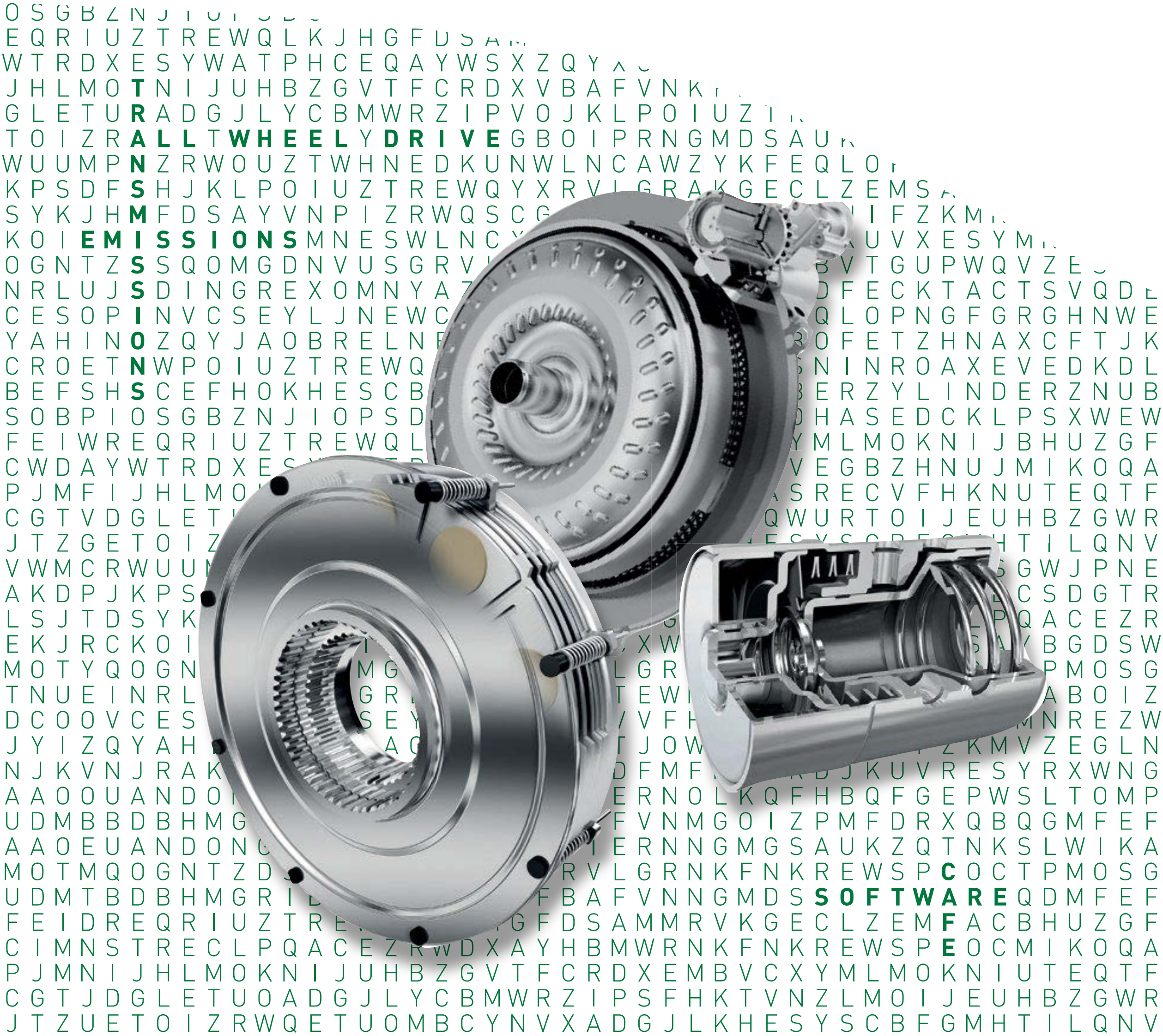
TRANSMISSIONS
ALL WHEEL DRIVE
EMISSIONS
SOFTWARE
CAFE

North American Fuel-Efficient Mobility

US CAFE Demonstrator

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Introduction

Global fuel economy standards are driving a push for energy-saving technology. At the same time, the consumer cannot afford large price increases for the vehicle. Therefore, high value technology is needed, especially in markets such as North America, where fuel prices are low. For example, a consumer who trades in a car meeting the 2020 CAFE (Corporate Average Fuel Economy) standard for a car which meets the 2025 standard, will only save $80 per year in fuel costs. The technology required to make that jump currently costs several thousand dollars, which means the consumer cannot recover his investment. Friction reduction offers a relatively high value in fuel saving but often raises the question: what is the best combination of friction reduction technologies?

