COSTLY DECISIONS – CREATING PRODUCT STRATEGIES ROBUST TO MARKET INSTABILITY AND COST VOLATILITY

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ABSTRACT

In a competitive and fast-paced EV marketplace, how can it be ensured that the right decisions today, will still be the right decisions tomorrow? With rapidly advancing technology, increases in demand, and uncertain supply chains, manufacturers must consider material availability and cost volatility alongside range and performance. Tools and processes need to adapt to not only optimise components but help manufacturers and their supply chain build robust product strategies.

Drive System Design (DSD) has developed a system led approach, an Electrified Powertrain Optimisation Process (ePOP), which enables manufacturers to develop powertrain architecture concepts which match component specifications to best achieve vehicle targets, with objective awareness of the potential future cost implications of their decisions. ePOP enables the potential system design space for a given application to be thoroughly mapped. Through validated characterisation of subsystems and components and rapid generation of concepts, vast numbers of complete powertrains variants can be simulated. Each system can be analysed for performance and range and compared using intelligent trade off algorithms to study sensitivity to cost variations.

This paper will demonstrate the value of using the process to explore; the impact of potential raw-material cost fluctuation (for example rare-earth magnet cost instability), the impact of alternative cost trajectories in battery and inverter technologies, whether the price of steel could result in new approaches to electrification. ePOP will be used to demonstrate the importance of objective system cost and performance analysis in the architecture concept stage, and how this can help manufacturers and their suppliers create product strategies that are robust to a variety of alternative market scenarios.

INTRODUCTION

While contributing a relatively small proportion of the total market currently [1], battery electric vehicles (BEVs) are expected to begin displacing conventional powertrain systems in the next five to ten years, before dominating the market place after 2040 [2]. However, for this to occur, there are a number of challenges that face manufacturers in order to increase widespread adoption, but also gain market share in a rapidly growing and changing marketplace.

Many studies and surveys have shown that the three main barriers to entry for consumers are cost, “range anxiety”, and fears related to charging and related infrastructure [1] [2] [3]. To gain market share, manufacturers must produce product strategies that tackle these issues, demonstrating more cost-effective solutions yet at the same time producing vehicles that meet growing range expectations.

Batteries are a significant contributor to overall vehicle cost (representing a huge shift in the relative value residing within the energy storage solution), as high as 75% [4], and so minimising battery capacity has major cost benefits. However, with “range anxiety” as prevalent as it is, guaranteeing satisfactory vehicle range is a factor that pulls in the opposite direction. As such, understanding how battery capacity can be utilised efficiently whilst still meeting operational range targets is a necessity for a robust product strategy. In this scenario, a much more holistic view to powertrain cost optimisation is needed, as traditional component focussed cost engineering can actually have detrimental effects. Removing cost from one component can increase that of another. For example, selecting a high-power density motor may reduce motor costs, but the need for higher current may result in a more costly inverter.

In order to do this effectively, careful consideration of each of the powertrain subsystems is required [5]. Downsizing components in each of the subsystems, the inverter, motor and transmission, as shown in Figure 1, as well as the battery, can provide cost savings. Improving the efficiency of these subsystems can also reduce the necessary battery capacity required for a given range, providing an opportunity to reduce costs further. Alternatively, this could provide competitive advantage in the marketplace through increased vehicle range.

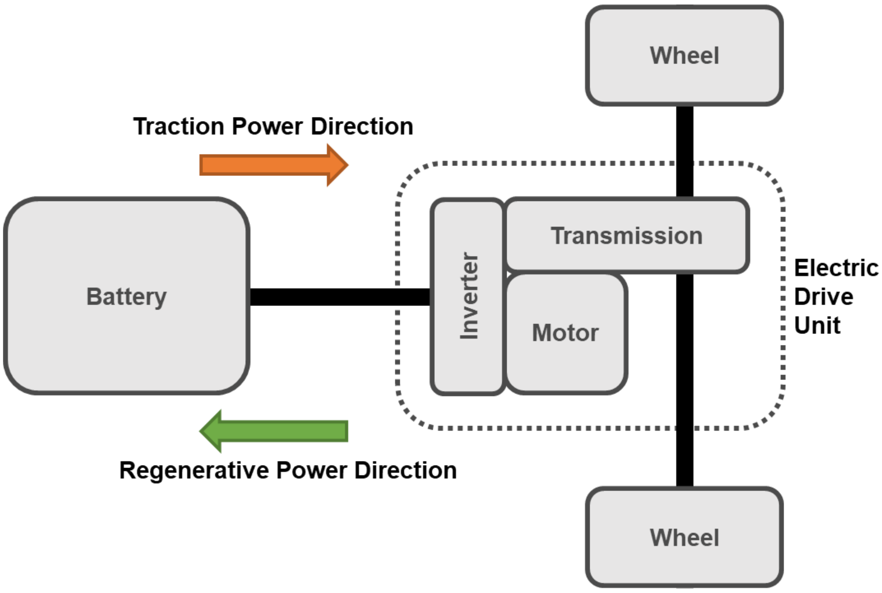

Figure 1 - Schematic diagram of an example electrified powertrain

Traditional tools and processes used to design and optimise powertrains have not necessarily kept up with this increasing complexity of sub-system interaction, nor the changing needs of the industry. This can make developing concept architectures time consuming, fragmented, and over dependent on subjective views, or bias towards “known solutions”. As a result, it becomes challenging to objectively determine answers to questions from “what is the best combination of components for a given vehicle?” to “what should a long-term electrification product strategy look like?”.

