could execute its function.

6.4.2 Technical Components

The design of the ATMS was separated into three stacks. These stacks were recognised as the rear stack, data transport and front stack, each with a specific role to producing a functional solution (Figure. 6.7). The separation of the entire solution in such a way ensured that the handling as well as communication of data could be clearly laid out in adoption of industry norms of web development solutions.

Moreover, at this stage in the project the overall stack was characterised as a WxMP (Windows, x, MySQL, Python) web application. This designation identified the system as an application that uses a Windows operating system, undefined server, MysQL database and a Python programming language. This specific solution stack was chosen as it reflected the methods of how users and organisations would interact with the system, while accommodating open source tools that allowed the flexible development of features for the asynchronous DTS. The application of web-service, specifically integrated with a global optimisation algorithm to maximise test-bed and resource utilisation provides innovative application and expansion of this technology towards the automotive R&D industry. Flexibility of using a web-service and configurable interface would also allow maximum coverage to accommodate a wide array of different test-beds that are present and may be developed with the future adoption of new test methods or technologies.

6.4.3 Rear Stack

The rear stack carried out functions in the background and out of sight of users. Data management, Application Protocol Interface (API) routing and automation scripting were designed to be hosted on a central server, where access to the system could be controlled. The underlying function needed to be kept in a central location for users and resources to access, while also remaining secure enough to prevent unauthorised changes or manipulation.

Data Management

A MySQL database was used to store, query and recall data. This database tool has the ability to store structured data across numerous related tables, and when scaled up, has an efficient recall function that quickly finds data irrespective of the total size of the database. This database solution was specifically chosen as it facilitated the common data types that were intended to be used, while also having the ability to coordinate data storage from multiple users and test resources.

The database held data in designed tables to control data input and form links between related pieces of information. From mapped interactions between users, test resources and the test automation script, data was stored in the following tables:

- Project Names and IDs
- Project Managers
- Project Investigators

- Test Locations
- Resource
- Statuses
- **Projects**
- **Test Table**
- **Verification**

Data was stored in tables so as to control data entry and manipulation, while relational tables '**Projects**', '**Test Table**', and '**Verification**' created links between stored data so that users and the automated scripts could logically interact with them [188]. The final structure of the database schema was outlined in a Entity-Relationship diagram (Figure. 6.8).

The '**Projects**', '**Test Table**', and '**Verification**' provided different capabilities for ATMS to functions. The test case generation process (which would be used for evaluation strategy performance) uses the data held in the '**Test**', and '**Verification**' tables to request new tests and respond to results received from the test resource. ATMS would use the '**Projects**' to contextualise data from active tests to be interpretable for users to interact with the system. This is executed in such a way to keep tables as distinct as possible, preserve redundancy in the database, and steps to update the system.

Automation Scripts

The rear stack also contained the Python automation script. The automation script contained the optimisation algorithm that was used to enhance test resource activities. This script was situated with the API script and database as it was a central process. Deployment of the algorithm was executed through a python script to conform and standardise the access to the database as with the other scripts.

The optimisation algorithm was designed with concepts drawn from dynamic programming. Recursive (the repeated application of a rule/process) and memoization (the calling of cached results to speed up future complex tasks) techniques used in dynamic programming examples focused on re-using results and processes from previous steps to simplify the solution execution in future steps. With the number of tests

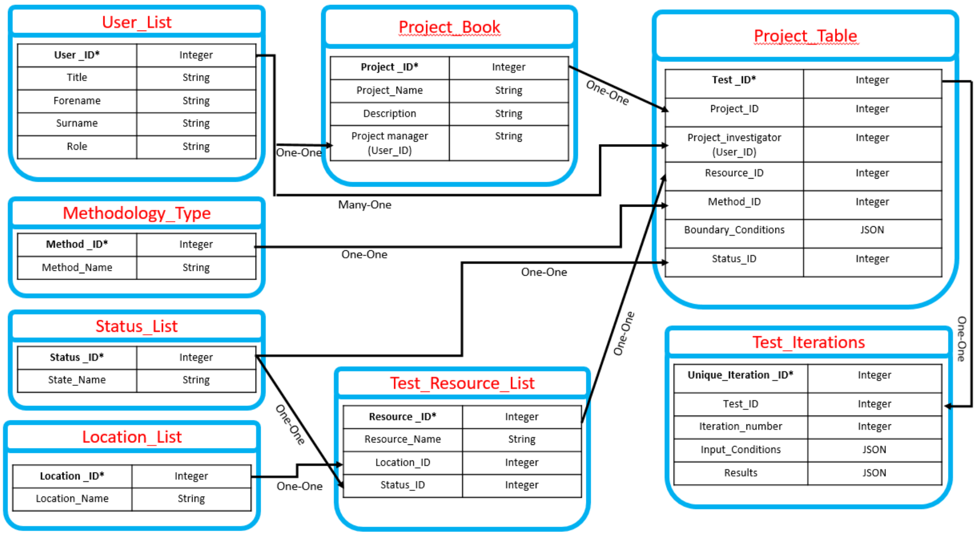


FIGURE 6.8: Entity-Relationship diagram used to implement the data store for the test web-service.

Command	Purpose
Get	Retrieve data from the database
Post	Create data for the database
Put	Update data in the database
Delete	Delete data from the data base

TABLE 6.1: API Create, Retrieve, Update and Delete (CRUD) command types.

recognised as the cost metric, the re-purposing of previous iteration results, were seen as a viable method to reduce the total number of test iterations required to estimate the optimal operation point at higher resolutions.

6.4.4 Data Transport

API

A FLASK-Restful API carried out the communication function between the database and user/test resources. Functions as part of the API's gateway toolset (Table. 6.1), allowed the controlled interaction of users and test nodes with the database through custom Hypertext Transfer Protocol (HTTP)/HTTP Secure (HTTPS) Uniform Resource Locator (URL)s. The specific commands can be found in *Submission 5*. The API provided a wide coverage data transport tool over Ethernet networks available at virtually all OEMs and ESPs and provided a robust control method of database interactions.

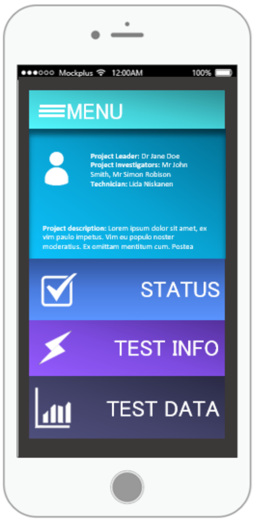


FIGURE 6.9: A visual interpretation of a mobile interface for ATMS.

6.4.5 Front Stack

The front stack was envisaged to be developed in two forms. One would be developed as an ergonomic website base or application graphical user interface (GUI) for users (Figure. 6.9), while the second form would be developed as a python script for interfacing test resources. This methodology was chosen for the front stack as it would establish a user-friendly interface, designed to assist users in using the system while also avoiding excessive constraints on the test resource side which operators would rarely interact with.

Resource Interaction

As an example, a process map was created to envision how physical apparatus connected through XIL platforms would interact with the ATMS. This process outlined the typical structure of component/system tests and defined the general commands expected between the resource and the rear stack (Figure. 6.10). Creation of this standardised interaction ensures that essential data to the database is parsed appropriately and that the system remains flexible to various test resources.

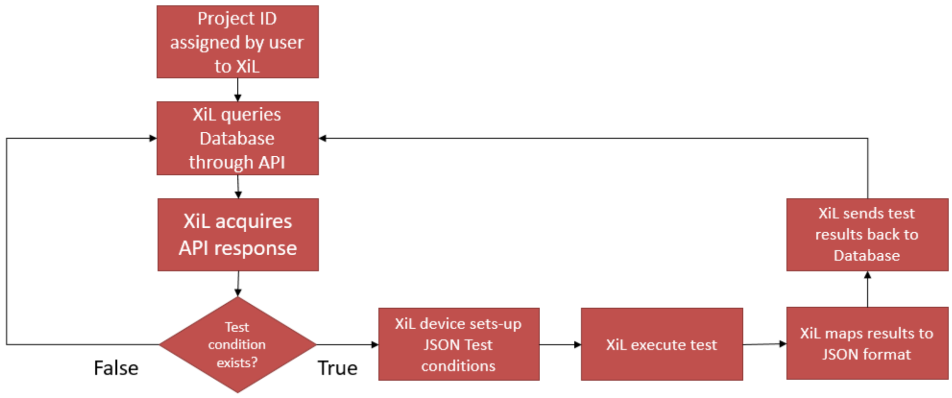


FIGURE 6.10: The internal system process at test resources.

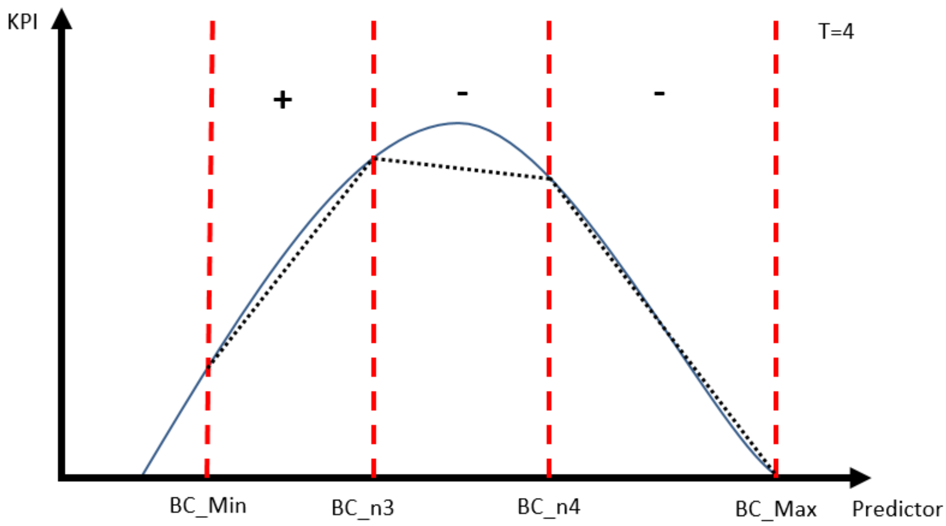


FIGURE 6.11: Zero-order polarity change detection - Step 1.