Against this background, Schaeffler set out to build a demonstration vehicle which would:

- Demonstrate by measurement an effective combination of friction reduction technologies
- Provide a platform to experience new technologies developed for the North American market
- Improve and verify Schaeffler system simulation and calibration tools
- Provide 5 years of progress against the US CAFE standard at < $ 40/% fuel saved

This vehicle is based on the Ford Escape AWD, model year 2013, which utilizes a 2.0-liter engine and 6 speed 6F35 automatic transmission.

Figure 1 2013 NA CAFE Demonstrator Car

Schaeffler Technologies GmbH & Co. KG, *Solving the Powertrain Puzzle*,
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Figure 2 PTU Disconnect

Hardware selection

The technologies used in the demonstrator vehicle were developed primarily in North America, with a few components supplied from Germany. A new TC (torque converter) damper was used which permits a lower lockup speed, or lower lugging limits. Clutch slip is often required to achieve anacceptable NVH subjective rating, however with a lower spring rate damper, it was possible to completely eliminate slip, further improving fuel economy and maintaining the overall capacity. The friction reduction components include coated camshaft tappets, a new balance shaft module with low friction bearings, and low rolling resistance tires.

An AWD (all wheel drive) disconnect system was introduced as an additional friction reduction enabler. The system allows the driver to select between AWD or FWD at the flip of a switch. The AWD disconnect brings the PTU (power transfer unit) and RDU hypoid gear meshes and the prop-shaft to rest. This functionality is achieved via a synchronizing clutch placed in the PTU, and a rear axle disconnect between the RDU and driver side rear wheel. The PTU clutch system is comprised of a stacked series of Schaeffler wedge clutch plates. The clutch operates in two modes; synchronizing and lockup. During synchronization, friction material affixed to the plates' surfaces is compressed with a hydraulic piston. Once synchronized, a cam mechanism switches the clutch to lockup mode whereby the clutch plates become self-energizing to carry full driveline torque. The PTU clutch is shown in Figure 2.

Stop-start technology reduces the total time the vehicle spends idling, thus lowering unnecessary fuel consumption. Hardware designed to achieve a comfortable stop-start event includes a wrap spring permanently engaged starter (PES) and a latching valve designed to hold pressure in the transmission forward clutch during engine shutoff. These components are shown in Figure 3.

Figure 3 Wrap spring PES and latching valve

Engine coolant temperature is controlled by a Schaeffler thermal management module, and serves to heat the engine up more rapidly. It is designed to precisely control engine coolant flow through the engine block, achieving active control of temperature. The module replaces the traditional wax element thermostat at the coolant inlet. The thermal management module is shown in Figure 4.

Figure 4 Thermal management module

Simulations

Vehicle modeling

Vehicle system level models were created to simulate the fuel economy driving cycles in DyFaSim. Figure 5 is a graphical representation of the entire vehicle. The baseline vehicle and NA CAFE demonstrator vehicle were constructed using data supplied by the customer, benchmark data, component level test data and measurements. Sub-systems containing Schaeffler technology were modeled in greater fidelity to accurately capture fuel savings. The goal for phase 1 was CAFE year 2020 requirements; phase 2 is CAFE year 2025.

