A telehandler vehicle as mobile laboratory for hydraulic-hybrid powertrain technology development

Lorenzo Serrao, Giulio Ornella, Luca Balboni, Carlos Maximiliano Giorgio Bort, Carl Dousy, Fabrizio Zendri

Dana Holding Corporation, Rovereto (Italy) and Brugge (Belgium). Corresponding author's e-mail: lorenzo.serrao@dana.com

Abstract

The paper describes the design of a prototype vehicle used by Dana Holding Corporation as a mobile laboratory for the development of Spicer® PowerBoost® hydraulic-hybrid powertrain technology. A telehandler vehicle was selected due to its versatility. Starting from the high-level requirements, design choices from the powertrain layout to the control architecture are discussed. The hydraulic-hybrid powertrain system is described, and its performance is analyzed based on representative driving cycles.

KEYWORDS: telehandler, hydraulic hybrid, powertrain, driving cycles

1. Introduction

As a leading drivetrain supplier for the off-highway industry, Dana offers a broad portfolio of options to the global market, from individual product solutions to fully optimized drivetrain systems. Pursuing Dana's mission to be the global technology leader in efficient power conveyance and energy-management solutions, Dana often develops prototype vehicles equipped with the company's innovative systems as turnkey prototype solutions for customers or for internal product and technology development purposes. When these prototype vehicles are targeted for internal usage, a modular and flexible approach needs to be applied in order to maximize the return and benefit of R&D investments.

This paper focuses on a vehicle that serves as a mobile laboratory for the development and demonstration of many of Dana's new technologies, including Spicer® axles, Spicer® hydrostatic continuously variable transmissions (CVTs), Spicer® PowerBoost® hydraulic-hybrid powertrain technology, the Spicer® central tire inflation system (CTIS), and many others. The vehicle was developed using a modular approach that allows engineers to easily modify all the systems under study, including the drivetrain architecture and components, electronic equipment, and controllers. In addition, it is equipped with an advanced sensor network that includes wireless telemetry logging and measurement technology to provide full analytical capability for the installed components.

Shown in **Figure 1**, Dana's mobile laboratory is a *telescopic boom handler* (TBH), also known as *telescopic handler*, *teleboom handler*, or *telehandler*. This machine is widely used in the agriculture, industrial, and construction markets. It is similar in appearance and function to a forklift while offering the increased versatility of a single telescopic boom that can extend forwards and upwards from the vehicle. The operator can fit one of several commercially available attachments on the end of the boom, such as forks, bucket, hammer, muck grab, or winch.

Figure 1: Dana prototype telehandler

Since 2013, Dana has used a refurbished 1997 hydrodynamic Manitou 728-4 telehandler equipped as follows:

- An electronically controlled Tier 4i Perkins engine (3.4 liters, 83 kW);
- Dana driveline components, including a Spicer® 318 hydrostatic continuously variable transmission (HCVT), Spicer® driveshaft, and Spicer® Model 212 front and rear steer axles;
- An electro-hydraulic steering system and work hydraulics, using technology provided by Danfoss Power Solutions;
- A modular hydrostatic drive solution, allowing multiple-provider installation possibilities;
- The modular Spicer® PowerBoost® hydraulic-hybrid powertrain system, including a Spicer® PowerBoost® Hub, a 20-liter low-pressure accumulator, and a 20-liter high-pressure accumulator;

- An LCD touchscreen driver interface, Wi-Fi telematics, on-board camera, global positioning system (GPS), and other interfaces for the operator.

In Section 2, the main requirements and design criteria are provided, while Section 3 presents a case study to illustrate the use of the mobile laboratory in a typical technology development project for the Spicer® PowerBoost® hydraulic-hybrid powertrain system. Finally, Section 4 discusses typical vehicle driving cycles and corresponding experimental results.

2. Vehicle lab requirements

2.1. General requirements

The main goal of this vehicle is to provide a useful development platform and demonstrator for a wide range of Dana products and technologies. Thus, the main design requirement was to develop a vehicle that can be used to test a wide variety of functions for material-handling operations, construction work, digging, lifting, and the like. The telehandler is the ideal baseline vehicle thanks to its versatility and ability to perform multiple types of operation involving traction and work functions such as lifting, handling, digging, silage, loading, and transportation. Other important high-level requirements are related to the flexibility of the powertrain layout and control system, as detailed in the following sections.