6.5 Performance

6.5.1 Proposed Strategies

Three zero-order automation strategies were put forward to determine an optimal method for reducing total test iterations between a set of boundary conditions (BC). Two of these focused on locating the minima/maxima by recognising a polarity change of the uni-modal system's gradient (Figure. 6.11-6.12), while the third method used the golden section method to determine the OOP of the SUT. Multiple strategies and configurations were evaluated to competitively find the method that best aligned with the target objectives. All three strategies used recursion by utilising results from iterations of the previous step to supplement the BC of the next step to be executed.

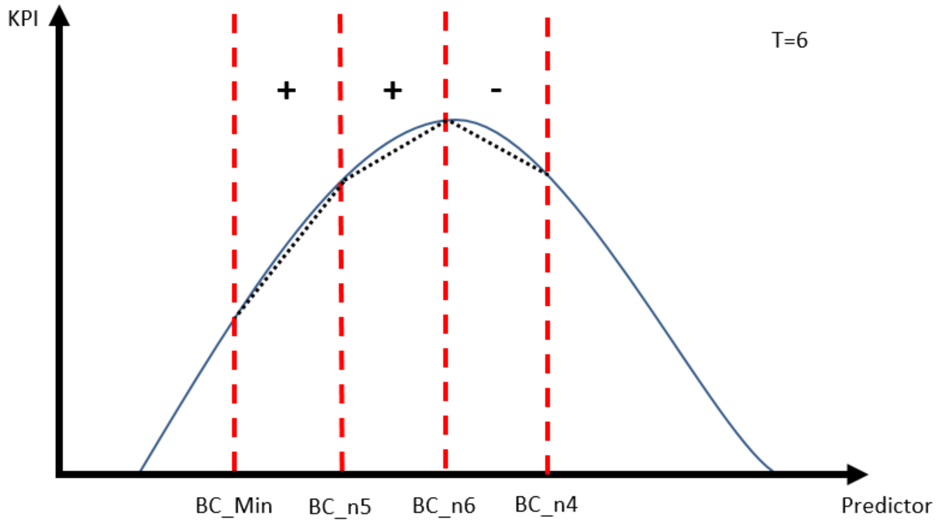


FIGURE 6.12: Zero-order polarity change detection - Step 2.

Strategy 1

The first strategy pre-determined the number of equally spaced test iterations required per step. This was done through a brute force algorithm that determined the minimum number of test iterations required from the user resolution request of the OOP. A brute force approach tests all the possible iteration configurations (iteration spacing in this case) to determine the optimal path. Though this method is completely exhaustive, computational demand increases as the scale of the search increases. This strategy re-uses the two outer most boundaries where a change of gradient was detected on the previous step, reducing the total number of test iterations to identify the OOP.

Strategy 2

Following this, strategy two used a similar change of gradient technique, but looked to improve the number of test iterations recalled from the previous set of test iterations. Constraints added by limiting the number of spaced iterations to even numbers created a situation where three previous iterations could be re-used. The actions of doing so would reduce the number of new iterations required per new step.

Strategy 3

Alternatively, the golden section algorithm used a zero-order method based on Fibonacci's golden ratio to minimise the number of iterations needed per step. This

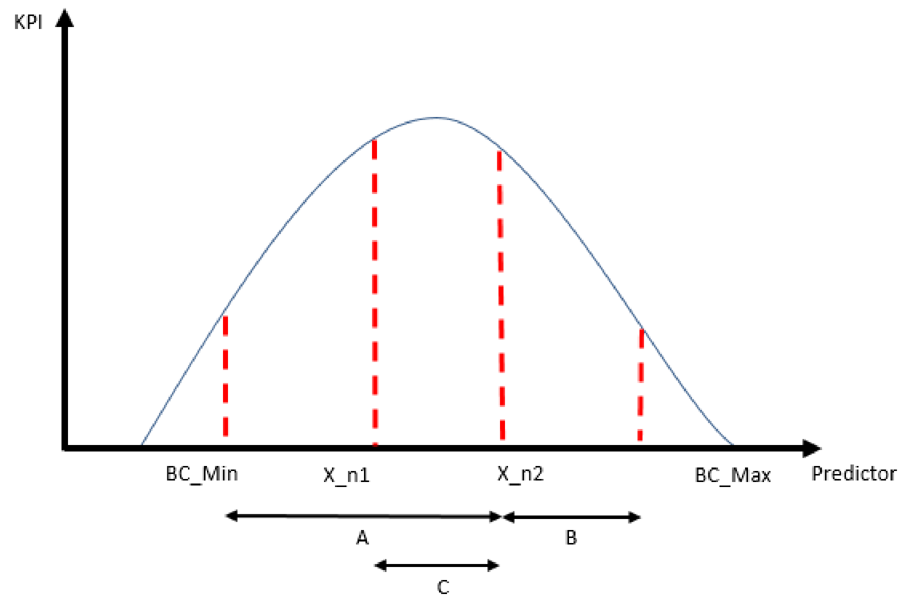


FIGURE 6.13: Golden section method.

method created two inner iteration points in proportion to the golden ratio, that would be compared (Figure. 6.13). The comparison of the two, determined which area outside of the two inner iterations to disregard over the next step. Due to the geometric effect of the Fibonacci ratio, only one additional iteration would be required per step to repeat the process.

Other potential algorithms

Other optimisation algorithms could provide alternative methods to determine a global minima/maxima offered by uni-modal test cases, these would need additional research and considerations before their application. All strategies in this study are fundamentally a form of an evolutionary algorithms with strategy 1 and 2 acting as pattern search methods searching for gradient patterns between iteration points, and strategy 3 pulling high-level concepts of genetic algorithms. Other methods such as particle swarm, complex genetic algorithms, gradient descent and surrogate also could be utilised and offer capabilities to accommodate multi-model test cases. Concepts such as particle swarm and complex genetic algorithms where avoided as they would required a high number of initial iterations per step (adding overall cost to the optimisation) [189]; gradient descent would of required a robust methodology to find a suitable learning rate to accurately find the minima without occurring adverse issue caused by test subject (long plateau regions) or numerical precision [190]; and surrogate models would require creation of virtual black-box model to replace costly test iterations, which could be drawn from the virtual evaluation of system, but limited by inaccuracies of the model in itself. As a result, the chosen strategies were chosen due to their robustness in finding the OOP with fewer iterations and without complexities such as tuning learning rates and developing additional black-box models.

6.5.2 Algorithm Performance

Model

A principle study was made to evaluate the performance of the optimisation strategy. Each of the proposed strategies and their configurations (Table. 6.2) were evaluated to determine their performance with an artificial function representing an SUT. The results of which would determine the most appropriate method to achieve the solutions objectives.

The strategies were explicitly graded to determine their performance. Metrics of, 'number of test iterations' as the independent variable, and 'Resolution of Optimum Instance (ROIN)' as the controlled variable were used. From this, a comparative analysis was made possible to determine the method that required the least number of test iterations, by locating the OOP in the least number of steps.

Benchmark

Besides the optimisation strategies, a benchmark method was created that represented a common method to ascertain the OOP. The methodology followed an approach where a user would split the test bandwidth in equal spaces correlated to their required resolution of OOP (Figure. 6.14). The benchmark provided a reference for which the optimisation strategy could be compared with.

6.5.3 Results

All of the optimisation algorithms presented an improved solution in relation to the benchmark method. ROINs < 0.1 clearly showed an advantage towards the optimised strategies, while the benchmark method grew increasingly inefficient. The conclusive

Test	Strategy	Configuration
1	Brute Force	
2-S3	Constant Gap	3 Sections
2-S4	Constant Gap	4 Sections
2-S5	Constant Gap	5 Sections
2-S7	Constant Gap	7 Sections
2-S4A	Constant Gap	4 Sections with added recursion
2-S6A	Constant Gap	6 Sections with added recursion
3	Golden Section	

TABLE 6.2: Dynamic Programming Algorithm test list.

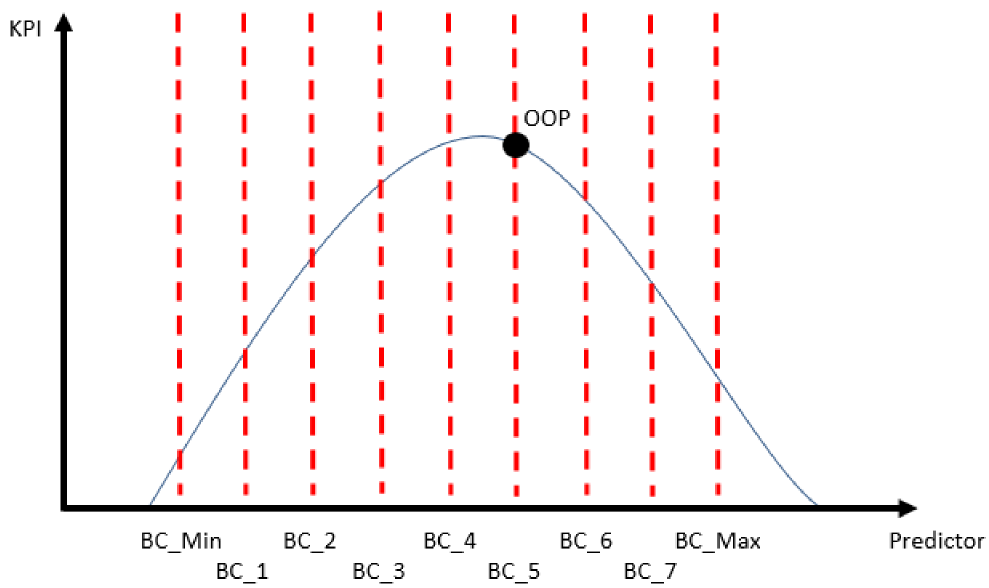


FIGURE 6.14: Split bandwidth sweep method to ascertain OP.