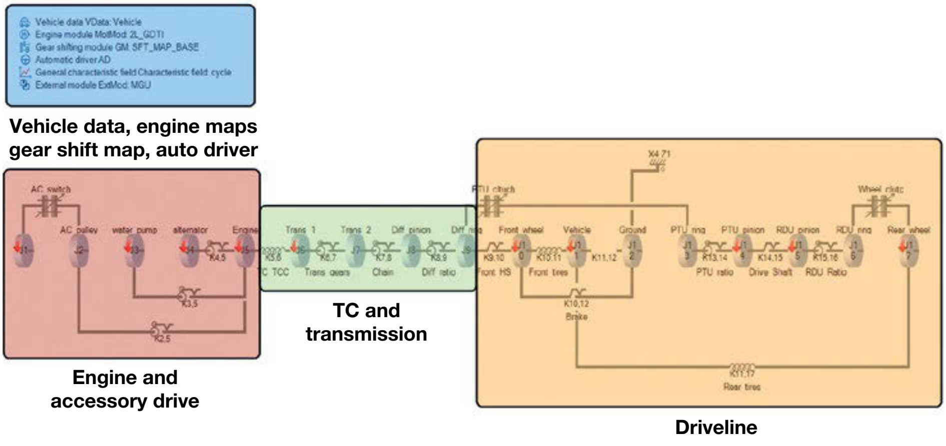

Figure 5 Vehicle system level model

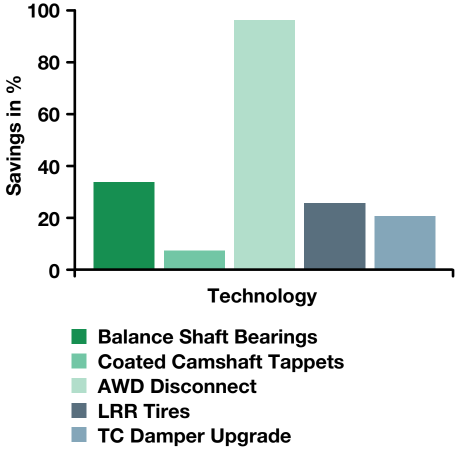

Figure 6 Bar chart of technology savings

Figure 6 shows the effective friction reduction savings of the selected technologies for phase 1. The savings are a function of torque and energy with respect to the baseline vehicle. Improved balance shaft bearings offer a 33 % improvement in friction reduction and low-friction coated camshaft tappets provide a 7 % improvement. The AWD disconnect system provides a 95 % improvement in friction, because the propshaft is brought to rest. Low rolling resistance tires offer a 25 % improvement in rolling effort. Finally, the upgraded torque converter damper permits the elimination of torque converter clutch slip and allows for a more aggressive lugging limit, a 20 % improvement over baseline.

The United States EPA FTP and HWFET tests were simulated to get a combined improvement number. Simulations of the European NEDC and the new worldwide harmonized light vehicles test procedure class 3 (WLTP) were also carried out to capture the fuel economy improvement on a global scale.

Figure 7 shows the US EPA FTP driving cycle and corresponding total fuel consumption lines over the cycle. The grey line represents the driving cycle over time. The dark green line represents the total fuel consumption of the baseline vehicle, the green line is phase 1 and the light green line is phase 2.