A fully considered system approach is required to begin to answer questions such as these, and it is this philosophy that has driven the development of tools at Drive System Design (DSD). The key enabler to the ePOP process is the characterisation of subsystem and component design, allowing the process to build complete powertrain variants for simulation.

ePOP rapidly generates a range of viable powertrain candidates, for a variety of topologies and layouts. The rapid generation of input data including component and subsystem size and masses as well as efficiency maps allows the simulation of many thousands of unique powertrain combinations, and comparison through intelligent cost functions and trade-off algorithms. This allows trade-off evaluations of cost and efficiency (or vehicle range), both of which are key to the future of electric vehicles.

Each of these concerns can be linked with one another, and mitigated through the optimisation of an electrified powertrain, and an electric vehicle as a whole. For example, range anxiety concerns could simply be addressed by using larger capacity battery packs. However, given typical battery costs, estimated at around $280/kWh in 2017 by the UK Advanced Propulsion Centre [2], tackling this as a single issue will likely result in increased costs, as batteries can represent as much as 75% of the total vehicle cost [4].

Approaching the issues in such a way is therefore clearly not appropriate. Optimisation of powertrain cost and efficiency must go hand in hand with optimisation of the complete vehicle. This may be in the form of minimising battery capacity and subsequent cost, or maximising vehicle range for a given vehicle platform. Each of these tackles the high-level market concerns surrounding BEVs. However, in order to create robust product strategies, understanding of the potential cost fluctuations for key cost contributors must also be considered.

An example of the expected cost trajectories as published by the Advanced Propulsion Centre are shown in Figure 2a. Manufacturers should develop products with an awareness of potential trends in future material costs, but also be prepared to manage the risks that the cost reductions predicted are not realised.

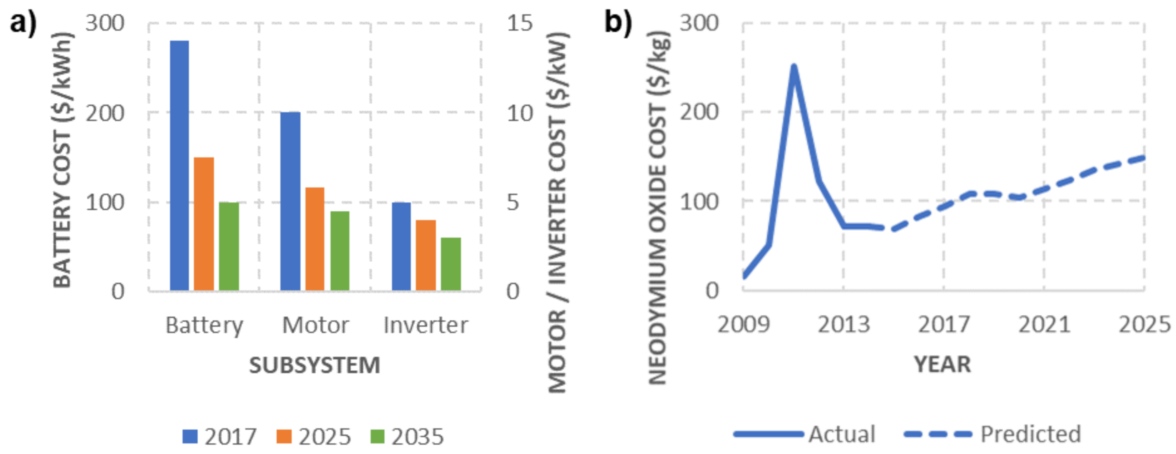

Figure 2 - Cost trends in electrified powertrain subsystems and materials; a) cost forecasts from the UK's Advanced Propulsion Centre [2], b) Neodymium oxide costs, 2009 – 2025 [6]

Figure 2b shows how the cost of neodymium, a dominant cost in many automotive motors, spiked massively in 2011 [6]. Robust product strategies will consider the potential implications of such cost volatilities and the potential value of alternatives whilst still considering their relative benefit on the system. For example, concepts that utilise higher levels of rare-earth magnet, whilst being sensitive to material cost fluctuations, may also reduce inverter current requirements and create more efficient systems. This in turn can yield battery capacity reductions and further cost benefits. This paper will demonstrate the value of the approach utilised by ePOP in providing engineers with the data to take an informed view on trade-off studies when selecting concept strategies.

SUBSYSTEM MODELLING

A key feature of the ePOP process is the ability to rapidly and accurately model subsystems and components, to create input data for a range of inverter, electric motor and transmission variants, tailored to the requirements of the application [7]. The process generates each subsystem's characteristics, required for the vehicle simulation and cost functions.

TRANSMISSION MODELLING

The transmission subsystem modelling procedure enables the generation of input data for any characterised transmission architecture. A modular approach is adopted where the transmission is broken up into systems of parallel shaft and planetary gears sets, supported by shafts and bearings, as well as the necessary casings. Each is sized by required torques and ratios, allowing representative masses and power losses, and subsequently an efficiency map, to be determined. Multi speed transmissions can also be included by adding in systems such as clutches, sized using similar methodologies.

Figure 3 - A range of transmission systems can be considered

An example of the power losses for a single operating point for two transmission architectures is shown in Figure 4. A three-stage parallel axis transmission is likely to be both more costly and have greater power losses than a two-stage alternative. However, the source of the power losses differs, as a result of the lower individual gear mesh ratios. Finally, a three-stage design enables higher total ratio, and in turn makes smaller, high speed, low torque motors viable.