2.2. Powertrain layout

The second requirement is the ability to test transmission technologies from several families at different times. Thus, the vehicle powertrain layout was specifically designed to be compatible with a wide range of Dana transmissions and powertrain solutions, including hydrostatic transmissions with single- or dual-traction motors — some including the option of a direct engine-transmission mechanical connection — as well as standard powershift transmissions. In order to meet this requirement, the engine is located in the back of the vehicle, in line with the vehicle longitudinal direction and centered with respect to the vehicle track. This required the original vehicle chassis to be stretched longitudinally in order to fit the new Tier 4 engine, which includes a new after-treatment system that makes it larger in size when compared with the original engine installed in the telehandler. The vehicle layout is illustrated in **Figure 2**.

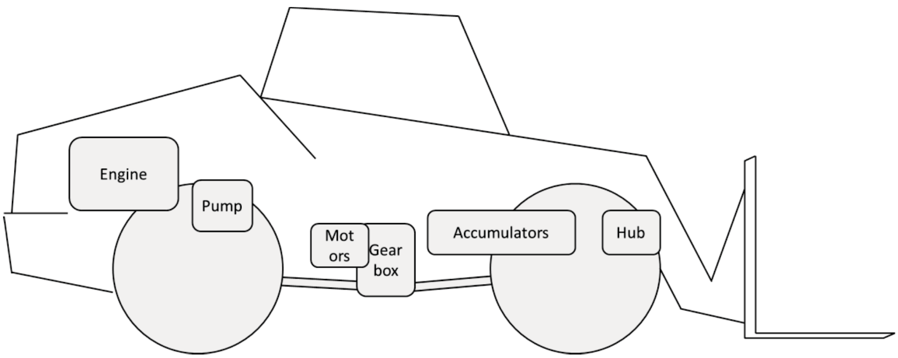

Figure 2: Telehandler powertrain layout

In addition, the space in the center of the vehicle frame provides room for the extra components required for the Spicer® PowerBoost® hydraulic-hybrid powertrain system — namely two 20-liter hydraulic accumulators and the Spicer® PowerBoost® Hub.

2.3. Control architecture

The control architecture is modular and allows for the implementation of different strategies, which can be adapted to the layout of the transmission installed in the system and the desired operating mode. It is built upon logic functions that can be replaced and reused in different applications. A high-level view of the control architecture is shown in **Figure 3**, where three macro-blocks are identified:

- *Control*: Algorithms, signal conditioning, generation of actuator setpoints;
- *Safety*: Low-level control overrides, for safety functions and error management;
- *Plant*: Interface to vehicle actuators, or, alternatively, to simulation model.

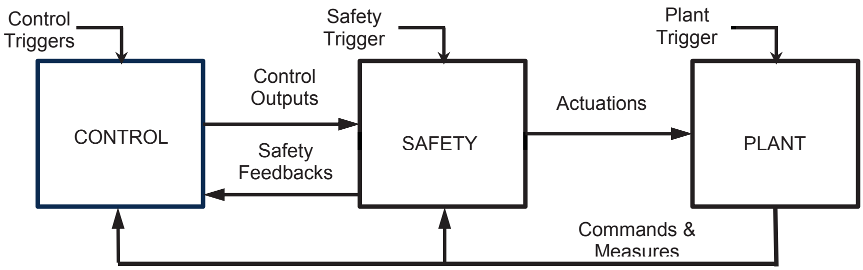

Figure 3: Control architecture

For maximum flexibility and computational efficiency, each element of the control architecture can be executed with a different sample time, in accordance with system and functional requirements. Model-based design is used for control development, especially focused on rapid control prototyping (RCP), based on a dSPACE MicroAutoBox platform.

Each macro-block can be replaced; for instance, the algorithms can be changed to match the powertrain configuration. In addition, macro-blocks can be individually modified as development progresses while keeping the same interfaces. In particular, the plant block allows switching between the physical prototype and a virtual prototype (simulation model). This allows engineers to easily test the control strategies in simulation without modifying the algorithms or software before implementing them on the vehicle.