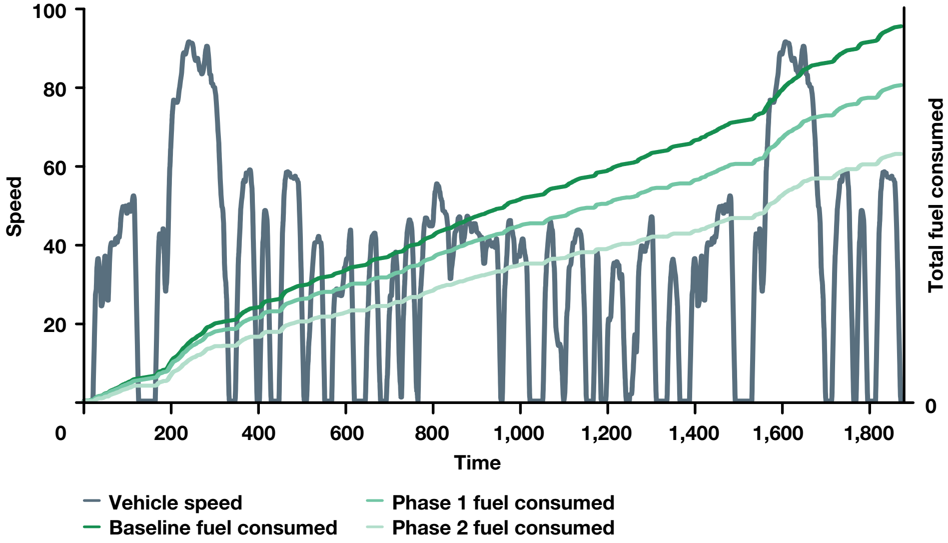

Figure 7 US FTP cycle

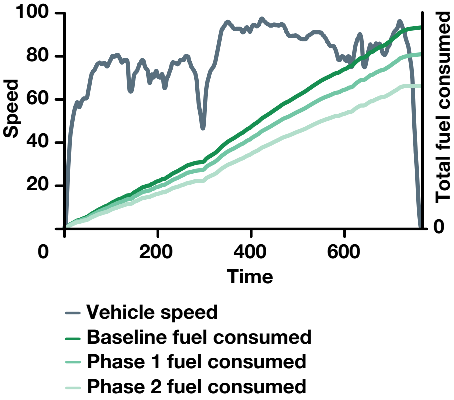

Figure 8 US HWFET cycle

Figure 8 shows the US EPA HWFET driving cycle with total fuel consumption traces over time. Figure 9 shows the New European Driving Cycle with total fuel consumption traces over time.

Figure 10 shows the Worldwide harmonized Light vehicles Test Procedure (Class 3) driving cycle with total fuel consumption traces over time.

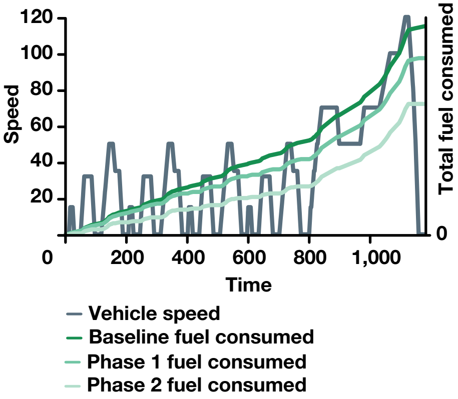

Figure 9 The New European Driving Cycle (NEDC)

The phase 1 simulation percent improvement estimations for each cycle are:

- US FTP = 18.7 %
- US HWFET = 15.5 %
- US combined = 17.5 %
- NEDC = 18.2 %
- WLTP = 17.2 %

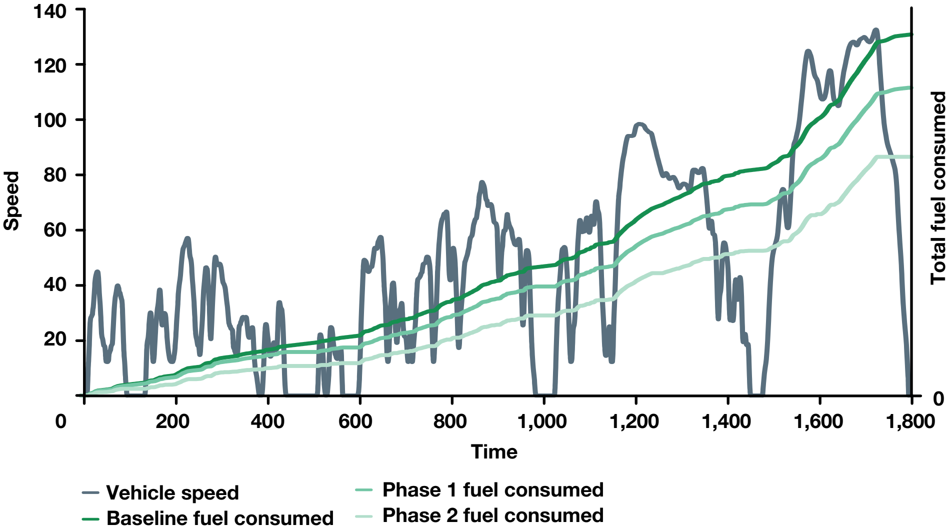

Figure 10 The global harmonized world light test procedure (WLTP)

Figure 11 is a plot of combined fuel economy, in miles per gallon, versus vehicle footprint. The lines represent each CAFE year fuel economy target. The baseline vehicle starts off just just below year 2015 target. The measurements conducted for phase 1 achieve CAFE year 2020 standards. Preliminary simulation results show that we are on target to reach CAFE 2025 with phase 2, with the aid of some of the off-cycle credits provided by the EPA.