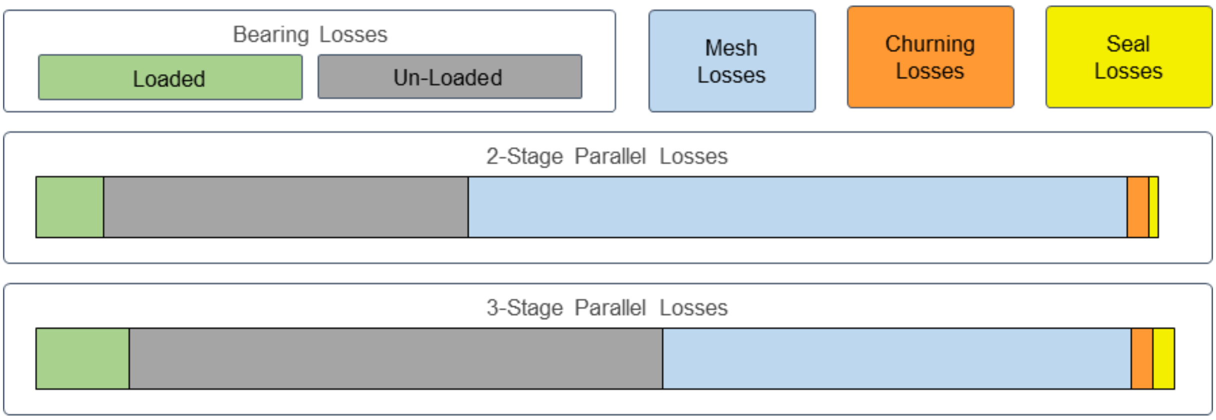

Figure 4 - Example power losses for two transmission designs for a given operating point

ELECTRIC MOTOR MODELLING

The electric motor models are generated through a subprogram developed in-house in Python, which calls Motor-CAD and automatically parameterises models to generate efficiency maps, material masses and inertias. The motor generation program is capable of generating a number of electric motor design types, utilising the appropriate Motor-CAD modules, including Permanent Magnet Synchronous Machines (PMSM) with multiple rotor topologies (surface permanent magnet (SPM) and interior permanent magnet (IPM) with multiple layers), induction motors and switched reluctance motors (SRM) as shown in Figure 5.

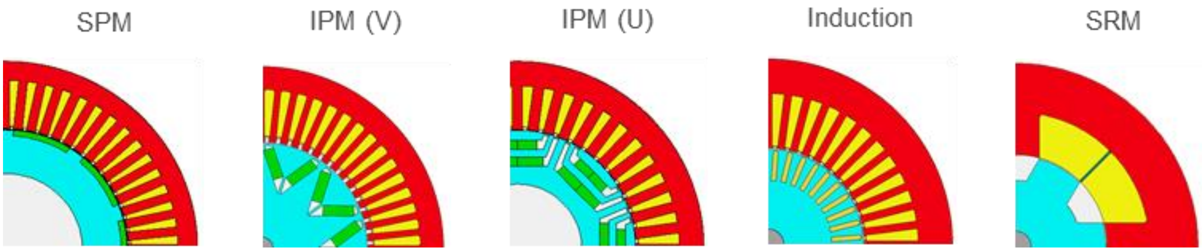

Figure 5 - A range of different motor types and topologies can be considered

The program receives a topology demand along other targets, such as peak or continuous torque or power. The program then selects suitable base geometry which meets the targets within thermal and structural limits, and iterates through a number of variables, to generate a range of viable designs that meet the required specification. Once a Motor-CAD model is generated, masses and power losses can be determined.

An example of the losses for a permanent magnet and induction motor for a single operating point are shown in Figure 6. As may be expected, reduced copper and iron losses offset the magnet losses resulting in the permanent magnet motor likely being more efficient. However, an induction motor could be expected to be lower cost due to the lack of magnet content, but without a complete system approach, it would be unclear as to whether this cheaper motor option would be offset by impacts on the system as a result.

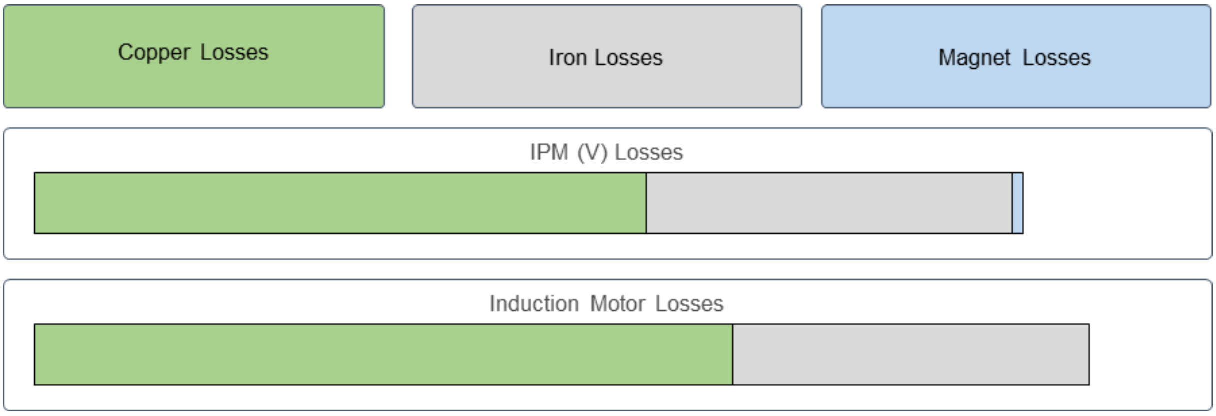

Figure 6 – Example power losses for two electric motor designs for a given operating point

INVERTER MODELLING

The two main inverter technologies currently in consideration are the conventional insulated-gate bipolar transistors (IGBT) and more recently available silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs). ePOP utilises a bespoke, DSD developed and validated inverter model that calculates the inverter efficiency map, mass and cost, all of which are required as inputs for the optimisation process.