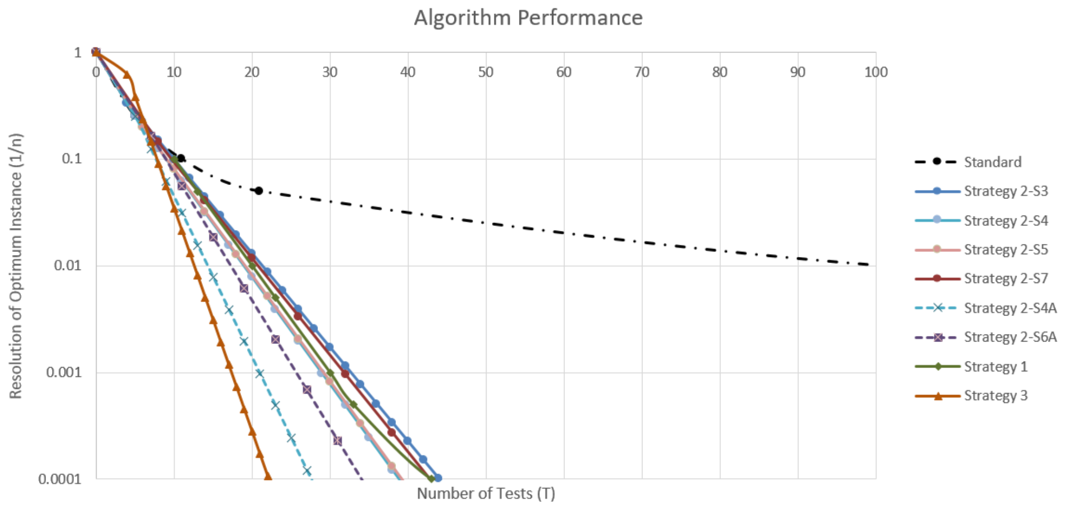


FIGURE 6.15: Numerical analysis results of the 3 optimisation strategies.

difference in results would suggest that adoption of the optimisation strategies investigated satisfy the ATMS requirement to reduce workload of test resources, henceforth improving their productivity.

Strategy 1 Results

Out of all optimised techniques strategy 1 performed least effectively towards the overall system objectives (Figure. 6.15). This strategy required additional iterations to characterise an OOP to equivalent resolutions. The increased number of iterations were caused by the algorithm's dependency on splitting the test bandwidth with a high number of segments that reduced the efficiency in locating the OOP in the least number of steps.

Strategy 2 Results

Of all the configurations tested as part of strategy 2, this algorithm constrained to 4 segments per step demonstrated a productive way to identify the OOP. At a consistent rate, this method resulted in defining the OOP faster than all other configurations and strategy 1 (Figure. 6.15). This was noted through its ability to reach an OOP resolution of 0.001 within 21 iterations, while the previous strategy required 30 iterations. The enhanced performance of this strategy was attributed to the increased memorisation of the system requiring only two new iterations per step.

Strategy 3 Results

Notably, strategy 3 exhibited a highly efficient method to finding the OOP. At ROINs < 0.1, an improved rate of bandwidth reduction per iteration was recognised in comparison to all other strategies tested (Figure. 6.15). This was attributed to the golden method's ability to reduce the test bandwidth by 38.2% per step in contrast to the optimal configuration of strategy 2 that only reduced the bandwidth by 25%.

6.6 Discussion

6.6.1 Application

Robustness

Critically, issues of robustness were identified for strategy 3. As part of it's internal process, if both inner iterations points (X_n1 and X_n2) are detected as equals (Figure. 6.13), the algorithm assumes that the OOP is located at the midpoint between the two test points. This assumption is however not necessarily true and could misrepresent non-uniform SUT performance functions.

This resulted in the summary that strategy 2 was most fit for the purpose of ATMS. Though it was sub-optimal to strategy 3, this methods robustness prevented false assumptions of the correct location of the OOP. As a result, it was deemed more reliable towards its core function, while out-performing the other tested methods.

Precision

The overall number of tests would be increased to account for variation of the experimental results. Following thorough experimental procedures, a sample of multiple sub-iterations should be undertaken to characterise a single iteration. Figure 6.16 outlines a visual representation of under sampling (left) where a single point that experiences some form of error, would be mis-representative of the SUT, a multi-sample approach could be statistically analysed to provide a more accurate representation. Taking a statistical sample from multiple points would reduce the sensitivity of the ATMS from experimental error that could influence the final estimation SUT behaviours.

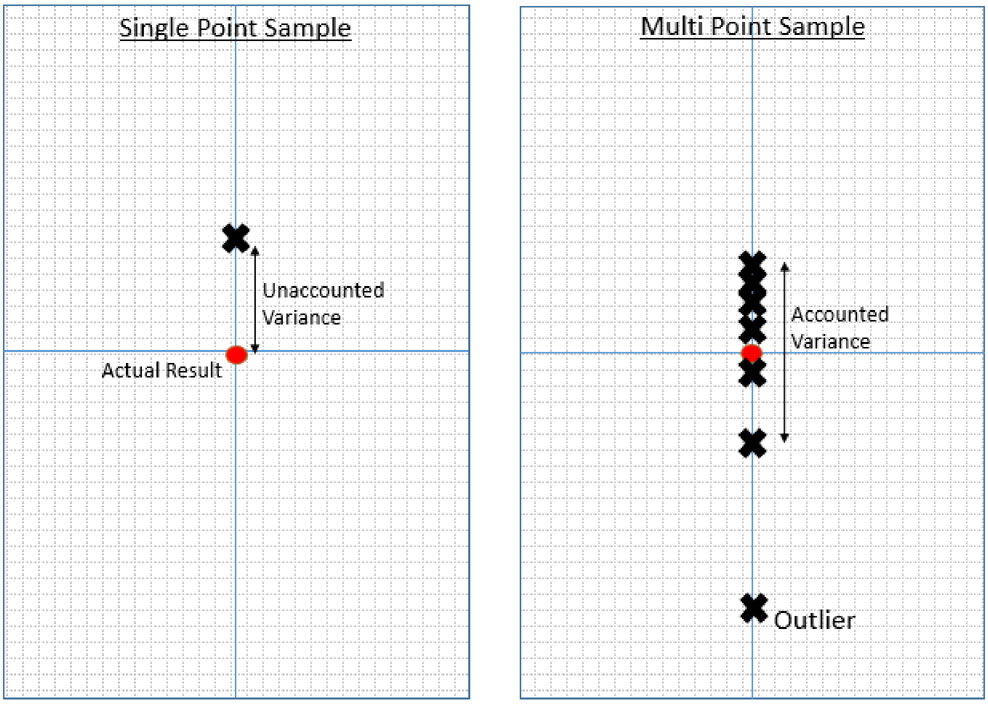


FIGURE 6.16: Conceptual benefit of taking multiple sample points.

Required Accuracy

The model resolution inputs used for this evaluation could differ from accuracy requirements set to be applied in industry. Users of the system may not necessarily need to identify OOPs for tested components higher than ROIN < 0.05-0.01, and therefore iteration saving provided by the system would be less recognisable. As a results, the real-world application of the system may have reduced opportunities to meaningfully reduce the number of tests and associated facility costs.

Application

The ATMS in its current form has a limited scope of impact to test activities that are undertaken in industry. Verification and product mapping tests that make up a higher proportion of physical test activities, could have a greater impact to automotive organisations in comparison to solely identifying the OOP of a product. Research studies have realised the applicability for test case generation for software fault finding and identifying suitable test methods through classification trees[179, 177]. Applied use of machine-learning or analytic concepts such as k-means clustering could be used to help select both suitable test methods, as well as selection of appropriate test conditions for automated test execution. Due to the lack of consistent data on test activities across the organisation, it would be difficult to ascertain what these algorithms would look like and what impact they would ultimately have on the vehicle development process. One of the aims of this study was to provide the centralised data store needed to enable such developments in the future.

Unstructured Data

In the current format of the system, data is strictly collected and analysed in a structured form. Some physical testing activities or important source of product information such as customer feedback in the automotive industry include data expressed naturally in unstructured formats. A business intelligence survey across various industries reported over 51% of organisations that used unstructured data (text analytics) highly benefited from its adoption, yet only 6% of all companies surveyed deployed it into their organisations [191]. To store and analyse these data types would require utilisation of alternate database solutions and optimisation tools to allow this functionality. The use of unstructured data could provide an opportunity to increase feedback sources both internally from tests within the organisation and externally from customers to refine test case generation by improving test parameters and new test cases to improve development quality [192, 193].

Data Security and accessibility

Developers of this system need to carefully consider data security and accessibility with the application of the ATMS to an industry environment. Governments and legislative bodies have recognised the security vulnerabilities and threat opportunities of supervisory control and data acquisition systems/distributed control systems in industry [194]. One of the key themes from this review highlighted the significance of growing utilisation and dependency on a shared network (i.e., the internet), increasing data exposure to others who may also use the system. An increase in exposure increases opportunities for data theft/manipulation. As a result, these types of systems, as a result, undergo a significant increase in risk as the impact of intrusion could lead to hard damage (physical systems) with catastrophic outcomes, and increased opportunities of intrusion could be expected to occur more frequently.

Adopters of ATMS would need to identify risks and their impact to ensure the system's security. Off-the-shelf hardware and software, and the system interactions are never immune to external threats, and bugs across hardware features, operating systems, and human faults have been demonstrated in the past. The utilisation of risk/fault trees analysis, thorough analysis of vulnerabilities of off-the-shelf components, and adoption of security tools are deemed as necessary steps towards securing ATMS [195]. The deployed system should adopt security features such as firewalls, API authentication, and data encryption to deter system intrusion or data theft.

Safety

6.6.2 Improvements

Multi-modal

Significantly, improvements to the existing optimisation algorithm should consider adding the capability to operate with multi-modal systems. It cannot be assumed that all SUT's performance are expressible as a uni-modal function. A more adept system should be able to identify all maxima and minima points within a test bandwidth through a holistic method of sub-division of the overall SUT performance function.