3. Technology development case study: Spicer® PowerBoost®

3.1. Hydraulic-hybrid powertrain technology

Spicer® PowerBoost® is a series hybrid-hydraulic powertrain technology for off-highway vehicles and material-handling equipment. This technology is intended for hydrostatically driven applications with frequent bursts of acceleration, deceleration, lifting, and lowering during cyclic maneuvering, which all support the recuperation of energy.

By using hydraulic accumulators, the system captures energy that would otherwise be wasted, and then uses this recuperated energy to help power the vehicle. In addition to the accumulators, the system includes the Spicer® PowerBoost® Hub, an innovative mechatronic device that integrates hydraulic manifolds, valves, and the electronic controller. The Spicer® PowerBoost® Hub has a modular design that includes a core block for the operation of the main system as well as optional modules that enable several extra functionalities, depending on vehicle configuration and customer preference.

Figure 4 is a circuit representation that shows the core functionality of the Spicer® PowerBoost® system, while **Figure 5** illustrates the physical implementation of the Spicer® PowerBoost® Hub installed on the Dana telehandler.

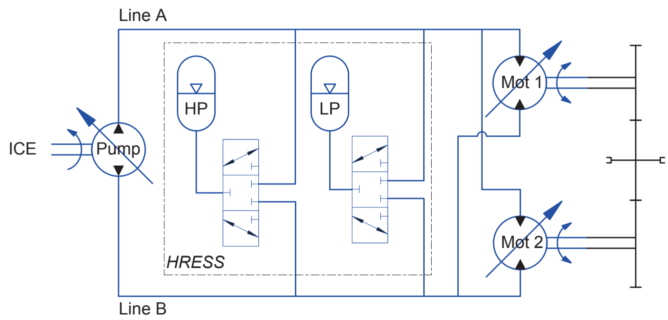

Figure 4: Series hybrid architecture. This simplified concept representation only shows core functionality

Figure 5: The modular design of the Spicer® PowerBoost® Hub. This configuration shows all optional modules

The core block contains normally closed hydraulic cartridge valves that, when actuated, connect the hydrostatic circuit with the high-pressure accumulator and low-pressure accumulator. These connections enable the drive system to store or utilize previously stored energy. Furthermore, the core block embeds the safety functions required by pressure equipment, including certified pressure relief valves to secure the hydraulic accumulators, accumulator discharge valves, and sensors to monitor pressure and temperature.

The other modules host other functionalities, such as start/stop. With this module, the vehicle's engine can be restarted by using the energy stored in the high-pressure accumulator. The hydraulic start/stop functionality is more responsive than an electric starter and saves the electric battery.

A second module connects the Spicer® PowerBoost® system to the vehicle's working hydraulics circuit. This connection allows the system to utilize energy accumulated in the travel hydraulics system to move implements or capture kinetic energy from implements and store it in the accumulator.

Electric valves are managed by a control platform that communicates with the general vehicle controller via CAN bus. The electric devices are covered by a plastic or metal sheet (shown partially open in the picture) to protect them from dust and dirt.

When a vehicle is purely hydrostatically driven, the hub is not actively used, since hydraulic fluid is only diverted from its initial route in hybrid mode when energy is recuperated or released. Under hydrostatic power, hydraulic fluid simply flows through the hydrostatic A-line and B-line of the hub.

3.2. Development process

Dana’s advanced engineering teams normally follow an agile systems engineering development approach, which is based on two factors: lean management of system requirements — which can evolve rapidly during the development of a prototype study — and the use of three main development environments: the vehicle lab, the test bench, and the simulation lab.

Normally, the vehicle lab constitutes the most realistic environment for testing a new technology, but the three labs complement each other and enable the development of advanced control systems. The test bench and simulation lab support the development of the vehicle, facilitating the interpretation of the experimental results on the vehicle. The test bench and the simulation lab are used extensively for system modeling and analysis in the preliminary stage, control development and testing in the implementation phase, and augmentation of the physical measurements for improved analysis and assessment in the verification phase.

