

Development and Validation of a Forklift Truck Powertrain Simulation

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ABSTRACT

Fuel economy has become an important consideration in forklift truck design, particularly in Europe. A simulation of the fuel consumption and performance of a forklift truck has been developed, validated and subsequently used to determine the energy consumed by individual powertrain components during drive cycles.

The truck used in this study has a rated lifting capacity of 2500kg, and is powered by a 2.6 litre naturally aspirated diesel engine with a fuel pump containing a mechanical variable-speed governor. The drivetrain consisted of a torque converter, hydraulic clutch and single speed transmission.

AVL Cruise was used to simulate the vehicle powertrain, with coupled Mathworks Simulink models used to simulate the hydraulic and control systems and governor. The vehicle has been simulated on several performance and fuel consumption drive cycles with the main focus being the VDI 2198 fuel consumption drive cycle.

To validate the model, a truck was instrumented and measurements taken to compare the performance and instantaneous fuel consumption to simulated values. The fuel injector pump was modified and calibrated to enable instantaneous fuel flow to be measured.

The model has been validated to within acceptable limits and has been used to investigate the effect four different torque converters have on the fuel consumption and performance of the forklift truck. The study demonstrates how the model can be used to compare the fuel consumption and performance trade-offs when selecting drivetrain components.

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INTRODUCTION

Forklift trucks are an essential element in the material handling sector. During the transportation of goods, forklifts are usually the first and then final link in the transportation chain between the origin and destination. Also, if the goods need to be transferred from one means of transportation to another during transit, a forklift truck can be used to perform the transfer.

The forklift truck has two main requirements. The first is to lift and position large and heavy loads, and the second is to transport these loads to a specific on-site location. Hence, the forklift must perform the functions of two vehicles within one platform. To achieve these tasks, the truck has a drivetrain that is significantly different from an automotive drivetrain,

and has been customised for moving and lifting very large and heavy loads. Several types of energy source and drivetrain can be used to power a forklift truck depending on the application and industry the truck is used in. The most common energy sources are diesel and LPG internal combustion engines, as well as battery-powered fully electric trucks. Electrical trucks are typically used for indoor applications with a 1000 kg to 5500 kg lifting capacity. Diesel and LPG are typically used in outdoor application with a lifting capacity from 2000 kg to 8000 kg and diesel is used exclusively for all lifting capacities above 8000 kg.

Traditionally, in the forklift truck industry, the research and development focus has been driven by the customer demands for durability, reliability, driving and lifting

performance, and cost. Usually, the biggest cost of running a forklift truck is the driver's salary. However, due to increased energy prices, the energy consumption of the vehicle has become an important consideration for customers.

Governments around the world are also enforcing strict emissions legislation for off-highway vehicles with internal combustion engines to curtail the generation of pollutant gases and particulate matter [1, 2]. One way to reduce harmful emissions is to produce fewer emissions by using less fuel. The increasing cost of fuel and pressure from governments to reduce emissions means that forklift truck manufacturers must focus on reducing fuel consumption as a means of reducing customer running costs and reducing emissions.

An engine's power output is used to determine which emissions limits are used and at what time the limit will come into law [1, 2]. Engines with lower power output are given more time to meet the limits. Therefore, in the short term, manufacturers have tried to derate or downsized the engines used to get into the lower power bands while still maintaining acceptable levels of performance. One forklift manufacturer has already successfully employed computer simulation in the process of engine selection for engine downsizing [3].

To reduce fuel consumption, truck manufacturers must first understand where the energy is consumed within the drivetrain, from the engine or battery through to the wheels. Areas of the drivetrain where the energy losses are high can then be targeted for design improvements or optimisation. One way to understand the transfer of energy within a truck is to physically test each component on a test bench and measure the energy consumed by it for all operating conditions. However, this method is difficult and expensive and will often produce results which are specific to the component being tested and do not transfer to similar components.

A better way to understand the flow of energy within the vehicle is to construct a computer model that represents the energy transfers and losses between each of the components of the vehicle drivetrain. The model can then be used to follow or simulate a typical duty cycle or drive cycle to replicate the behaviour of the truck in the real world. A detailed analysis of the simulation can be carried out and used to identify areas of unnecessary energy consumption. The entire energy flow within drivetrain can be analysed on a step-by-step basis and component changes can be made to the model and simulations rerun to calculate the effect of the component change. Therefore, small improvements and optimisations could be made to the design of the truck which previously could not be accurately measured with physical testing. A further advantage of the energy simulation is that the models can be quickly adapted to test and develop new and unproven components and systems before building physical prototypes saving both time and cost.