6.6.3 Alternative Strategies

Other accepted methods such as statistical techniques could be as advantageous in locating an OOP. Non-linear regression analysis, and unsupervised machine learning could be as efficient in developing a representative SUT performance function, with higher order techniques or derivative methods. The adoption and application of these methods have grown significantly in the last decade with the various project using these function and availability of libraries in mainstream programming languages. The adoption of these methods were considered, but were ultimately to discounted as they only provided offline post analytical approach to optimisation rather than an real-time approach offered by the zero order methods that were investigated. These

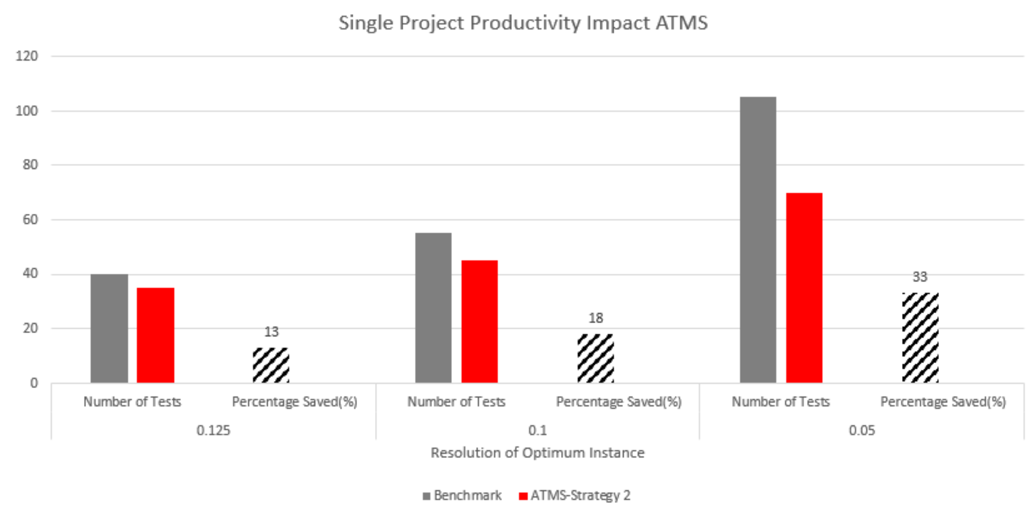


FIGURE 6.17: The expected productivity saving from employing ATMS on a single test resource.

methods could reduce the number of tested points required to determine OOP. Although it should be noted that the accuracy of these techniques are in correlation to number of samples taken across the function, and that the OOP is implied rather than experimentally demonstrated. An in-depth comparison would be required to determine the transition point at which these techniques would surpass the performance saving provided by a zero-order function.

6.6.4 Productivity Impact

Resource Capacity

A numerical model regarding the operational performance was created to investigate the effectiveness of ATMS. The model outlined the number of tests required to effectively evaluate an OOP to three different resolutions. The performance of ATMS was recognised to provide a saving of 13-33% of total tests (Figure. 6.17). The total time saved could ultimately be re-purposed to other projects to reduce operational constraints or be used to test additional technologies.

Financial Saving

In addition, an estimation was made to evaluate the financial saving that would be facilitated by ATMS per project. The calculation showed that for physical resource costs

	ROIN					
	0.125		0.1		0.05	
Resources	Standard	ATMS	Standard	ATMS	Standard	ATMS
Dynamometer	£10,667	£9,333	£14,667	£12,000	£28,000	£18,667
Pack Cycler	£30,000	£26,250	£41,250	£33,750	£78,750	£52,500
Cell Cycler	£6,000	£5,250	£8,250	£6,750	£15,750	£10,500

TABLE 6.3: Impact of ATMS cost reduction introduced to individual test resources.

alone, use of ATMS created significant financial saving only at higher OOP precision for singular projects (Table. 6.3). Due to the resource dependencies of the optimisation algorithm, the number of avoided test interactions was smaller where low resolution were required, this entails a reduced holistic rate of saving and therefore needing the system to be scaled to recognise benefits.

This estimation however excluded human resource costs. Human resources such as Engineers, technicians and other staff member required to operate test equipment and facilities can attribute to a significant portion of the operating costs, but also greatly differ between individual projects. This cost metric was disregarded in the displayed estimates as human resource involvement would not be equally reflected across all OEMs and ESPs due to varying levels of automation functionality of test resources and perception of safety requirements. Though the human cost benefits would be expected to scale with the number of tests and hours required to evaluate a SUT.

Chapter 7

Application and Industrial Benefits

7.1 Product Innovation

Of all technologies developed for the automotive industry, 40% failed to reach market, while an additional 40% were necessary for serial development and legal requirements, leaving only 20% of all innovation generating a profitable outcome [196]. Effective management of R&D activities are necessary to maximise this uptake of technologies and minimise research failures to ensure the overall investment benefits the organisation.

JLR's unique product line requires a hybrid development strategy be used to facilitate the necessary innovations to best suit its product. The defining factors of innovation capacity and capability are dependent on the product strategy for OEMs. Luxury vehicle markets are likely to rely on agile innovation strategy, while mass-market products focus on sustainable innovation to reduce product cost (Table. 7.1). Thus, the former would be reliant on improved productivity to ensure latest technologies are first to market, while sustainable innovation looks to decrease to the product costs and remain competitive. The test technologies developed as part of this study were designed to target both of these as result to accommodate the complex strategy used by JLR.

	Low Value Market	High Value Market
Market	Mass	Niche
Profit Margins	Low	High
Order Winner	Cost	Feature
Example Models	Discovery Sport, Evoque, E-pace	Velar, I-Pace, Range Rover

TABLE 7.1: Market Characteristics of the automotive models sold by JLR.

7.2 Organisational and Industrial Impact

Importantly, the relationship between suppliers and OEMs are a necessary consideration for vehicle electrification product development. In 2019, the automotive sector R&D expenditure was estimated at £75.2 billion globally and increased by 5% from 2017 [197]. 75% of automotive industrial R&D overheads are accounted within the supply chain, where by percentage of revenue this is split 60.5% for suppliers, 31.4% OEMs and 8.1% by Engineering Service Providers(ESP) [196]. With such a significant investment contributed by suppliers and the costs transitioned to OEMs through procurement, DTS advancements demonstrated for automotive manufacturer should be extended to the supply chain to maximise industry performance.

7.2.1 Cost Impact

As noted within their respective discussions in Sections 4.6.3, 5.5.3 and 6.6.4, the technologies innovated as part of this study exemplified the potential cost saving through the adoption of automated/connected systems. An Excel model provided an estimate of the research's impact towards benefiting an automotive manufacturer. The model considered various elements around the capital costs, saving potential, JLR's engineering capacity, product lines and specification to determine the return on investment, and contributors to saving. These details provided a best estimate on the overall impact compared to a benchmark.

Benchmark cost of development

The impact model used JLR's product and financial data to determine an estimate for the total cost converting their current combustion product line like-for-like to an electric alternative. Strategy reports from JLR provided details around overall product revenues, product margins, and sales volumes per model. JLR's website identified product prices, while informed assumption captured necessary information around break-even periods, and sales mix (*J. Parson, 2022, personal conversations*). These key data points with the impact model estimated the development costs per type of vehicle produced [198]. It was important to establish these estimate as it would provide a base case to make a comparison against.

Model type	Models	Total development costs
Large SUV	2	£2.8bn
Medium SUV	3	£1.0bn
Small SUV	3	£1.1bn
Saloon	3	£0.2bn
Sport	1	£0.2bn
Total	12	£12.9bn

TABLE 7.2: Total development cost per model type *See calculation in Appendix C.*

An overview of these results deemed that SUV-based vehicles' estimates were fairly appropriate, while saloons and Sport vehicles were significantly undervalued. SUV vehicles were valued greater than £1-3 billion, while other types where below £200 million (Table. 7.4). The low development cost estimates are caused by over-estimating break-even performance of saloons/sport models and using an average margin percentage to calculate the development cost. Due to the sensitivity of development data from JLR, its exceptionally difficult to verify appropriate estimation that could indicate the actually development costs per vehicle, however by aggregating values to their highest level we can mitigate opportunities of error.

The some additional assumptions where omitted due to the uncertainty of behaviours in the future. This benchmark omitted effects from macro economic effects e.g. inflation, product margins changing due to market volatility and foreign exchange. Vehicle are likely to developed in sequence and therefore have varied economic influence that could affect yearly sales, margins and development pay-back periods.

Impact methodology

A two-dimensional value model represented both total development costs for the benchmark approach and an approach where each technology from this innovation report was implemented. The total development cost was a product of the total man-hours required to develop each vehicle and cost per hour of development (Equation. 7.1, Figure. 7.1). This methodology allows input of the direct saving proposed by each implemented technology while providing model mechanics to determine project duration and cost saving mix.

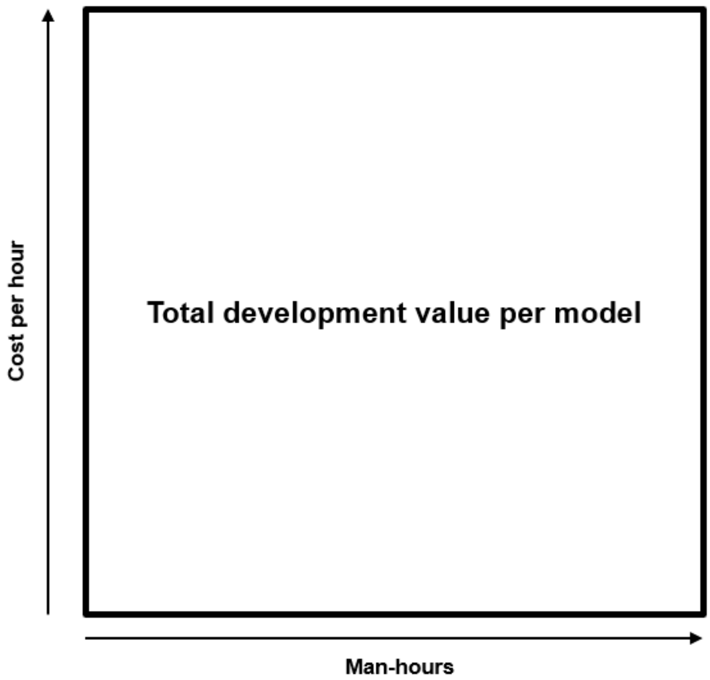


FIGURE 7.1: Two-dimensional value model.

$$Totaldevelopmentcost = Totalman - hours * costperhourofdevelopment. \tag{7.1}$$

Saving per technology

Results from Sections 4.6.3, 5.5.3 and 6.6.4 provided as estimate of saving per project. Saving factors from section and list of costs where combined with assumption drawn from their degree of adoption, and duration of their adoptions. The saving were aggregated and implemented into the total development value per vehicle platform (Figure. 7.2). The assumptions chosen were indicative of a moderate utilisation and duration for which these activities would occur (*J. Parson, 2022, personal conversations*). These two assumption are likely have recognisable flexibility and are likely to differ with product complexity.