An example of the losses for an IGBT and SiC inverter are shown in Figure 7. The SiC inverter can be seen to be more efficient than the more standard IGBT, by reducing gate losses, and eliminating diode switching losses. However, this benefit comes at an additional cost. This is an interesting trade-off that ePOP allows the user to investigate: for a given application, when does a SiC inverter become a viable solution, and what can be done in the remainder of the powertrain to enable this decision?

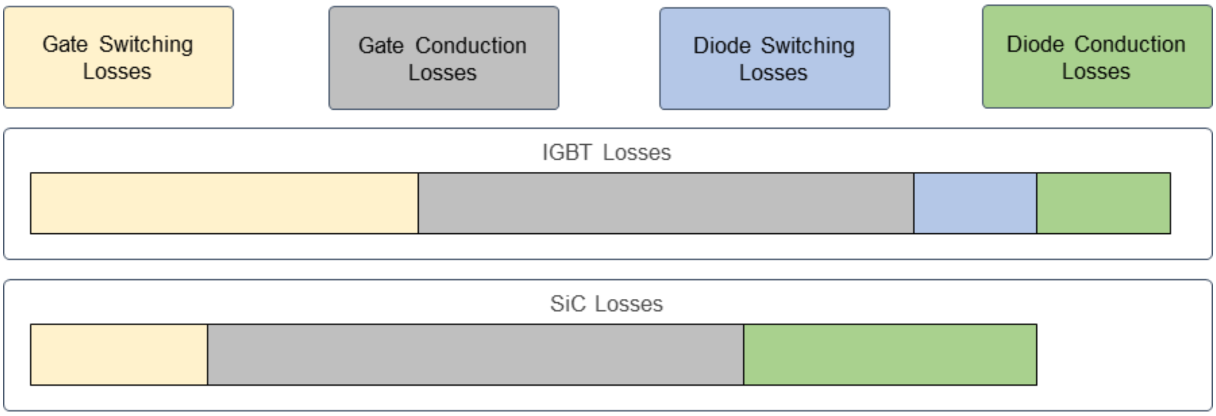

Figure 7 - Example loss breakdown for IGBT and SiC inverters at a given operating point

VEHICLE MODEL

The vehicle models are based in MATLAB / Simulink with a backwards-facing model being utilised for drive cycle simulation, and a forward-facing model used for performance simulations. The backwards-facing vehicle model accounts for the vehicle and component inertias, rolling resistance, aerodynamic drag, gradient and efficiency map to calculate operating conditions and drive cycle energy consumption.

The vehicle model allows subsystem performance to be directly related to vehicle attributes such as acceleration, top speed, or drive cycle efficiency, and allows assessment and comparison of different systems across their operating conditions in a fair comparison. This allows the user to identify trends that result in quantifiable performance benefits.

When simulating multi-speed transmissions, an idealised approach is taken to allow the fairest comparison of powertrains architectures, avoiding the influence of pre-defined control strategies. As a result, the vehicle can operate in the optimal gear at each time during the cycle. The shift energy is calculated during post processing to account for all energy losses/regeneration, with shift efficiency also considered.

SYSTEM COST

The cost function is primarily based on the bill of materials cost of each powertrain subsystem which is accurately estimated for each subsystem architecture considered. Additional costs and weightings can be added based on exceeding or not meeting targets for weight and / or performance, or penalised as a result of associated NVH risk, or exceeding a given package volume or shape.

A key contributor to electric vehicle cost is the battery. Within the cost function, the process compares the vehicle range determined by a defined battery capacity and the drive cycle energy consumption and compares it with the target range for the vehicle or application. Each powertrain subsequently receives a cost penalty, or cost reduction, proportional to the shortfall or surplus in range achieved. The magnitude of this penalty is determined on a cost per kilometre basis, utilising estimated battery costs such as those previously shown in Figure 2a from the APC. This method allows the user to quantify the benefit of investment in powertrain efficiency.

CASE STUDY

In order to understand the benefits of system approach as described, a case study vehicle will be defined, and the potential design space for the electrified powertrain explored. The aim of the study is to identify a range of alternative solutions for the powertrain and its subsystems and how several application specific trade-offs must be considered in order to identify an optimal solution that meets both energy consumption and cost targets.

For this example, an all-electric four door sedan has been selected, and market typical performance targets identified; minimum top speed of 160 kph, acceleration from 0 to 100 kph in 7.5 seconds or less, and a fixed battery capacity of 100 kWh. Other application typical vehicle simulation parameters can be found in Table 1 in the Appendix.

A range of alternative powertrain options were to be investigated, with variations in the major subsystems, inverter, motor and transmission, all considered. For the motors, two interior permanent magnet topologies were considered, “V” and “U” shape, alongside induction motors. The peak power of all the motors were between 170 and 200 kW and varied in both pole number and phase current levels. Each motor was paired with either an IGBT or SiC MOSFET based inverter. Finally, each motor-inverter combination was matched with three alternative transmission types. To limit complexity in this case study, only parallel shaft configurations were considered, and were limited to either a single or two-speed transmission. The single-speed transmission consisted of either two or three gear stages, whilst the two-speed was limited to two stages. The ratio of each gear mesh was varied over a wide range, in order to simulate vast numbers of different operating conditions in order to assess optimal configurations for energy consumption and cost.

RESULTS

Each powertrain variant that met the constraints set by the performance criteria for the case study vehicle, over 17,500 viable options, was analysed over the WLTC. The resulting energy consumption and powertrain cost for each potential variant are shown in Figure 8, where the large number of unique powertrains that have been analysed can be seen. Figure 8a shows the powertrain cost in isolation from the energy storage, whilst Figure 8b includes the combined impact of battery cost as part of the overall powertrain cost.

