The Future of the Connected Powertrain

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Abstract: This paper will propose a cost effective monitoring system that provides a step change in the understanding of individual transmission usage profiles. It proposes a simple infrastructure in which a central analysis system can provide not only an accurate assessment of current transmission condition but a prediction of future failures at a component level. It then details how the analysis of actual usage data enables fleet cost and weight reductions through the significant downsizing and optimisation of transmission and driveline subsystems.

Keywords: Connected powertrain, duty-cycle prediction, pre-emptive maintenance, lightweight systems.

1. Introduction

The future of passenger transport is coupled with connected vehicle technologies. Manufacturers are exploiting the wealth of opportunities for product enhancements in the areas of safety and customer convenience systems through improved navigation and more accurate traffic information.

The ability to continuously exchange data between the vehicles via the internet to a whole range of connected devices represents real opportunities for powertrain design optimisation and cost reduction.

Large organisations such as Bosch are also utilising connected technology in vehicle development fleets for actively monitoring, evaluating and even calibrating vehicles across data connections [1].

At a time when powertrain efficiency and emissions are the key drivers for any manufacturer or commercial vehicle fleet operator, the ability to leverage new technology will become a key competitive advantage in an increasingly legislated industry.

2. Duty cycle definition and its influence on design

As is the case in many engineering disciplines, mass and cost of the powertrain are closely coupled with the specification of the duty cycle to which they are designed. As a result much of the mass and cost of a transmission or axle is defined even before the concept design has been realised.

At Drive System Design the design process starts in the world of simulation and analysis. Early product concepts are quickly assessed for component durability and life using tools that have been developed over many years of design and development experience whilst benefiting from correlation with many design realisations.

Figure 1 shows a typical early concept model of a transmission system designed for a specific package and functionality. The model supports space envelope studies and provides invaluable early feedback on any potential issues with component loads and life.
Whilst confidence is high in the models ability to predict the life of bearings, shafts and gears for given load profiles, if the load profiles are not representative the resulting design is likely to be designed with excessive safety margins to allow for uncertainty in the target specification.

Figure 2: Typical duty cycle data for transmission analysis

Estimation of the in-life loading therefore drives these attributes. Experience across design projects over many years suggests that design duties are typically over-specified with the result that unnecessary mass and cost is embedded into many vehicles. The very low failure rate in driveline components such as shafts, gears and bearings supports this theory.

The majority of genuine component failures can be detected in development durability testing and traced back to specific design issues. Failures such as the gear tooth tip failure shown in figure 3 are therefore very rare in service.

Whilst high safety factors and low warranty rates might appear to be a positive attribute, this is limiting the ambition of manufacturers and legislators to reduce mass and drive efficiency improvements in vehicles.

High factors of safety on duty cycles have come about for a reason. Duty cycles are typically derived from a relatively limited sample of development vehicles, which are used in a fairly limited range of environments and conditions. These conditions also tend to be representative of the heaviest of users i.e. worst-case situations.

Additional factors of safety to allow for uncertainty in the use of vehicles are also often included in the design process. The end result of this is that the vast majority of customers will end up paying for heavier drivelines which are over-specified for their needs in order to accommodate the needs of the heaviest duty users and the uncertainty in the specification and design process.

Figure 3: Gear tooth tip failure

3. Big-data informed design

The technologies enabling connected vehicles introduce opportunities to better understand how vehicles are used across a much larger sample of vehicle fleets in-service. Access to this data will allow designers to formulate a well-informed compromise between the requirements of the majority and the real worst-case loads.

First consider a typical normal distribution of vehicle usage profiles ranging from a very light duty to the very heaviest duty. We can expect the curve to have a normal distribution. A conventional design approach would aim to specify a system that meets the life requirements for the vast majority of drivers. This could be up to and above the 99th percentile user.

Now consider the effect of taking this same approach, but to correct the estimated distribution curve using measured data from a fleet of connected vehicles. Figure 4 illustrates how we might expect observed data to reduce the design duty of a given
product, simply by obtaining a better sample of real world data.

Figure 4: Usage profile for a vehicle fleet

Whilst this may seem a fairly obvious approach, data collection on such a large scale has not be economically viable for many manufacturers until recently. Reducing design duties, even by small percentages, across a range of components can accumulate significant mass reductions and associated cost savings.

The extent of potential savings will depend on how well the duty cycle has been estimated in the first place, but a recent study undertaken by researchers at the University of Darmstadt has predicted that simply correcting the reference duty to something closer to real-world could make mass savings in the region of 5% [2]. It is quite possible, however, that some manufacturers may find that the potential savings are even greater.

Figure 5: Impact of reducing design duty on warranty, mass and cost

A more precise understanding of fleet usage and duties increases confidence in the data and hence enables manufacturers to take a more informed choice to balance the embedded cost and mass in a system with the potential costs of failures in service.