The technology proposals hinted a 1.75% saving with largest contributor drawn from man-hours. Overall costs contributed to 1.04% saving, while capital costs and savings sourced from a mix only resulted in a saving of 0.71% and 0.01% respectively (Table. 7.3). This is primarily driven by the coverage of automation providing reduced

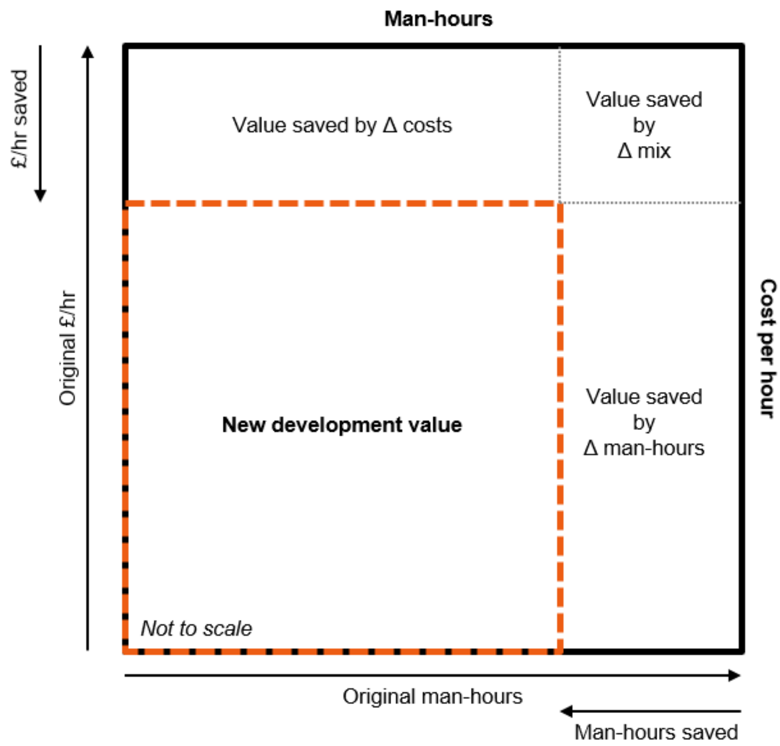


FIGURE 7.2: Valued saved visualisation between benchmark and proposed innovation approach.

	Benchmark	Innovation proposed	Value saved
Total Value	£12.81bn	£12.64bn	1.75%
Total man-hours	37.60 m	37.21 m	1.04%
Cost per hour	£342.07	£339.62	0.71%
Mix			0.01%

TABLE 7.3: Mix shift of key levers of development value change. *See calculation in Appendix. C.*

Total cost	£2.9m
Automated dynamometer	£0.6m
DTS	£1.2m
ATMS	£1.1m
Saving	£225.2m
ROI	7646%

TABLE 7.4: Return on investment for proposed technologies with JLR. *Costing in Appendix C.*

man-hour across all the proposed innovations, while capital costs are fairly limited to the DTS tool.

Return on investment

The technology's savings were compared to original investments and costs to determine its industrial effectiveness. Cost of the system where determined by taking account minimum product costs of hardware and additional development time needed to verify their application. The technologies proposed brought on a combined ROI of 7646% (Table. 7.4). The multiple saving opportunities drive the high ROI bought on by 12 vehicle models under development and one-off purchases of equipment that limit the overall investment. In addition, most of the technology implementation relies on upgrading existing facilities, and therefore avoiding the high costs of developing new facilities. Several assumptions are made throughout the model, limiting the model's accuracy. Further models should use exact product data such as pay-back periods, margins, and pay-back periods to estimate the technology impact on a specific industrial situation.

Impact to customers

Consequently, the proposed innovations savings enable an estimation of cost reduction to customers. Using the total saving from the innovations proposed and assumptions that: JLR sell the equivalent number of cars as historically, models have a production span of 5 years and 100% of savings are transitioned to customers, each vehicle would have overheads reduced by £91. This is a limited saving per customer. The savings gained by customers is unlikely to make a noticeable difference in decision-making by customer to transition to EV alternative from existing combustion alternatives.

Real worlds influences could further distort this number. Factors such as vehicle demand (driven by populations/consumer demand/consumer confidence), varying production duration and other macro changes could heavily influence assumptions. Consequently, real-world values would likely differ from historic values used in this estimate.

7.2.2 Intangible influences

The model discussed above highlights the impact of the proposed technologies within an automotive manufacturers, but additional benefits may be seen at other levels of the automotive supply chain. The application of these technologies are expected to contribute improvements to both manufacturers and their supply chain (Figure. 7.3), though technologies such as ATMS have greater significance. With research overhead costs established [196], it can be argued that technologies like ATMS would be best suited and adopted by suppliers where majority of component development takes place. Any cost-savings as a result should naturally be passed down the supply chain. While synchronous DTS's designed to improve development quality at the vehicle system integration stage would be most appropriate to be led by manufacturer's who would gain the experience the largest benefit from improved quality and reduced reliance on functional prototypes.

In contrast, the adoption of component test resource automation should be driven across all stakeholders to maximise benefits across the automotive industry. Unlike to the other two technology proposals, the applicability the automated component test resource are distinctly evident in both category of stakeholders. The benefits drawn from this particular technology are associated to the specific activity and therefore advantageous to the operating stakeholder, due to the predominant direct saving being achieved through human resource costs minimisation.

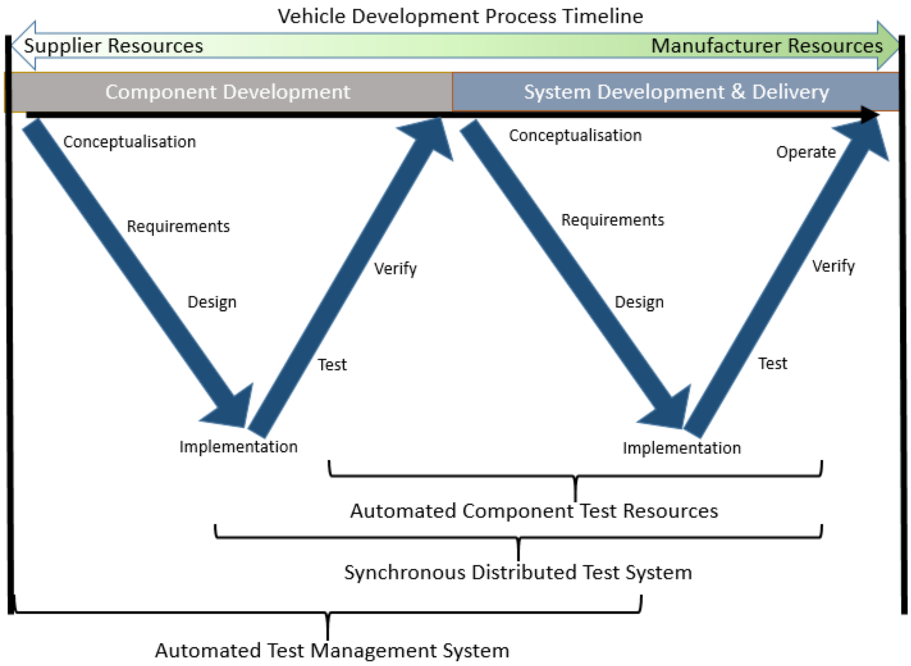


FIGURE 7.3: Vehicle development process and coverage of technologies developed within the EngD.

Use of Asynchronous Methods

The benefits drawn from asynchronous DTS investigation would aid OEM suppliers who operate large scale component orientated development or ESPs who operate various test resources. Both these applications align with the inter-organisational coverage and resource flexibility supplied by ATMS. The investment to upgrade their suite of test resources enable OEMs/ESPs to overcome challenges of communication between organisations, while also improving R&D productivity.

Use of Synchronous Methods

With respect to supply chain impact, synchronous DTS benefits could be shared to improve joint development between suppliers and vehicle manufacturers. The application of this test tool would see internal test rigs at suppliers and manufacturers be jointly used to towards emulation of complete physical vehicles or subsystems. The combined effort across the supply chain would aid in the principles of partnerships and joint ventures to establish bilateral sharing of expertise, resources and risk associated with vehicle product development projects.

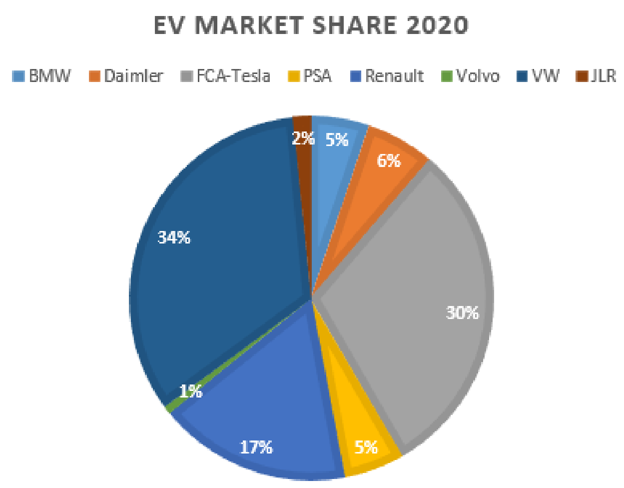


FIGURE 7.4: 2020 EV Market share of all major OEMs.

7.2.3 Market Impact

A market forecast was created to estimate the impact of improved productivity through the integration of automated and connected technologies. This model considered key organisational and economic characteristics to establish 5-year overview between JLR and other major OEMs [199]. The model illustrated the necessity of DTS for JLR to maintain current EV market share.

Firstly, a benchmark was created to establish all OEMs performance over the next 5 years. The model assumed that OEMs continue their pace of change in EV product sales. This indicated that all OEMs except for FCA, Tesla and VW were expected to lose market share from their current position (Figure. 7.4-7.5). In JLRs case this was attributed to low pace of change to electrification and reliance on hybridisation to meet immediate legal requirements.

For JLR to maintain or expand its current market share, there needs to be a rapid increase in pace of EV deployment and sales. To remain competitive, JLR requires an increase in EV shares of sale of approximately +5.5% a year. This would forecast that JLR's product line would be 100% electric by 2038. To ensure this JLR must scale up electrification R&D into the transition of its current platforms. The suggested value is however highly conservative and excludes assumptions that legislative bodies do not accelerate restrictions at a global or national scales.

Henceforth, the work conducted as part of this EngD could provide significant opportunities for JLR's sustainable operation in the consumer automotive industry.