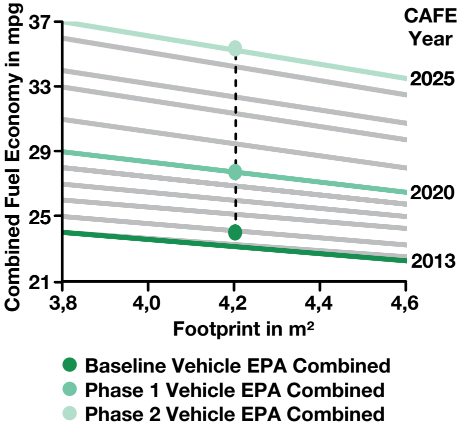

Figure 11 Combined fuel economy as a function of vehicle footprint for CAFE years

Software

The phase 1 software development process began after the initial fuel economy simulations were completed. Development work on the software for the demonstrator was divided into four stages; strategy determination, software development, SIL (software in the loop) simulations, and software implementation. The Schaeffler Engineering PROtroniC ClassicLine control unit housed the software used to control the systems added to the demonstrator.

Strategy determination

Technologies like coated tappets, new balance shaft bearings, and low rolling resistance tires do not require a control strategy. The new TC lockup schedule was simply flashed on to the vehicle's powertrain control module (PCM) with the help of the customer and did not require software strategy development. Control strategies were necessary for the stop-start, AWD disconnect and thermal management.

The stop-start system requires the engine to shut down when the vehicle is stopped. The piston at the transmission forward clutch is positioned to the touch point of the clutch pack and is held with hydraulic pressure via a latching valve when the engine shuts down. During engine shutdown, hydraulic pressure throughout the transmission is no longer available, but the latching valve holds the clutch in place by trapping fluid behind the piston. The clutch consequently need not be repositioned to the touch point during startup, allowing for faster restarts. An engine which has not yet reached normal operation temperature can result in restart instability, as well as requiring a rich mixture for starting, therefore the stop-start events should only be executed while the temperature is above an acceptable threshold. Constant stopping and starting can also negatively impact fuel economy, as well as the starter's durability, so a minimum vehicle speed must be reached after each stop-start event. This protects the vehicle from rapidly occurring restarts in stop-and-go traffic.

AWD disconnect provides the greatest friction reduction benefits out of all the technologies in the demonstrator. The driver has the option of keeping the AWD permanently engaged, permanently disengaged, or switching between the two on the basis of a predetermined strategy. The strategy mode attempts to provide fuel economy benefits with the advantages of AWD. The rear wheels and propshaft are disconnected at higher speeds via the PTU disconnect clutch and the rear axle disconnect. AWD is connected at lower speeds, high throttle demand and when the front and rear wheels rotate at different rates. Switching between engaged and disengaged is not possible during a start-stop event as clutch actuation at the PTU requires hydraulic pressure, which is not available when the engine is switched off. The clutch actuation must be smooth enough for the driver not to experience any adverse NVH events.

The thermal management system brings the engine up to temperature faster than the original strategy by modulating coolant flow through the engine. The main coolant flow to the engine block is cut off during warm-up, but modulated during temperature control. There is a small bypass circuit which allows a small quantity of coolant to pass through continuously for accurate temperature management when the TMM is closed. The actuator used to control the coolant flow is set to the required temperature and controlled via temperature feedback.

Software development

The software design was created primarily in the Mathworks Simulink environment. The control strategies were developed using Model Based Design (MBD) – a design method using flow diagrams to represent handling inputs and outputs for each system. A screenshot of the MBD for the demonstrator is shown in Figure 12.