Once confidence in the duty data improves, designing for the 99th percentile duty might not be the only solution. Manufacturers could choose to design for lighter duties and accept some limited failures within the heaviest duty applications in the knowledge that replacement (warranty) costs will be offset by reduced system costs across the entire fleet. Figure 5 illustrates the step of selecting a lighter duty design reference, highlighting the balance between the increasing cost of warranty and reducing cost within the base design.

The study undertaken by the researchers in Darmstadt suggested that for the transmission example chosen, changing the target driver profile from the 99.9th percentile to the 90th percentile could yield a mass reduction in excess of 15%. [2]

Such an approach does come with an element of risk, which manufacturers will be reluctant to take. Technology may however offer further solutions to mitigate against increased warranty costs and reputation damage.

4. Active fleet management and maintenance

Analysis tools can be utilised to actively predict risk of failure of products in use. Figure 6 shows the level of detail in which an analysis model (in this case a transmission) can predict the relative risk of failure in a system. This particular data was used to upgrade the torque of an existing product, which was applied into an application beyond its original design duty.

Figure 6: Analysis output for specific component failure risk at loads above rated torque

High bandwidth data connections (4G, 5G) permit active monitoring and communications with vehicles in service. In combination with analysis tools and techniques, in-built mobile communication devices on board vehicles provide opportunities to stream
data to servers which can run live data analysis models to evaluate transmission health and predict remaining life.

The concept of actively monitoring powertrain in service is well established in other industries such as energy generation and aerospace, whereby high value systems such as offshore wind turbines or aero engines are continuously monitored by on-board telematics to provide information on system health to a service provider’s maintenance team.

Furthermore, system prognostics (the prediction of future failure) are common place in industrial applications such as wind turbine gearboxes when the cost of repair in service is very high. The ability to plan in routine service before failures occur is vital to keep critical systems online.

Figure 7: Offshore wind turbine telematic systems and pre-emptive maintenance

Figure 7 shows a typical wind turbine telemetry concept whereby a connection between the active system streams information from condition monitoring equipment and sensor data back to a land based control station. Data is processed and used to inform active maintenance schedules which promote planned maintenance, avoiding costly emergency repair and machine downtime.

Figure 8 shows how this service model could operate within connected vehicle fleets monitored by a manufacturer or service provider. Information can be fed back to the vehicle, or into dealer networks to inform pre-emptive repair or component replacement before the customer experiences any issues with their vehicle.

Such active monitoring systems give manufacturers or vehicle service providers the ability to identify and support heavier duty users with scheduled maintenance and part replacement before failure occurs. Manufacturers could then take a bolder approach to defining design duties and can strike a more informed balance between the needs of the majority of users and the cost of failure in heavy duty applications.

Figure 8: Connected powertrain model for active maintenance through dealer networks

5. Generating and processing data

Figure 9 illustrates a simple schematic diagram of how data could be shared between a vehicle and analysis models running on a central data server. Existing drivetrain and passive component data can be processed and turned into valuable sources of vehicle intelligence to inform future designs and actively manage vehicle fleets.

Figure 9: Data streaming for offline damage modelling

Much of the information needed to understand the loading on a drivetrain is already available on the modern vehicle. Signals within the engine control unit (ECU) (such as demanded and estimated torque, engine speed, and acceleration) are routinely shared on vehicle CAN networks and could be made available to a centralised connected module.

Automatic transmission systems have access to data such as; input and output shaft speed, predicted clutch torques, oil temperatures, and coolant pump speeds, all of which can contribute to a full system view of component loading throughout the vehicle.

Finally, electric braking and steering systems have access to; wheel speed, vehicle longitudinal and
lateral acceleration, vehicle yaw, steering angle and brake pressure information, which can further provide information on loads that are applied into the system, e.g. rapid wheel locking on ice.

The concept of recording key vehicle data is already routinely applied on road going vehicles in commercial trucks and passenger transport, as well as high end sports cars, via connected telemetry systems. Such systems are typically implemented in much smaller fleets and actively managed by a service provider.

The data shared is usually recorded at fairly low frequency with load data pre-processed on board using a “torque bin” approach. This records the time spent by the vehicle at various torque levels within the system, therefore providing more precise information on the duty and usage profiles of each vehicle.

Extending such an approach to larger vehicle fleets with mobile communication technology and cloud computing will provide better data for future development programs, and provide a starting point for development of online prognostics and active servicing.

Steady state load information, however, only paints part of the picture. Many drivetrain failures can be traced back to short, transient, or shock type events, which might be missed by conventional telemetry systems. Such events might occur, for example, during a kerb strike, pot-hole strike, or a variable or rapid change in the road surface friction coefficient. During these events the instantaneous torques seen in the driveline due to rapid acceleration of shaft and gear inertias can significantly exceed the steady state torque applied and reported by the engine. A more sophisticated approach is required to identify, capture and assess the impact of these load cases.

Measuring transient loads directly would require additional sensing within the driveline. Torque transducers that measure torsional loads via strain, either in conventional strain gauge technology or by relative displacement sensors (such as those used in modern electric steering systems), could be used to capture higher frequency load components. Adding sensors and their associated cost would however offset any potential savings within the system and therefore cost neutral solutions need to be found.