It is clear that a simulation tool is also required to advance the development of fuel efficient forklift trucks. G. Stein et al. have already used simulation in the process of engine

selection for forklift trucks [3] while Böhler et al. have used simulation to demonstrate the advantages and disadvantages of a forklift truck with a mild diesel-electric hybrid drivetrain [4].

To ensure the simulation results are correct and the model can accurately predict energy consumption, the model must first be validated against real physical test results. The total energy used by a truck on a drive cycle must equate to the total simulated energy consumption. More importantly, accurate prediction of the instantaneous energy consumption throughout the simulation must be achieved to ensure that under prediction in one part of the simulation are not compensated for by over prediction in another part of the simulation.

Vehicle Description

Working closely with a forklift truck manufacturer, a vehicle model was developed to simulate fuel consumption of a counterbalance forklift truck on an industry standard drive cycle. The truck selected is the manufacturer's best selling truck in the European market. The truck is powered by a 2.6 litre naturally aspirated diesel engine with a governed variable-speed fuel pump. The drivetrain has a torque converter and single-speed forward and reverse transmission. The transmission feeds into a single-ratio gearbox and differential which drives the front wheels. The tyres used were pneumatic-shaped solid tyres. The engine also powers a hydraulic system that is used to operate the transmission clutches and the hoisting, tilting and steering functions. The maximum lifting capacity of the truck was 2500 kg.

Forklift Drive Cycle

All forklift manufacturers have customised drive cycles for which fuel consumption, vehicle speeds and accelerations, and the productivity of the truck (number of loads moved per unit of time) are determined. However, when publishing data sheets for a truck, the industry follows a standardised test cycle known as VDI 2198 [5]. This standard specifies a summary table in which the published truck information is contained so that one truck can be compared directly to another. The table includes basic dimensions, engine type, tyre type, etc. However, more importantly the manufacturer specifies a fuel consumption that has been achieved on a drive cycle defined in the standard by an actual truck of the type and build stated.

The VDI 2198 drive cycle is very different to the drive cycles used in the automotive sector. Automotive drive cycles use a velocity versus time profiles to specify the vehicle's speed at any given time. However, the VDI standard specifies only a number of repeating duty cycles per hour. The drive cycle also includes a combination of steering, tilting and hoisting, none of which occur in automotive drive cycles. The speed and time taken for each of these processes throughout the cycle are wholly determined by the operator. [Figure 1](#) shows an aerial view of the VDI course for material handling vehicles.

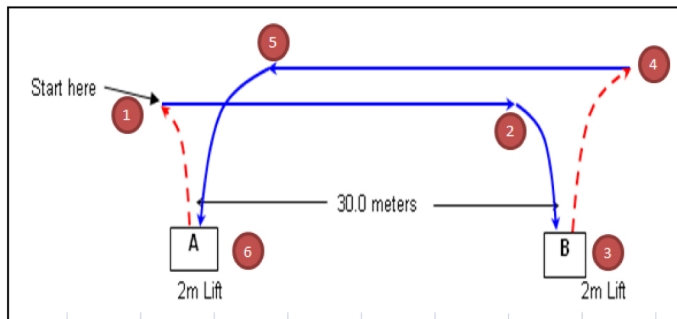


Figure 1. Aerial view of VDI 2198 duty cycle

The driver starts at Position 1 and drives forward 30m with the truck carrying its maximum rated load. At Position 2, the driver turns through 90° and advances forward by twice its load centre (the distance from the back of the forks to the centre of gravity of the load) to Station B or Position 3. Here the driver tilts the mast forward to the lifting position and raises the load to a height of 2m. The driver then lowers the load and tilts the mast back to its travel position. The driver then reverses the truck to Position 4 before moving forward 30m to Position 5, turns through 90°, and advances forward twice the distance of the load centre to Position 6 at Station A. The driver then goes through the same tilting and lifting process as before and then reverses to Position 1 to complete 1 duty cycle. It is worth noting that the load remains on the forks at all times. In the case of the counterbalance forklift truck, this course must be completed 60 times in 60 minutes. The fuel consumption is then measured in litres and recorded as litres per hour for diesel trucks (l/h) or kilograms per hour (kg/h) for LPG trucks. For electric trucks, the energy consumption is measured as kilowatt-hours and then stated in kilowatt-hours per hour or just kilowatts (kW).