The majority of the software consists of logic gates and event-driven control algorithms. Certain vehicle situations prompt the control unit to execute a series of checks, resulting in a fixed action. When the vehicle is stopped for two seconds, the

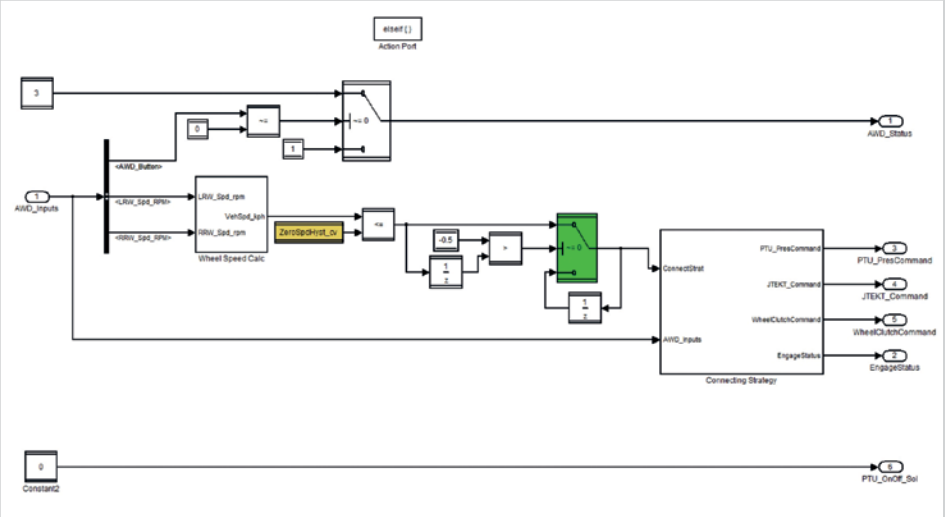

Figure 12 Example of MBD used in Demonstrator

software checks the engine temperature, the maximum speed achieved, the stop-start switch and several other inputs before shutting the engine down for a start-stop event. The vehicle will not execute a stop-start event if not all of the conditions are met. Cold starts are inefficient, so the system would not engage the start-stop strategy if the engine temperature is too low.

PI (proportional, integral) control loops are used for events that require active control strategy. The stop-start system requires control of the forward clutch actuation, which is originally managed by the vehicle's transmission valve body. A solenoid controls the flow of pressure to the clutch based on the programming inside the PCM. The PROtroniC control unit intercepts the original solenoid signal coming from the PCM and the Schaeffler strategy is forwarded to solenoid in its place.

Multiple systems in the demonstrator require active control, necessitating multiple forms of feedback through the PROtroniC. The proper gain values for the PI controls could only be estimated in the initial development and would later be explicitly determined through calibration. Testing the control strategies through 'software in the loop' simulations was the next step before flashing the software on to the PROtroniC.

SIL simulations

Simulations were performed once the initial software design was complete. The necessary inputs for the control strategies were taken from different driving cycle data files and fed into the model in order to simulate various driving conditions. The behavior of the different systems was observed through the outputs of the design, allowing for model adjustments that assured each system acted according to its strategy. Each time an error occurred and the predicted outputs were not achieved, the control strategy governing the incorrect output was studied until the problem was corrected. The production code for the PROtroniC was auto-generated from the software model on completion of the SIL tests.

Implementation

The auto-generated code was compiled and flashed onto the PROtroniC using Schaeffler Engineering's PROtroniC software suite. The function and operation of each component and system was verified. Once the calibration phase was complete, the vehicle was ready for official fuel economy measurements.

Fuel economy was measured at an independent, non-affiliated lab. Two FTP and two HWFET cycles were run for the baseline vehicle, then repeated again once phase 1 was complete. A 16 % improvement in combined fuel economy was measured, attaining the CAFE model year 2020 target.

Transmission-driven accessories

Phase 2 of the demonstrator project consists of drivetrain hybridization and ride-height adjustment. Ride-height adjustment is accomplished with a ball screw adjustment system that can actively vary the ride height of the vehicle. Variable positioning can reduce the vehicle's drag coefficient throughout a drive cycle. The hybridization component is achieved through a Schaeffler concept entitled Transmission Driven Accessories, or TDA. The technology will improve fuel economy by adding engine boosting and the ability to disconnect the vehicle accessories from the drive-train, greatly reducing engine drag.