3.3. Simulation model

Engineers use LMS Amesim in co-simulation with Simulink for control development to implement a simulation model of longitudinal vehicle dynamics and hydraulic-hybrid powertrain technology. The model is based on a 1-D modelling approach for the hydraulic circuit, which includes the hydrostatic machines (variable-displacement pump and motors), fluid hoses, control valves to connect and disconnect the accumulators, and accumulators. The hydrostatic machines are modelled using an efficiency map and a 1st order dynamic response for the current-to-displacement transfer function. The control valves are represented by standard orifice equations to represent the pressure losses vs. flow and by a 2nd order dynamic response (current to opening area). The accumulator model is based on ideal gas law, and it includes heat exchanges with the external environment.

The internal combustion engine is represented by an efficiency map, and the driveline is assumed to be composed of a sequence of lossy gear ratios, neglecting the torsional driveline dynamics. The power loss associated with the gearbox and axle is modelled using a Coulomb + viscous friction approximation, based on experimental characterization of these components. The vehicle dynamics are purely longitudinal and account for tire rolling resistance.

All model parameters are identified from experiments at the test bench (for the hydraulic components) or the vehicle (such as vehicle dynamics and overall energy balance). The simulation model is validated with experimental testing using standard cycles at Dana's own test track, which is detailed later in this paper.

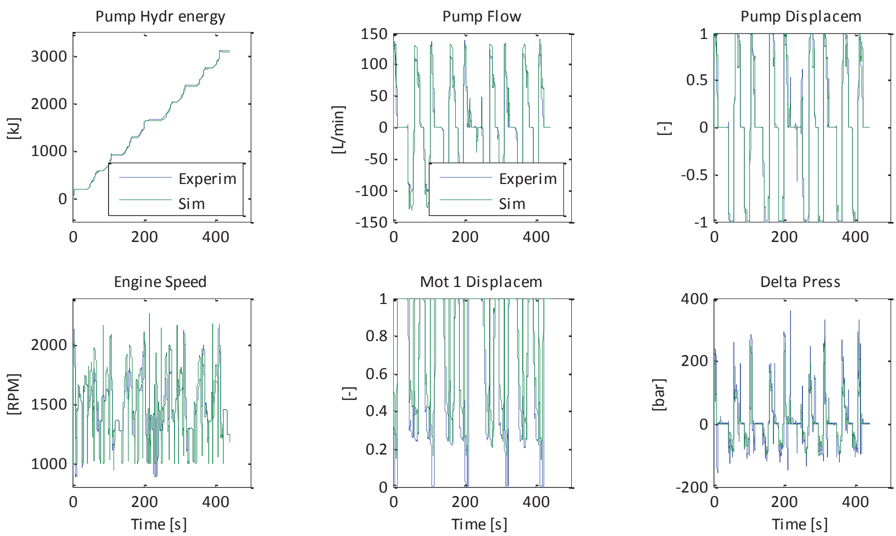

Figure 6: Graphical comparison of simulation results with experimental testing

Figure 6 shows a comparison between simulation results and experimental data on a reference driving cycle, while **Figure 7** shows a synthetic representation of the model quality based on the Alignment Index (AI), defined as follows:

$$AI(y) = 1 - \frac{RMS(y_{sim} - y_{meas})}{Avg(|y_{meas}|)} \quad (1)$$

where y is a generic variable of interest (one of those listed in Figure 7), and the subscripts sim and $meas$ denote its simulated and measured values, respectively.

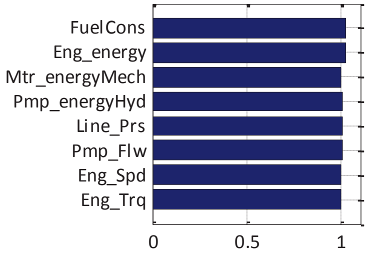

Figure 7: Model alignment indices, a metric to assess the match between simulation outputs and experimental data. A unit value indicates a perfect match.

4. Testing and driving cycles

4.1. Test track

Dana's prototype telehandler was instrumental in the development of Spicer® PowerBoost® technology. This prototype allowed for testing and validation in several usage scenarios, thanks to the ability to perform multiple types of operation involving traction and work functions such as lifting, handling, digging, silage, loading, and transport. These scenarios are formalized into a set of driving cycles performed at Dana's own test facility.