Simulation Software and Model

AVL Cruise and Mathworks Simulink were linked to create a model which was capable of simulating the performance and fuel consumption of the chosen forklift truck. The AVL Cruise software was used to simulate the vehicle powertrain components that were common to both automotive and forklift applications including the engine, transmission and wheels. A Simulink model was linked to the AVL Cruise model to represent the parts of the drivetrain which are more specific to forklift trucks such as the fuel pump, hydraulic systems and control systems.

The AVL Cruise software was the primary simulation interface and contained the drive cycle, driver model and environment variables. The Simulink model received inputs from the AVL Cruise model for computation and output its results back to the AVL Cruise model via the in-built Matlab interface module. A simplified pictorial representation of the software is shown below in Figure 2. Each box signifies the main sections of the simulation loop and each arrow represent

the transfer of multiple channels of information between each section.

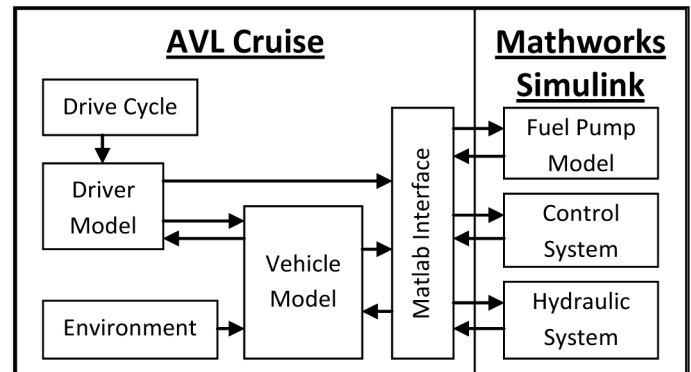


Figure 2. Schematic of software layout and interface

The model employed a forward-facing approach. A forward facing model uses a driver model to control the vehicle model via the traditional driver inputs such as the accelerator and brake pedals. The driver model tries to match a desired velocity profile or drive cycle defined by the user, by adjusting the accelerator, brake, etc, to accelerate or decelerate the vehicle model and follow the desired profile.

A forward facing model was chosen over a backward facing model for several reasons. The drawbacks of a backward facing model are that it will follow any desired velocity profile even if it is not physically possible and it has difficulty handling transient situations. A forward facing model closely represents the behaviour and response characteristics of the truck which is dictated by the amount of energy available and its environment. Also, a forward facing model has the potential to become a much more powerful simulation tool by allowing for the integration of existing control systems directly into the vehicle model. Therefore, the forward facing approach not only gives accurate and realistic control of the vehicle model, but allows for the vehicle model to be used for the development and simulation of new control systems without the need of physical prototyping thus making the simulation tool much more useful to engineers.

The driver model calculates the error between the current vehicle velocity and the desired vehicle velocity stated in the drive cycle information which is input by the user. A PID type controller uses the velocity error to calculate how much to adjust the accelerator pedal and brake pedal to achieve the desired velocity. The drive cycle and environment variables such as temperature, gradient, etc, are input as tables of information by the software user. The vehicle model itself is made up of several modules that represent the main components in the drivetrain as shown in Figure 3. Each module contains information on the performance and characteristics of the component. The Matlab/Simulink interface can also be seen as a module in Figure 3. This

interface allows the AVL Cruise software to interact with the additional Simulink models required for forklift modelling.

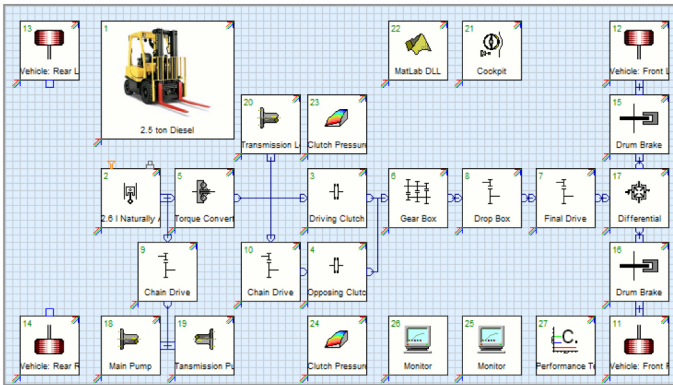


Figure 3. AVL Cruise vehicle model

FUEL PUMP & GOVERNOR

In an automotive application, the driver directly controls the fuel load delivered to the engine with the accelerator pedal position (APP), as represented by the control loop in Figure 4. However, with a governed engine the APP determines the control lever position (CLP) on the fuel pump. The control lever does not directly control the fuel load but is used to control the engine speed. A governor within the fuel pump determines the fuel load based on the CLP and current engine speed to maintain a desired engine speed. The governor can vary fuel load between 0 % and 100 % for any CLP.