TDA mechanical architecture

The TDA architecture consists of two clutches, one connecting the engine crankshaft to the accessories (engine accessory clutch) and one connecting the transmission input shaft to the accessories (transmission accessory clutch). A 48-volt battery and a 12 kW MGU (Motor-Generator Unit) is used to boost the engine and provide independent power to the accessories when needed. The TDA architecture can be seen in Figure 13.

One accessory clutch is connected at a time. The transmission accessory clutch will be connected during deceleration for regenerative braking purposes, but only at effective transmission speeds above engine idle. Both clutches are disengaged while decelerating, when transmission speeds are below idle, during which the MGU powers the accessories at idle speed. The engine accessory clutch connects when the 48-volt battery state of charge (SOC) drops below the minimum threshold and during boosting.

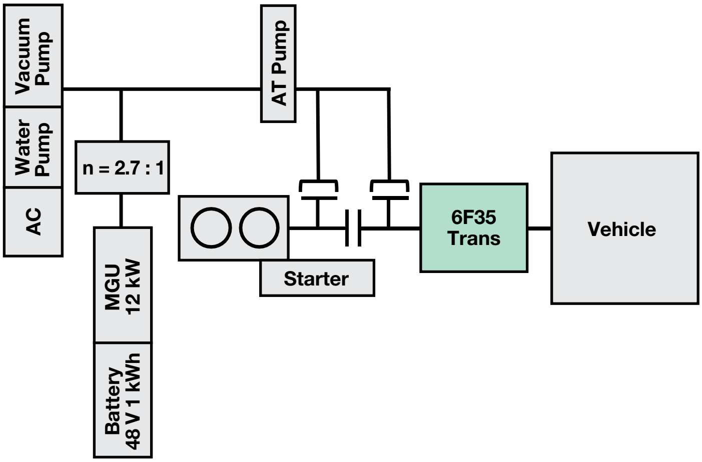

Figure 13 TDA architecture

Battery and motor calculations

Simulations for phase 2 required information on the additional electrical systems necessary for hybridization. The new 48-volt battery and MGU were added to the simulation to perform boosting and model the charging and discharging effects throughout the drive cycles.

The boosting option is achieved with the MGU through the engine accessory clutch, decreasing the amount of fuel required for the engine to achieve certain torques. Boosting also discharges the 48-volt battery, limiting the amount of boost assist before the battery must be charged. A balance between charging and boosting is needed to ensure optimal fuel benefits and a healthy battery life cycle.

The battery is charged by the MGU through regenerative braking. During vehicle deceleration, the engine accessory clutch opens and the transmission accessory clutch closes. The MGU induces a drag torque that decelerates the vehicle and charges the battery simultaneously. The amount of regenerative braking torque is dependent on the battery's SOC (state of charge) and the driver's input.

The levels of boosting and regenerative braking were manipulated in order to achieve our fuel economy goals and the proper final SOC. Certain driving situations presented particular challenges. Highway cycles tended to decrease the battery SOC faster because there was less braking and decelerating involved. Less time decelerating means more aggressive regenerative braking and a less aggressive boosting strategy. City cycles spent more time decelerating, requiring less aggressive regenerative braking and more boosting. However, there was more idling during the city cycle, which required the MGU to run the accessories during a stop-start event, thus draining the battery further. As seen in Figure 11, phase 2 simulations project fuel economy to reach the 2025 standards.

Conclusion

The NA CAFE Demonstrator project serves as an example of the system level engineering and development expertise of Schaeffler North America. Systems modeling, simulation, software and controls development, calibration, hardware design and development were all primarily executed in North America. It demonstrates Schaeffler's ability to take an idea from the early stages of simulation through to functioning vehicle components in a short amount of time.

Following the success of stage 1, the stringent requirements of phase 2 of CAFE 2025 will be quite challenging. Schaeffler has proven to be a reliable customer-driven supplier, focusing on systems level hardware aimed at fuel economy reduction for efficient future mobility.