The two clear clusters shown in Figure 8a indicate the two inverter types analysed in the study, with silicon carbide inverters in orange, and IGBT inverters in blue. Two characteristics that may be expected can be seen; that using a silicon carbide inverter may result in reduced energy consumption due to reduced switching and diode losses, but the newer technology comes at a cost. However, once the impact of the battery cost is considered, as shown in Figure 8b, the relative system cost difference between the two inverter options is significantly reduced, illustrating the dominance over battery cost of the remainder of the powertrain.

Of further note is the difference in energy consumption across each of the simulated variants. Many Tier 1 suppliers and vehicle manufacturers are either utilising silicon carbide inverters or considering their implementation for their efficiency gains. The difference between the best and worst IGBT system however is far greater than the gains yielded by switching to SiC inverters, which highlights the potential benefit of this level of system analysis in the concept phase.

Figure 9 shows the same data set as in Figure 8 but analyses the impact of the alternative transmission designs considered; two and three stage single-speeds, and a two stage, two-speed, all based on parallel axis gears. For the simpler single-speed configurations, it can be seen that the reduced number of gear meshes and bearings and their associated losses results in a reduced energy consumption over the drive cycle.

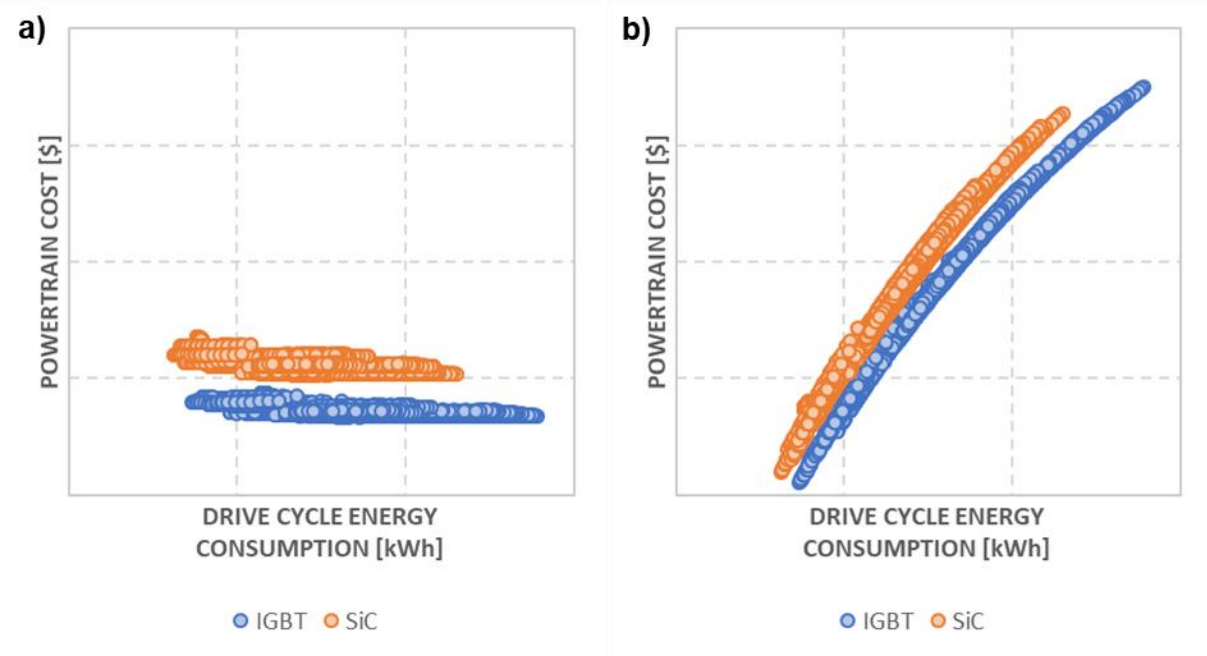

Figure 8 - Drive cycle energy consumption vs. powertrain cost for alternative inverter designs; a) powertrain cost only, b) powertrain cost including current battery cost