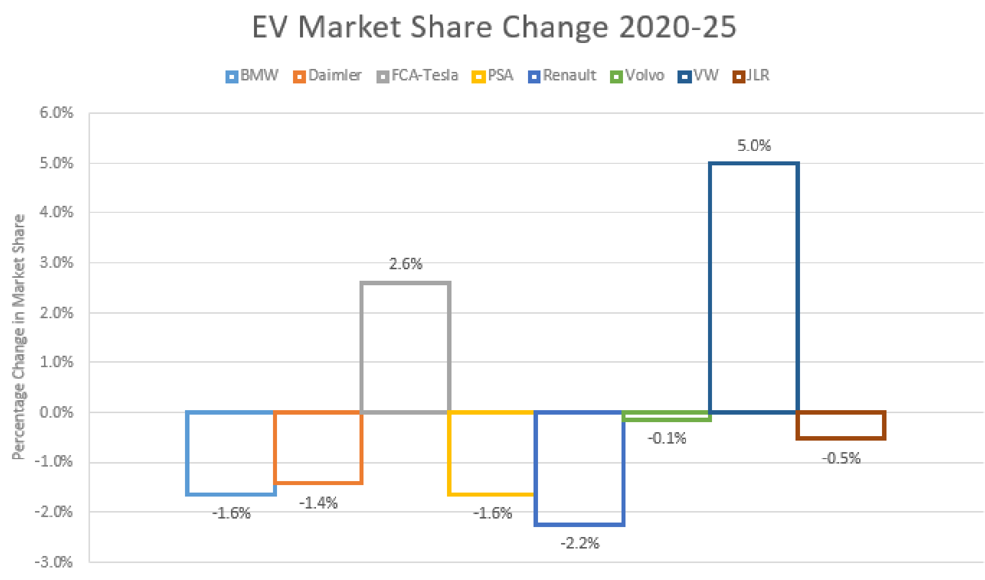


FIGURE 7.5: Change in EV market share 2020-2025.

The noted benefits from upgraded test resources and DTS variations align with the requirements for JLR to remain competitive. Automation of individual test resource and ATMS would increase capacity of electrification developments and improve agility needed to transform JLR's rate of electrification, while the synchronous DTS solution would improve quality to reduce costs associated to prototype and late project integration issues.

7.2.4 Market Advantage

First-mover Advantage

The developments as part of this study were targeted towards organisations pursuing first-mover advantage. This strategy of market domination looks for:

- Early access and capture of customer.
- Refinement and mastery of product and market knowledge.
- Accumulation of scarce resource, and denying competitors of them [200].

The payoffs created as part of this strategy have influenced the market share and competitiveness of companies.

Critically, the success of the first-mover strategy in the automotive industry is subjected to the characteristics of the market and development of vehicle technology. The

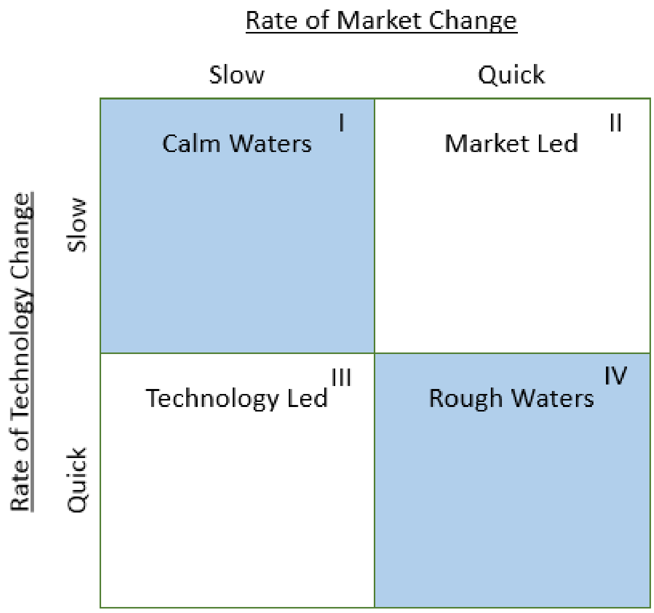


FIGURE 7.6: Market-Technology matrix that categorises the impact of first-mover advantage in various markets.

rate at which the product technology changes and the rate at which the market evolution occurs, influences the rate at which the first-movers advantages occur as well as the overall up-take of the new technology. This can be visualised in market technology matrix (Figure. 7.6) [201]. With respect to the luxury automotive industry that resides in the 'calm waters' quadrant, the behaviour of this market benefits first movers through the ability to capture a larger portion of market share and aggregation of product knowledge to establish long-term durable first-mover innovation [202].

Powertrain Advantage

In particular, battery electric powertrains can be argued as a product that would benefit from a first-mover advantage. The current layout of this powertrain as well as the purchasing habits of consumer are unlikely to significantly change. OEMs that release their product earlier than competitors would be more likely to claim a greater market share, while developing knowledge to gain long term sustainable innovation and securing supply chains for advanced battery technologies.

This could be further sub-divided to consider rates at which key powertrain components mature. Notably, this would place inverter and electric machine technologies in 'calm waters' quadrant (Figure. 7.6) where customer market demands have remained unchanged and the maturation of these components results in no major technical jumps. This protects current first-movers from being under-cut from followers and are unlikely to have product become redundant due to a lack of market change.

However, battery technologies could be perceived to be in a mix between 'Calm water' and 'Technology lead'. The maturity of liquid lithium batteries could be interpreted as slow changing, while advances in solid-state and other exotic cells as rapidly growing technologies (Figure. 7.6). This would suggest that a first-movers position is favourable, but would likely require long-term commitment towards technology to ensure that its position is preserved from competitors.

Quantitative Analysis

With reference to JLR's current SUV product line, quantitative analysis of the first-mover advantage revealed the opportunities for additional or lost revenue potential. A numerical model based of 2019/2020 production volumes (Figure. 7.7), model / specification pricing (Figure. 7.8, and back calculation of price mix (Equation. 7.2) revealed that flagship products such as the Range Rover Sport and Range Rover would generate almost £800 million per month in revenue (Table. 7.5). Utilisation of the first-mover advantage through the application of improved test productivity and quality could result in this additional capture of revenue (Figure. 7.9). From an alternative perspective, the improved research quality provided by the EngD's innovation could prevent the lost revenue associated with late delivery of products in a similar magnitude.

$$\begin{aligned} Revenue._{model} = {} & (Productmix_{low-high} * Production.volume * price_{low}) + \\ & ((1 - Productmix_{low-high}) * Production.volume * price_{high}) \end{aligned} \tag{7.2}$$

The results from the impact analysis provide an estimate of the time saved per vehicle model to determine the additional revenue gained from the proposed innovations. In an ideal case with the same innovation adoptions rate, each vehicle would be completed 0.49 months earlier, providing a total of £1.1 billion in revenue. This

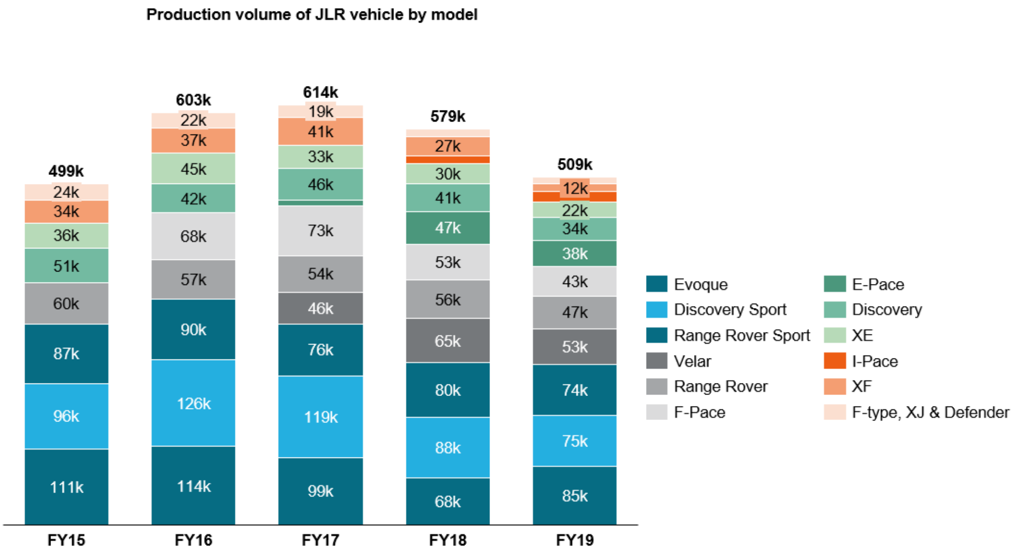


FIGURE 7.7: JLR reported production volumes between FY15-19.

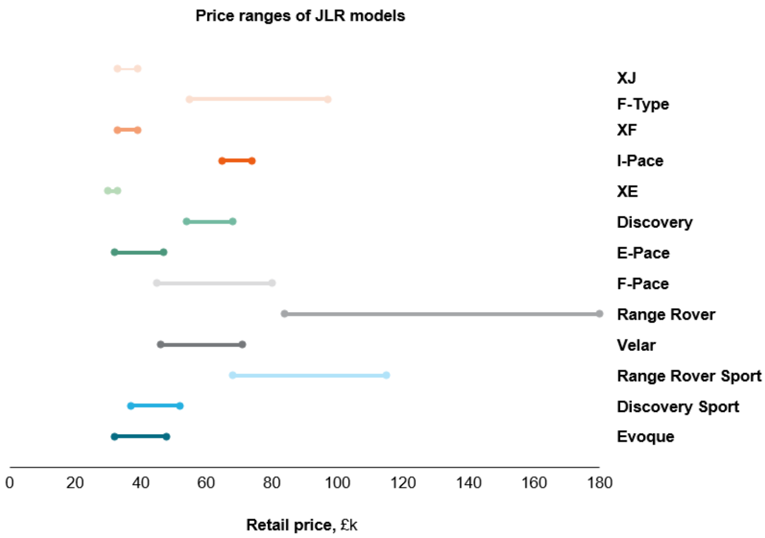


FIGURE 7.8: JLR model pricing FY19.

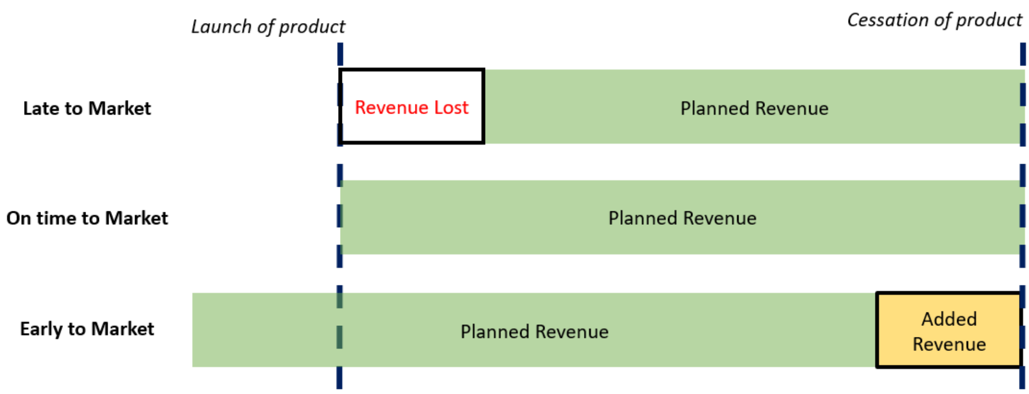


FIGURE 7.9: Visualisation of first-mover added revenue.