Figure 8 represents the layout of the test track at Dana's facility in Arco, Italy. It consists of a flat area paved with asphalt and concrete, surrounded by guard-rails. A sand pile is available for conducting load tests with the bucket, while different weight ballasts can be used for tests with the fork. A control room is available for engineers working on vehicles, and the entire area is accessible with Wi-Fi.

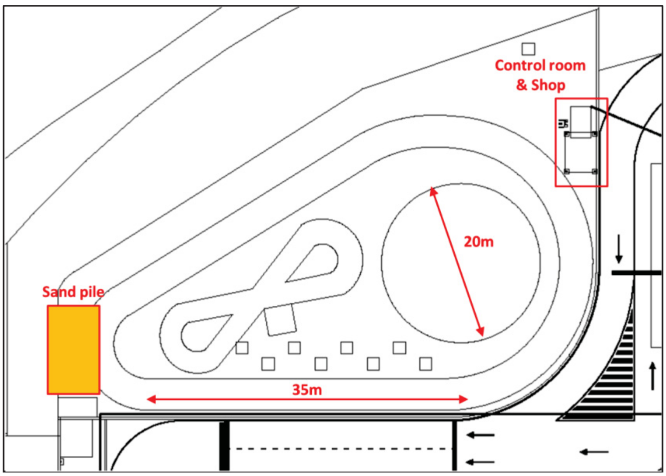

Figure 8: Layout of Dana's test track in Arco, Italy

4.2. Driving cycles

A set of basic maneuvers is identified and performed in order to verify the functionality and performance of the vehicle in elementary operations and controlled conditions. In addition, complete driving cycles are defined to cover the vehicle's range of operation and allow an assessment of vehicle performance in complex operations that reproduce real-life scenarios. The cycles, listed in **Table 1**, are also applicable to other vehicles performing similar operations, such as forklift trucks and wheel loaders.

Cycle	Description
Travelling unloaded	Transport of the vehicle by driving on tarmac road, pavement and other smooth roadways. Typical travel speed is between 15 kph and maximum vehicle speed.
Travelling loaded	Transport of the vehicle by driving on tarmac road, pavement and other smooth roadways, with load on the forks. Typical travel speed is between 15 kph and maximum vehicle speed.
Towing a trailer	Transport of the unit by driving on tarmac road, pavement and other smooth roadways, towing a trailer of given weight. Typical travel speed is between 5 and 20 kph
Short Y-cycle	The cycle involves removing relatively loose material from a pile and depositing it into a truck. The vehicle follows a Y-shaped path picking up material in one area, backing away in reverse, shifting into forward, turning a few degrees to the left or right, traveling to an unloading area, depositing material, and backing to the starting area. Transport distance is about 30 m.
Long Y-cycle	Same as Short Y-cycle, but transport distance is about 170 m.
Short material-handling cycle	The cycle involves picking up material from one point, transporting it to a location at a certain distance, and safely unloading the material at this location. The material is located on a pallet, which is picked up with the forks of the vehicle. Transport distance is about 150 m.

Table 1: List of driving cycles

4.3. Hybrid powertrain performance evaluation

In this section, the performance of the hybrid driveline is compared to a conventional hydrostatic driveline using experimental results collected at the Dana test track. The comparison is obtained by running two different control strategies on the vehicle. The KPIs taken into account are vehicle productivity and fuel consumption. Two of the driving cycles listed in Table 1 are considered: *short Y-cycle*, where the vehicle is used to dig into a pile of sand, and *travelling unloaded* with a speed between 15 and 30 kph.

Velocity profiles are shown in **Figure 9**, along with other experimental results. Each duty cycle is performed with the standard and hybrid control strategies. In order to have statistical relevance, the Y-cycle is repeated 20 times, while the traveling cycle is performed for 10 minutes. The digging phase of the Y-cycle happens after 10 seconds, a point when the speed of the vehicle goes to zero abruptly.