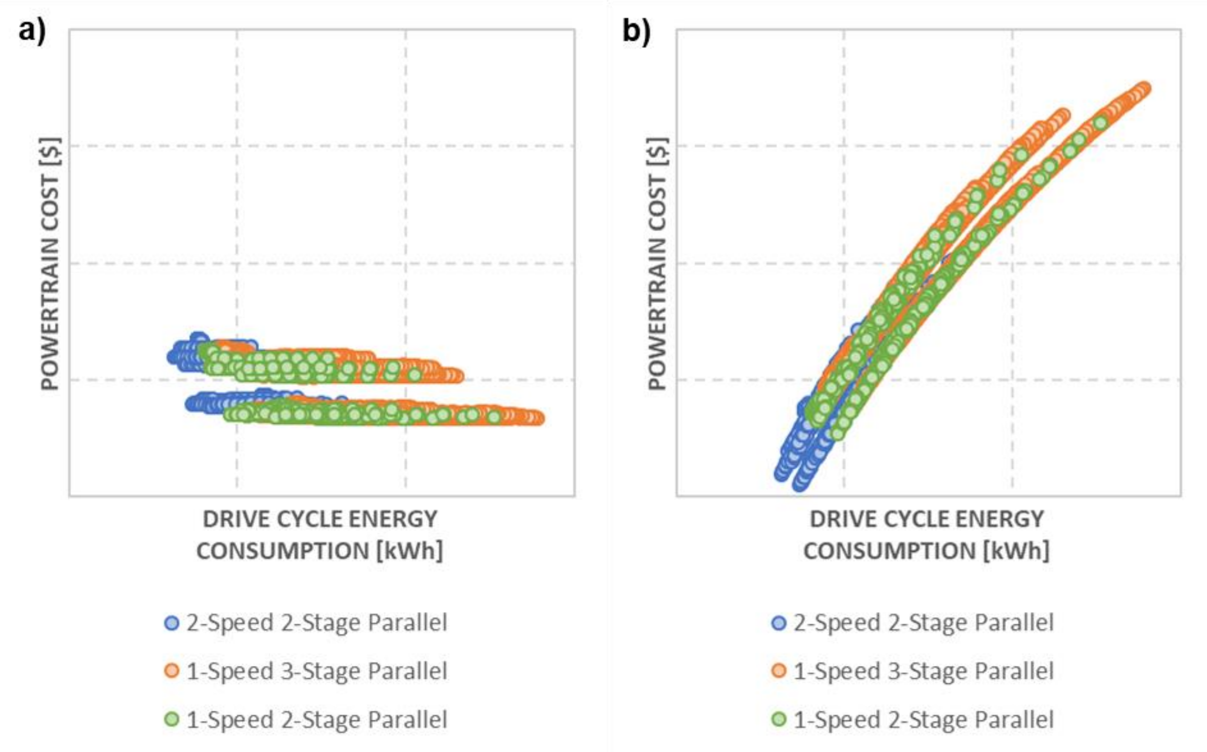

Figure 9 - Drive cycle energy consumption vs. powertrain cost for alternative transmission designs; a) powertrain cost only, b) powertrain cost including current battery cost

The two-speed transmission however results in reduced energy consumption over both single-speed configurations. The two-speed transmissions enable the peak efficiency region of the powertrain to be more effectively utilised, shifting between gears when efficiency reduces. This results in a reduced energy consumption, and less variation between the most and least efficient powertrains. As with the inverter selection previously shown, this performance improvement comes at cost. In this instance, the two-speed transmission options not only incur additional costs associated with the additional rotating components, but the shift mechanisms and subsequent control requirements. This is evident in Figure 9a where just the powertrain costs are considered, but the difference is offset once the battery cost is considered as in Figure 9b, which suggests that the efficiency benefit of a two-speed transmission can effectively pay for itself.

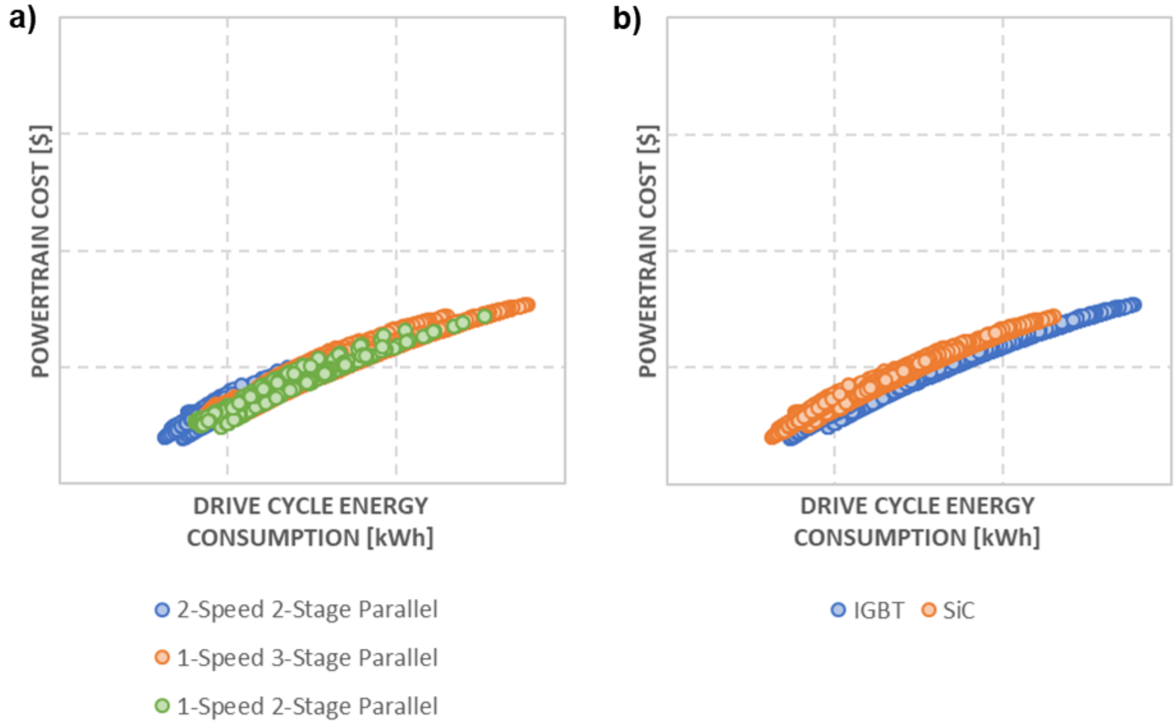

Figure 10 - Drive cycle energy consumption vs. projected 2035 powertrain cost including battery for; a) alternative transmission design, b) alternative inverter design

At this stage, the powertrain and battery have only been considered at costs typical of today. However, the decisions made today are regarding products to be manufactured years into the future, and product strategy decisions may be informing investment decisions which define technology choices for even longer periods (for example in manufacturing line investments). Figure 10a and Figure 10b considers the impact of cost changes on the two areas of investigation previously discussed, the inverter and transmission.