Model	Category	Units	Revenue	Profitability
Range Rover Sport	Large SUV	6190	£417,192,200	High
Range Rover	Large SUV	3941	£368,927,700	High
Velar	Medium SUV	4409	£195,020,300	High
Discovery Sport	Small SUV	6214	£192,689,100	Low
Evoque	Small SUV	7092	£192,098,700	Low
F-Pace	Medium SUV	3616	£150,804,900	Mid
Discovery	Medium SUV	2806	£130,520,100	Mid
E-Pace	Small SUV	3158	£84,673,400	Low
I-Pace	Medium SUV	1322	£73,357,300	Low

TABLE 7.5: Monthly revenue potential of current SUV product line up based of FY 19/20 data. [171]

gained revenue would spread throughout the development period, improving vehicle pay-back periods and profitability. However, these financial gains may not translate in reality with complex work scheduling resulting in saving only indirectly impacting completion dates.

Follower-Advantage

However, there are arguments that oppose the first-mover advantage of product and technology deployment. Termed as the follower's-advantage, this approach follows a critical mind-set of observing the first-movers, acquiring further knowledge to adjust products and then only releasing technology to market [203]. This strategy as a whole benefits followers as the observation of the performance of the first-movers builds an informed perspective on investment of business and technical resources towards building a superior product to out-compete first-movers. As with the first-mover advantage, counter strategy is also highly dependent on technology and market characteristics. In rapidly changing technology environments such as those in quadrant III and IV of the market-technology matrix (Figure. 7.6), the follower strategy has an ability to protect itself from R&D in obsolete technologies. Thus with consideration of market behaviour the overall benefit of this strategy is suited to technology led environments (quadrant III), where new entrants can out-perform incumbents, whereas rough water (quadrant IV) environments snub the long-term advantage of first movers, but also increase the difficulties for followers to react in deploying competitive products.

Technology Advantage

A follower-advantage could be suggested as a more effective strategy for the development of vehicle technologies such vehicle thermal comfort, lighting and accessories. With a relatively short development turnaround, combined with a frequently changing market demands, this alternate strategy would likely de-risk R&D investment. This strategy would allow OEMs to selectively pick successful vehicle technologies and avoid the necessary investment into developing technologies that would become obsolete and without little return.

In the perspective of the work conducted, application of ATMS would aid in product development agility for a followers-advantage strategy. The increased productivity achieved through this system would align with agile principles needed to mobilise technologies to quickly follow successful first-movers. As noted in *Chapter 6*, one of the key purposes of the automation of ATMS was to reduce total test duration for projects which enables an agile response to changes in the market.

7.2.5 Industrial Comments

In addition to the analysis conducted, a independent stakeholder/observer within JLR's provided their perception of the technology innovation proposed by EngD and how it would impact their department. A written response provided JLR's reflection on the applicability of both types of DTS and their impact onto JLR's strategy (Figure. 7.10). The stakeholder chosen was outside of immediate interaction of the project to minimise bias, while ensuring that they had enough exposure to provide a meaningful comment based on sound understanding of the work conducted.

The comments aligned with several aspects raised through the discussion around the technical and operational benefits. The poor economic climate caused by COVID-19 and the uncertainty of the U.K automotive market imposed by the United Kingdom's exit of the European Union, established circumstances disincentivised vehicle manufacturers, OEMs and ESPs from investing in such technologies presently without guarantees of positive market growth.

Importantly, a perception of the research's contribution to innovation from a source external of JLR would be difficult to attain at the this stage of development. This

SYNCHRONOUS DISTRIBUTED TEST NETWORK *– This has the potential to transform JLR's testing strategy. The biggest problem that we have is coordination of effort to ensure everything comes together at the right time at the right level of maturity. This could reduce testing costs significantly by reducing the number of prototype cars required if the subsystem and system tests could be done remotely. This could enable earlier testing and give a greater level of confidence earlier in the development cycle. A single vehicle prototype is of the order of a million pounds. Such a system could possibly avoid multiple vehicles for a given vehicle programme. Again the difficulty in implementation would be significant and would need to be driven by our Purchasing team who would ask our supply base to set up a suitable interface. The current economic climate is not suited to such an undertaking.*

ASYNCHRONOUS DISTRIBUTED MANAGEMENT SYSTEMS *– whilst the idea is sound and will obviously reduce waste it is difficult to estimate a monetary value. If it were completely and properly implemented the value would be large, mainly in terms of man-hours saved. The largest part of the engineering budget is spent on man-hours, therefore, this figure would likely run in the millions of pounds. The difficulty involved in implementing a system of this type would be significant and would involve a sizable investment. JLR is constantly on the look-out for such innovative ideas but has no appetite for such disruption and investment at this point in time due to uncertainty relating to Brexit and COVID-19.*

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FIGURE 7.10: Stuart Roberts (Manager of STRIVE), JLR's response to the finding of the DTSs investigated as a part of the EngD study.

EngD conducted under JLR's funding and assistance through the understanding that the research's intellectual property is owned solely by JLR. Therefore, it would be difficult to gain an external perception of innovation at this stage where work has been conducted internally of JLR. The nearest alternative option would be only viable once the system is deployed in a partnership where an external stakeholder would be aware of the developments and a non-disclosure agreement in place to protect JLR's property.

7.2.6 Coordination and Competition

The success and impact of these developed test technologies is dependent of the strength of long-term relationships across the supply chain. The coordination of test resources especially those established by the introduction of DTS look to strengthen relationships between manufacturers and suppliers. This requires significant commitments from all stakeholders to introduce and maintain these technologies for mutual benefit.

The fundamental of knowledge sharing by these technologies looks to expand capability by the promotion of explicit over tacit knowledge. The sharing of product requirement and verification data looks to share explicit information that creates consistency among objectives and actions along the supply chain [204]. Explicit data is not tied to specific resource or individual, as seen with tacit data that is more driven by culture. The proposed technologies are intended to optimise the current processes as a strategic innovation that could be reflected across multiple areas, rather than developing tacit knowledge in a single location which is difficult to transfer at various stages, both internally and externally of organisations.

Market Competition

Importantly, market competition has an effect on an organisation's willingness to invest in knowledge sharing technologies. In cases where product maturity exists, tendering by manufacturers for components are likely to create competition between multiple suppliers and therefore provide purchasing power enabled by quality and cost. Though this may promote technical and costs innovations by the suppliers, these relationships are short-lived with the manufacturer capable of choosing an alternative supplier to gain a price advantage. For this specific reason synchronous DTS maybe only supported for specific components, where both stakeholders perceive a long-term relationship provided by exclusivity of value adding products, technical knowledge and costs.

However, the elevated motivation for long-term partnerships and joint ventures around coordinated and automated test resources could received better by organisations with aligned perceptions and beliefs. Studies have found that culture, openness and communication as vital foundations that prevented early dissolution of partnerships [205, 206]. With the basis of the technologies developed to increase communication and de-risk R&D activities, stakeholders could perceive engagement in distributed test systems by partners as commitment to invest and champion sustainable collaborative long-term growth. These are collaborations with existing partners are more likely to arise during periods of uncertainty (such as those brought about from COVID and electrification revolution), were the alternative of forming new relationships are perceived as risky due to required investment and interaction ambiguity in a new unfamiliar partnership [207].

Agility

The time taken to establish a suitable joint venture between numerous suppliers and manufacturers to effectively use this technology could reduce the holistic industrial impact of DTS. Common failure of IJVs typically centre around issue with insufficient planning, excessive compromising, lack of internal on-boarding and balancing expectation of progress [208]. DTS deployed between manufacturers and external stakeholders would need to take steps to either overcome or mitigate these issues. The degree of achieving this is subject to the time pressure, willingness to absorb costs and quality expectation of deliverable (as related to a standard project scope triangle, where organisation in most cases can only priorities two of the three elements and must sacrifice the third). Regarding JLR's adoption of a DTS across a joint venture, stakeholders are unlikely to sacrifice expectation of quality leading to compromise between cost and speed of deployment. On one hand, manufacturers like JLR are pressured to accelerate their development of electric vehicles and manage costs to minimise lost sales brought on by rapidly approaching restrictions for combustion vehicle sales. However, wariness of unproven investments and sensitivity of costs in organisations could also deter stakeholders from committing to costs of the system without guarantees. As a result, with the novelty of DTSs and necessary stages for real-world deployment, manufacturers would be hesitant to commit the spend needed to push for the technology as soon as possible, and therefore need to expect and prepare for long-term partnerships with all stakeholders when deploying such a systems.

Chapter 8

Conclusion

8.1 Outcomes

In conclusion, the research evaluated the potential savings provided by implementing automated and connected technologies towards bridging the gap between combustion and electric vehicles. Three implementations of these technologies were proposed to illustrate their benefits across the testing and development of electric vehicle powertrains. By carrying out these investigations, it was possible to determine the capital and productivity savings that could be gained and utilize them to estimate the financial impact that could benefit manufacturers and consumers.

The study found that overall savings could be made with the proposed technologies. However, the impact on consumers would be minimal and unlikely to bridge the gaps between upfront costs for combustion and electric vehicles alone. Using JLRs production data, the study found an overall 1.71% saving could be made across the transformations of JLRs remaining models that require the shift to electric. Consumers would only see a little saving of approximately £91 per vehicle. As a result, the proposed technologies only provide a marginal benefit to the consumer, and other technical/business innovations are needed to incentivize consumers to electric vehicles.

However, the savings would still be significant to manufacturers. With an estimation based on JLR's product line, a £225m in saving provides significant capital benefit. An additional opportunity to release models earlier produces a net gain of £1.1bn in revenue. Such changes could help financial stresses on manufacturers who have struggled to remain profitable in recent years.

8.2 Success

The aims of this research were achieved by taking a holistic approach to target costs for the research and development of electric vehicle powertrain components and systems. This was achieved by targeting savings made through costs attributed to human resources (man-hours), capital costs of parts and assets (£), and costs associated with the development of facilities (£). The broader approach allowed full utilisation of benefits presented by automated and connected technologies.