The productivity of the standard and hybrid hydrostatic drivelines is comparable for both driving cycles. The time required to perform the 20 Y-cycles with the standard hydrostatic driveline is 12 minutes, 8 seconds, compared with 11 minutes, 59 seconds for the hybrid driveline. Moreover, the same distance is covered after the 10-minute duration of the travelling cycle.

The charts in Figure 9 that show the operating points of the engine are related to the cycles performed with the hybrid hydrostatic driveline. The blue dots show the engine operating points during the boosting and regenerative phases (hybrid ON), while the green crosses are associated with those time periods when only the hydrostatic driveline is driving the vehicle (hybrid OFF). These points are similar to those obtained with the standard hydrostatic control, so they can be used to compare the two cases. The red ellipse centered at 1500 rpm marks the position of the minimum brake specific fuel consumption (BSFC) region.

It is important to note that, during the hybrid ON phases, the engine speed shifts to lower values. This is especially clear in the Y-cycle, when the engine speed is reduced to 1200 rpm while the driveline is delivering less power. When the vehicle is running at high speeds and the driveline is delivering more power in the travelling cycles, the engine's operating points shift to the zone of minimum BSFC, delivering maximum efficiency.

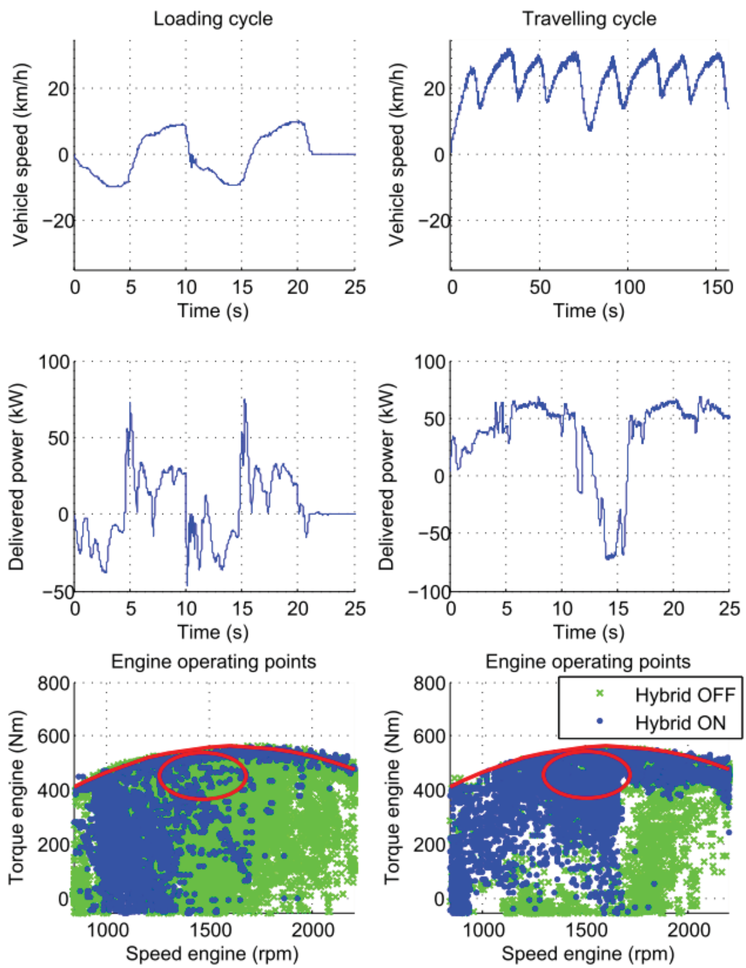

Figure 9: Measured duty cycles and operating points of the engine. The left column illustrates one out of 20 cycles of the loading cycle, while the right column shows the first 150 seconds of the handling cycle

The fuel savings obtained with the hybrid driveline with respect to the standard hydrostatic driveline is 16 % during Y-cycle operation, when the vehicle is moving slowly and with continuous inversions of the direction that allow for numerous regeneration phases. During fast travelling maneuvers, the decelerations are shorter since the vehicle does not fully stop, it simply reduces its speed to corner. However, it is possible to recover enough kinetic energy to reduce the engine load for the subsequent acceleration phase, thus reducing the fuel consumption by 13 %.