As previously shown in Figure 2a, the APC has projected that by 2035 batteries will reduce in cost by over 60% relative to their 2017 costs, whilst over the same period, inverter costs will also reduce by approximately 40% [2]. It could also be expected that whilst silicon carbide options for the inverter cost more in comparison to IGBT options currently, this gap will reduce as the technology is more widely adopted.

As a result, Figure 10 shows that the impact of the battery cost has been dramatically reduced, whilst the difference between the inverter options has closed accordingly. This may result in an alternative interpretation of the data, and subsequently, an alternative decision. For example, Figure 10a shows that the efficiency benefit of the two-speed transmission no longer has such an impact, and so the difference in comparison to single-speed alternatives has been greatly reduced. In this example, a single vehicle application has been considered, but when considering a number of vehicles or platforms, the decision to utilise single-speeds could more appealing. Figure 10b shows that the difference in cost between silicon carbide and IGBT options has become very small. This kind of analysis can be utilised alongside the assessment of technology at today's costs to determine the potential of new technology, and when investment is feasible for the longer-term gain.

A further area to consider is the impact of magnet cost. Figure 2b showed the cost volatility of neodymium since 2009, and as a dominant cost of many automotive motors, the impact of such variation must be considered. Figure 11a shows drive cycle energy consumption against powertrain cost, excluding battery, using current typical magnet costs. Figure 11b shows the same results, but instead considers magnet costs using the peak neodymium cost from 2011.

This results in a cost shift in both powertrain configurations utilising permanent magnet motors. Induction motors, with no magnet, remain unaffected. In Figure 11a, powertrains utilising induction motors are typically found at the higher costs for each of the inverter types previously discussed. A factor in this is the increased phase current that is required to achieve the performance requirements in an acceptable package volume. However, this increased phase current results in an increased cost in the inverter, so whilst the motor cost is typically lower as a result of no magnet, the net effect results in increased cost.

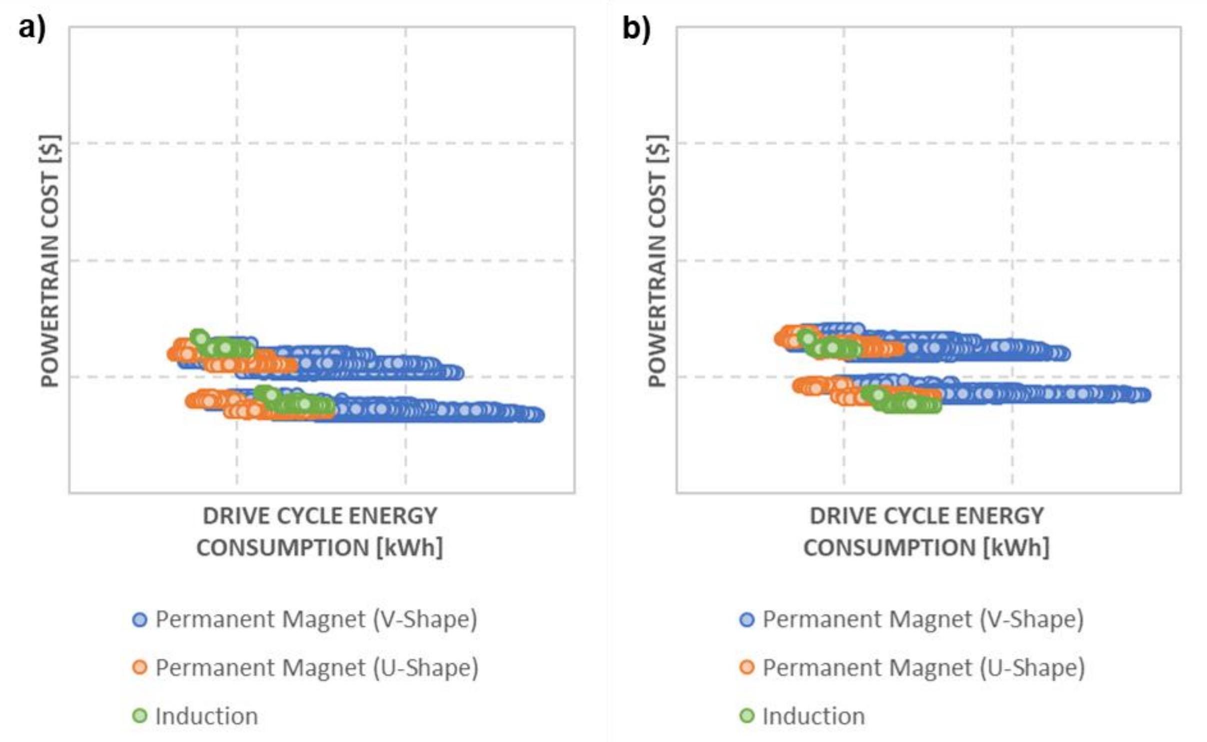

Figure 11 - Drive cycle energy consumption vs. powertrain cost excluding battery for; a) current magnet costs, b) peak 2011 magnet costs

If peak neodymium costs from 2011 are considered as in Figure 11b, this trend changes. The higher magnet cost results in the permanent magnet-based powertrains increasing in cost. Induction motor-based variants are now found at the lower end of the costs for each inverter.

This characteristic behaviour is further demonstrated in Figure 12, where the impact of battery cost has been considered. Figure 12a uses cost data representative of typical costs of today for both the powertrain and battery. In this scenario, whilst competitive, permanent magnet motor-based powertrains outperform induction motors in energy consumption and in cost. Figure 12b presents a scenario similar to previously discussed, where both batteries and inverters reduce in cost substantially by 2035. However, in this scenario, magnet costs have been increased to the same peak 2011 cost as in Figure 11.