DTS and the automated dynamometer provided the most significant net benefit towards the 1.04% (1.3m man-hours) in human resources. They provided 90% and 9% respectively in total savings. DTS reduced the number of prototypes needed and the resources required for their development, while the automated dynamometer specifically targeted a reduction in human resources through task automation.

Moreover, the 0.71% of capital cost saving was primarily made through the DTS' implementation. DTS offered a nominal opportunity saving of £7.5m per vehicle model. Manufacturers adopting DTS could avoid developing a noticeable number of vehicle prototypes that hold development value due to the low production volumes and costs associated with developing and modifying them.

8.3 Significance of findings

Firstly, the innovations proposed made an effort to reduce physical testing and development costs in response to their expected increase in demand with the industry's transition towards vehicle electrification. Manufacturers hold a reduced understanding of the details of EV components and systems compared to combustion alternatives. As a result, manufacturers are more dependent on physical testing to inform modelling methods and decisions needed to understand and extract the best performance from vehicles. They were saving made by the proposed technology help to minimise any increase in development costs due to their demand.

Furthermore, the research introduced steps toward automating the physical testing of EV components and systems. Using HIL RT technologies, off-the-shelf components enabled automation and connectivity of test rigs to a) reduce human demand to operate tests and b) reduce the necessity for costly processes and assets needed to evaluate vehicles fully. The impact could ultimately have a broader influence once the full applications are realised and applied to examples outside of the ones highlighted within this study. This wider influence could ultimately lead to more significant savings improving the financial performance of manufacturers and costs to consumers.

Notably, the research into DTS captures additional knowledge on the influence of network performance on the testing of EV powertrains over a network of facilities. Research into DTS performance and applications towards EVs highlighted an initial overview of the capabilities and limitations of a delivered product. The research sets a foundation for additional research into developing simulations required to evaluate the performance of other DTS configurations and a set of minimum requirements around the infrastructure needed to evaluate EV powertrains successfully.

Finally, ATMS draws corresponding elements of DTS and applies them in combination with optimisation algorithms to improve testing capability. The research evaluates connected technologies outside of applications that need synchronous RT communication. The base structure of the system was proposed and developed, while an example of optimised test case generation was evaluated. Findings from the research could be used to develop the system further to automate component testing and utilise additional data sources (external of manufacturers, e.g., customer data) to test vehicle components and systems efficiently.

8.4 Limitations

In summary, the work conducted to evaluate these technologies uncovered initial insights into these technologies and would need additional research and physical verification to exact the precise functions and benefits. The research provided proof concepts for each of the areas. Additional work would be needed to exact the details and integrate them into existing industrial processes.

In addition, the innovations' impact on broader vehicle engineering stakeholders would need to be determined. The net saving provided was taken from its adoption to an automotive manufacturer and did not speak to the saving made from OEMs and

ESPs. These other stakeholders' savings should also impact the final developmental value of vehicles but would need a deeper analysis into where these technologies could be applied to maximise their benefits.

8.5 Further research

Notably, the research highlighted several vital questions that could further unlock the proposed technologies' potential and expand their application further. Research should be conducted to understand the appetite among automotive stakeholders across the supply chain to engage in large-scale DTS use and what expectations would be. By understanding what these are, the DTS research could be guided by this information to identify detailed applications and understand its broader benefit in the supply chain.

Furthermore, ATMS' other optimisation processes should be understood and evaluated. Research briefly looked over a specific case of optimisation for component tuning. However, other test purposes such as verification testing, mapping, and calibration could also provide opportunities for value refinement. Once these have been evaluated, they could be added to the existing capability of ATMS to improve its ROI impact.

Finally, ATMS used data internally within components and systems to optimise test performance. Data externally could be used from customers and other automotive partners to improve test case creation and generation. By establishing this link, an effective feedback loop could be generated to ensure changes to the product are reflective of the real-world performance of vehicles at an earlier stage in the vehicle development cycle.

Appendix A

APPENDIX A

A.1 Facility Cost Table

Facility	Cost per day
Hub Dynamometer	£1200-£2000
Battery Cell Chamber	£800-£1000
Battery Pack Chambers	£3000-£6000

TABLE A.1: Daily cost of test facilities at WMG.

A.2 Hourly cost of staff

Human Resource	Hourly Rate	Cost per day
Engineer	£19.44	£145.8
Technician	£15	£112.5

TABLE A.2: Human resource costs at WMG.

Appendix B

APPENDIX B

B.1 DTS Simulation Tabulated Results

B.1.1 Velocity Mean Absolute Error

Exec. Rate	1ms	10ms	100ms	1000ms	2000ms	5000 ms	10000ms
10kHz	0.0399	0.0399	0.0399	0.0399	0.3099	0.0399	0.0399
1kHz	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399
100Hz		0.0399	0.0399	0.0399	0.0399	0.0399	0.0399

TABLE B.1: Average absolute velocity error (m/s) observed over execution rates 10khz, 1kHz and 100Hz in the DTS simulation.

B.1.2 SOC Error

Exec. Rate	1ms	10ms	100ms	1000ms	2000ms	5000 ms	10000ms
10 kHz	0	0	0	-2.20E-6	-2.19E-6	-2.17E-6	2.12E-6
1kHz	0	0	0	-2.20E-5	-2.19E-5	-2.15E-5	-2.08E-5
100Hz		0	0	2.17E-6	4.75E-6	1.44E-5	3.34E-5

TABLE B.2: Final Delta in Battery SOC (%) measured against non-distributed simulation.

B.1.3 Average Absolute Voltage Error

Exec. Rate	1ms	10ms	100ms	1000ms	2000ms	5000 ms	10000ms
10 kHz	0	0	0	5.90E-5	1.30E-4	3.43E-4	0.007
1kHz	0	0	0	5.90E-4	0.0013	0.0034	0.007
100Hz		0	0	0.0071	0.0142	0.0353	0.0698

TABLE B.3: Average absolute voltage error (V) observed over execution rates 10khz, 1kHz and 100Hz in the DTS simulation.

B.1.4 Average Absolute Current Error

Exec. Rate	1ms	10ms	100ms	1000ms	2000ms	5000 ms	10000ms
10 kHz	0	0	0	5.37E-4	0.0013	0.0035	0.0073
1kHz	0	0	0	0.0054	0.0128	0.0352	0.0724
100Hz		0	0	0.0746	0.149	0.3707	0.7355

TABLE B.4: Average absolute current error (A) observed over execution rates 10khz, 1kHz and 100Hz in the DTS simulation.

Appendix C

APPENDIX C

C.1 Impact model calculations and assumptions

C.1.1 Benchmark

Sub-model assumptions

Name	Value	Justification / Source
Gross margin	25.1%	2020 JLR strategy report. Only available from group.
Break-even period	2 years	JLR fleet present estimates 1 year, EVs are likely to increase break-even periods. (*J. Parsons, 2022, personal conversations*)
Engineering staff	8000	JLR strategy report 2015.
Working weeks	47	Account for 25 days annual leave.
Weekly hours	37.5 hours	Nominal hours at JLR.
Productivity	80%	Estimate of typical productivity of staff.
Models develop in parallel	6	1.5 vehicle developed per year, each model developed for 4 years.

TABLE C.1: Assumptions and justifications in development cost benchmark calculations.

Calculations

Model development costs

$$ModelDevelopmentCost = ModelRevenue * ProfitMargin * BreakEvenPeriod \tag{C.1}$$

Man-hours

$$Manhours/model = \frac{N_{Engineering_staff} * WorkingWeeks * WeeklyHours * Productivity}{ModelsDevelopedInParallel} \tag{C.2}$$

C.1.2 Proposed savings

Total saving per model

	Cost saved	Man-hours saved
Auto. dynamometer	£0.14m	7050
DTS	£7.5m	70500
ATMS	£0.02m	917

TABLE C.2: Savings made through each proposed technology per vehicle model.

Breakdown of savings

	Cost	Man-hours	Justification
Volume	1	1	One deployed
Duration	94 wks	14,100	2 years in development. x4 Engineers at 37.5 hours per week.
Saving	£1.5k	50%	£750 per week per engineer.

TABLE C.3: Indicative savings made the automated dynamometer.

	Cost	Man-hours	Justification
Volume	10	10	10% off 100 prototypes per model.
Duration	-	3525	Each prototype assigned 2 engineer for a year development period.
Saving	£750k	-	Mid-estimate to prototype value.

TABLE C.4: Indicative savings made by DTS.

C.1.3 costs

Overall costs

Details costs

	Cost	Man-hours	Justification
Volume	2	2	Deployed to develop BTMS and PTMS systems.
Duration	70500	3525	An engineer for two year development period.
Saving	13%	13%	

TABLE C.5: Indicative savings made by ATMS.

	Cost per unit	Number of units	Sub-total
Auto. dynamometer	£0.1m	6	£0.6m
DTS	£0.2m	6	£1.2m
ATMS	£0.1m	12	£1.1m
Total			£2.9m

TABLE C.6: Implementation costs for each innovation product with ATMS serving both BTMS and PTMS development. Scaled for 6 vehicles model developments in parallel.

Items	Unit costs	Quantity	Sub-total
HIL RT controller	£750,000	1	£750,000
Network equipment	-	-	-
Safety equipment	£1,000	1	£1,000
IT equipment	£500	2	£1,000
Existing work overheads	£700	9wks	£6,020
Implementation costs	£1,600	12WKS	£19,200
Total			£102,220

TABLE C.7: Costs and existing overheads associated with materials and effort required for the deployment of a single implementation of an automated dynamometer.

Items	Unit costs	Quantity	Sub-total
HIL RT controller	£750,000	2	£1,500,000
Network equipment	1,000	2	£2,000
Safety equipment	£1,000	1	£1,000
IT equipment	£500	2	£1,000
Existing work overheads	£700	9wks	£6,020
Implementation costs	£850	48WKS	£40,800
Total			£200,820

TABLE C.8: Costs and existing overheads associated with materials and effort required for the deployment of a single implementation of a DTS.

Items	Unit costs	Quantity	Sub-total
HIL RT controller	£750,000	1	£750,000
Network equipment	£1,000	1	£1,000
Safety equipment	-	-	-
IT equipment	£500	1	£500
Existing work overheads	£700	4wks	£3,010
Implementation costs	£850	12WKS	£10,200
Total			£90,710

TABLE C.9: Costs and existing overheads associated with materials and effort required for the deployment of a single implementation of ATMS.

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