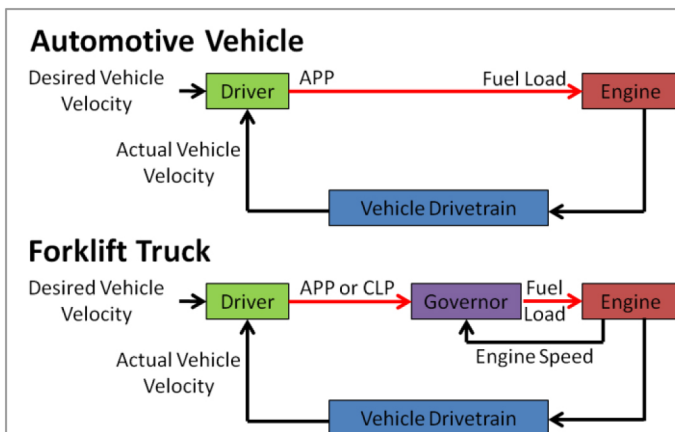


Figure 4. Schematic of fuel load control in ungoverned and governed engines

In initial versions of the whole vehicle model, the accelerator pedal was used to directly control the fuel load as in automotive vehicles. However, the APP also has the secondary function on a forklift as an input to the vehicle's clutch control system. The clutch control system performs several performance enhancing and safety functions on the truck and so accurate simulation of the APP was essential to

properly control the transmission clutches. As there is no direct relationship between APP and fuel load within a governed fuel pump, it was necessary to create a fuel pump model that would account for the behaviour of the governor and allow the APP to be used as the engine speed controller as in the real truck and thus allowing correct operation of the clutches during simulation.

Fuel Injection Pump

To build a fuel pump model, a detailed understanding of the fuel pump was required. The fuel pump used on the 2.6 litre 4-cylinder engine was a VE-type axial-piston distributor pump with a variable-speed mechanical governor as shown in Figure 5. This pump design uses a low pressure vane-type feed pump to draw fuel from the fuel tank and works in combination with a regulating valve to ensure fuel is always available for the high pressure end on the pump. Both the feed pump and a cam plate are driven by the engine at half engine speed. The cam plate rotates over rollers to produce reciprocating as well as rotary motion of the attached piston or plunger in the high-pressure distributor end of the pump.

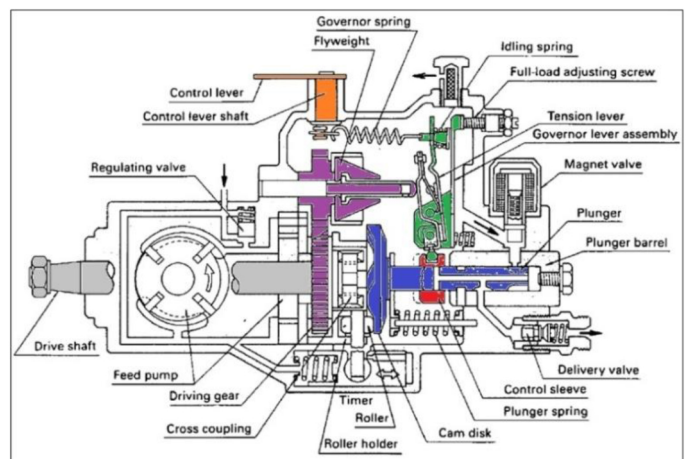


Figure 5. Variable-speed governor construction [4]

This piston produces four separate shots or injections of fuel for each revolution of the pump, one for each engine cylinder. The amount of fuel injected is determined by the positioning of a control sleeve. The control sleeve covers the relief port on the high pressure piston shown in Figure 6. As the piston draws back, fuel enters the piston barrel in the distributor head under the relatively low feed-pump pressure. The rotation of the piston then covers the inlet and the piston starts to compress the fuel to a high pressure. As the piston continues to rotate, the high pressure outlet port is exposed to one of the injector ports and high pressure fuel is injected into the engine. As the piston reaches the end of its stroke, the relief port becomes uncovered and injection pressure is suddenly reduced and fuel flow stops. The control sleeve position determines when the relief port is exposed.