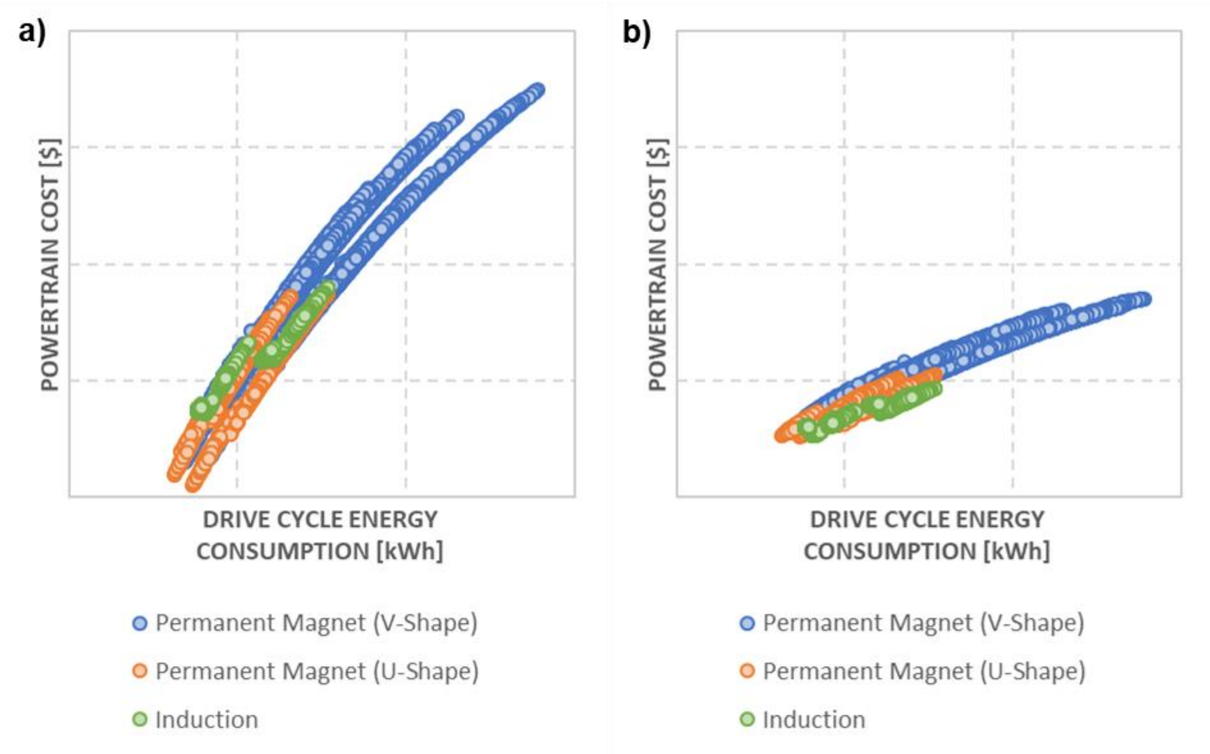

Figure 12 - Drive cycle energy consumption vs. powertrain cost including battery for; a) current costs, b) peak 2011 magnet costs with projected 2035 battery and inverter costs

The projected reduction in battery cost by 2035 reduces the relative impact of any efficiency gain on the total cost, resulting in a smaller difference between permanent magnet and induction motor-based powertrains. Similarly, as inverter costs have reduced, the impact of the higher currents utilised by the induction motors has a reduced effect. In combination with the peak magnet costs from 2011, a very different picture can be seen in Figure 12b. Both the difference in energy consumption and cost between the most efficient permanent magnet and induction motor-based powertrains is small, suggesting that induction motor-based powertrains have a justifiable place in considerations of future electrified powertrain strategies.

CONCLUSIONS

The range of technologies that exist in hybrid and battery electric vehicles is diverse and quickly evolving. As a result, manufacturers and suppliers face huge challenges to determine product strategies in such a fast-moving industry. The product strategy decisions made today will ultimately result in massive investments in manufacturing that commit to specific technologies for years to come. The more data that manufacturers can leverage to inform these decisions as early as possible the better. In order to create robust product strategies, these decisions, should consider market conditions both now and in the future.

The system approach adopted by DSD in ePOP facilitates the evaluation of powertrain product concepts in this manner and future impacts can be determined. Battery costs dominate the system cost in the current market, affording a significant value to technology that improve efficiency, such as silicon carbide inverters, multi-speed transmissions and permanent magnet-based motors. However, popular technologies do not necessarily provide the most robust solutions for the future.

If expected battery cost trajectories are to be believed, then it can be expected the relative value of high efficiency technology will be reduced over the next ten to twenty years. However, this assumes that current vehicle range expectations do not increase. If these expectations continue to increase, then battery costs will continue to dominate, as the impact of increased range will offset any potential saving per kWh, and efficiency improving technology will remain valuable.

A system approach such as ePOP allows the overall effects of such developments to be considered, and potential trade-offs analysed. In this paper, several other examples of the potential of such an approach have been presented. Whilst efficiency improving technologies have been shown to be beneficial, such as silicon carbide inverters, multi speed transmissions, or permanent magnet motors, the value of choosing the right overall powertrain concept for the vehicle application is critical. This can be seen by the efficiency improvement and potential cost reduction that can be achieved relative to any subsystem or component level selection.

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APPENDIX

Table 1 - Vehicle simulation parameters

Parameter	Unit	Value
Mass	kg	1700
Wheel radius	m	0.30
Drag Coefficient, Cd	-	0.23
Frontal Area	m^2	2.7
Rolling Resistance Coefficient	-	0.013