High fidelity torsional models of transmission and driveline systems can be used to help development engineers investigate issues on vehicles related to either noise, vibration and harshness, or component durability. Once correlated to test rig or vehicle data such as shaft speed and system torques, these models can give a unique insight into component level behaviour which would be impractical and very costly to measure directly.

Developing algorithms that can identify the sensor signal signatures of transient events could potentially enable us to predict loading using data observed from existing sensors. If key event information such as shaft speed traces can be captured and fed back to the analysis environment, the model could be used to recreate events in the virtual world from the basic data collected.

A good example of a sensor signal signature that indicates the occurrence of a transient event is a shaft speed oscillation. Identification of the magnitude, frequency and decay parameters of an oscillation could allow system identification tuning to repeat the event in simulation and predict the resulting component loads.

Figure 10 illustrates some of the information that can be inferred from within the model once it has been correlated to available measurement data. Component torques and speeds through the transmission can be estimated once the model behavior has been matched to the behavior of the recorded sensor data.

Once transient component torques are known, they can be fed into analysis models that evaluate shaft, bearing and gear tooth contact loading and build live damage profiles which are more accurate than those based on steady state loading alone.

![Figure 10: Output torques and speeds from torsional transmission models](image)

Embedding these models into a vehicle controller would require additional onboard processing power and is therefore not necessarily an economical option. If the processing power is available offline (on the data servers) then the vehicle data needs to be sent to the offline models. Streaming high frequency data, however, comes with an additional cost in data charges and uses up data bandwidth that could be adopted for other features.

To avoid these issues DSD aim to develop efficient onboard algorithms within existing ECU’s to detect and characterise detrimental high frequency events within the driveline (those that might impact...
component loading). Once identified, these events will be coded into a package of event data which would store sufficient characteristic data for each event to permit them to be recreated in offline high fidelity models.

Consequently, this method would have the benefit of minimising onboard processing power requirements and the amount of event data needed to be transmitted to support the accurate recreation of the event in offline models. This strategy will ultimately form part of the overall duty and life cycle prediction model of the transmission, and be fed into a more precise duty for future design and development cycles.

Figure 11: MASTA analysis model of a layshaft transmission

6. Opportunity and Challenge

The opportunity offered by the connected vehicle is significant in the context of creating better informed design choices and actively managing vehicle fleets.

The benefits for business fleet and commercial vehicles are clear: developing the capability to meet reduced cost and mass targets whilst scheduling maintenance to avoid costly downtime while also improving the customer experience.

If big data is handled wisely, designers for high volume passenger car drivetrains can make a more informed choice about the trade-off between the embedded costs of the materials in the base design, the mass of the system, and the warranty costs (cost of failure) of the heaviest users. Small mass and cost savings when applied to high volume fleets are highly significant, i.e. every 1kg saving on 1million vehicles is a 1000 tonne mass reduction in the fleet.

When considering warranty costs we must consider the potential risk to reputation and brand. Failures in the field have further reaching implications beyond the cost of part replacement. If manufacturers are to protect their reputations based upon reliability and durability, then cost and weight reductions need to be based on reliable data sets, and proven analysis and modelling approaches. Active and predictive maintenance needs to identify and support the heaviest users of vehicles.

Further opportunities for competitive advantage gains come in the ability to use this data to improve the service customers are offered. Manufacturers will differentiate themselves based upon their in-service support rather than simply their component reliability. This could provide opportunities for lighter and cheaper system designs.

7. Security and privacy

Understanding data privacy and security issues is a significant factor in the successful implementation of any connected vehicle system. Customer trust in connected systems is likely as important a factor as any other. How data is used and accessed by manufacturers and third parties, such as insurers and dealer networks, is already a clear concern within the industry.

In one potential implementation of the proposed system, data could be completely encrypted and anonymised when sent to the cloud for processing and the resulting life or damage information re-sent to the vehicle for on board storage and communication to the user. Such a system would keep the customer in control of who has access to the data and how it is communicated.

8. Future vehicles

Personal car transport ownership trends are shifting: car pools and Uber style transport models are part of our future. As ownership models move from single user to fleet or shared ownership, vehicles are set to become more akin to commercial vehicles: longer service lives and continuous use profiles, resulting in very different load and speed profiles.

Studies suggest that autonomous vehicle calibration is likely to reduce component loading significantly, as passenger comfort and trust dictate a much smoother and less aggressive driving style [3].

The ability to leverage and use the amount of available data from these vehicles will be a key competitive advantage for OEMs in their design of future powertrains and the services they offer to customers.
9. Next steps

The technology to collect data on vehicles exists already. The sooner we can access this data and develop how it is used, the sooner mass and cost savings can be realised by trading increased costs and embedded mass for the calculated, and debatably controllable, risk of failure in service for the most abusive user cases.

The better our data and tools, the better we can take advantage of the opportunity.

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