

Drivetrain Energy Distribution and Losses from Fuel to Wheel

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ABSTRACT

Depending on a vehicle's drive cycle, an improvement of the overall drivetrain efficiency does not necessarily have to go along with an improvement of its mileage. In here the ratio of energy to overcome rolling resistance, aerodynamic drag, acceleration and energy wasted directly in wheel brakes is responsible for potentially differing trends.

A detailed knowledge of energy flows, sources and sinks makes up a substantial step into optimizing any drive train. Most fuel energy leaves the drivetrain via exhaust pipes. Next to usable mechanical energy, a big amount is spent to heat up the system directly or to overcome drive train friction, which is converted into heat to warm up the system additionally. An in depth quantification of the most important energy flows for an upper middle-sized class gasoline powered drive train is given as results of warm-up cycle simulations. Combustion engine heat losses are split into four paths to be compared with the heat of ten engine friction components. Total engine friction of engines, started at room temperature in low load cycles used for emission legislation, makes up about one third of the heat input of the thermal system.

Energy flow manipulation in terms of thermal management measures are quantified as well as secondary effects and benefits seen in a holistic approach covering all relevant paths from fuel to wheel. Investigated is the effect of a split cooling system, a map controlled thermostat, the use of an electric water pump and combinations of those for a cold started FTP75 test cycle. Split cooling yields a benefit of $\sim 2.2 - 2.4\%$ fuel reduction potential; the use of an electrical water pump shows $\sim 0.3 - 1.2\%$. The benefit of a combination of both measures is simulated to $\sim 2.3 - 2.5\%$.

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INTRODUCTION

Increasing demands to fulfil vehicle emission legislation and decreasing world energy reserves need to be answered with highly efficient technological solutions. The evaluation of methods for improvement can either be gained by testing or, if applicable, by simulation. Simulation models describing vehicle drive trains for different applications can be found in numerous publications, such as in [1,2]. Warm-up models for a combustion engine alone with a detailed description of engine heat distribution had been developed before either with zero-dimensional thermal capacities [3,4] or in newer investigations by making use of 3D finite elements [5]. The results presented in this paper are based on a simulation model for a coupled 1D and 3D simulation performed with the simulation environment GT-SUITE and developed and described in detail in [6].

The scope of this work is to give a detailed overview of energy flows within a complete drive train to show where most of the supplied fuel energy is spent and how it interacts

with the complicated warm-up system. Engine warm-up is displayed and characterised by material and fluid temperatures. Measures to manipulate the warm-up phase show different effects on respective temperatures and system efficiency, seen in a holistic model capable of covering secondary effects on various subsystems.

The paper starts with general thoughts on system efficiency by discussing drive train energy distribution. Methods and operating strategies for improvement are derived from there and finally quantified.

FUEL ENERGY DISTRIBUTION

When simulating the FTP75 cycle, the energy distribution at the end of it is shown in [Figure 1](#). The given results are gained for an upper middle-sized class gasoline powered drive train, namely for the Mercedes M271 KE super charged 1.8 l 4 cylinder gasoline engine with multipoint injection built in a Mercedes C-Class (W204) with a manual 6-speed gear box. Geometric and nominal data of the engine is given in [Table 1](#).

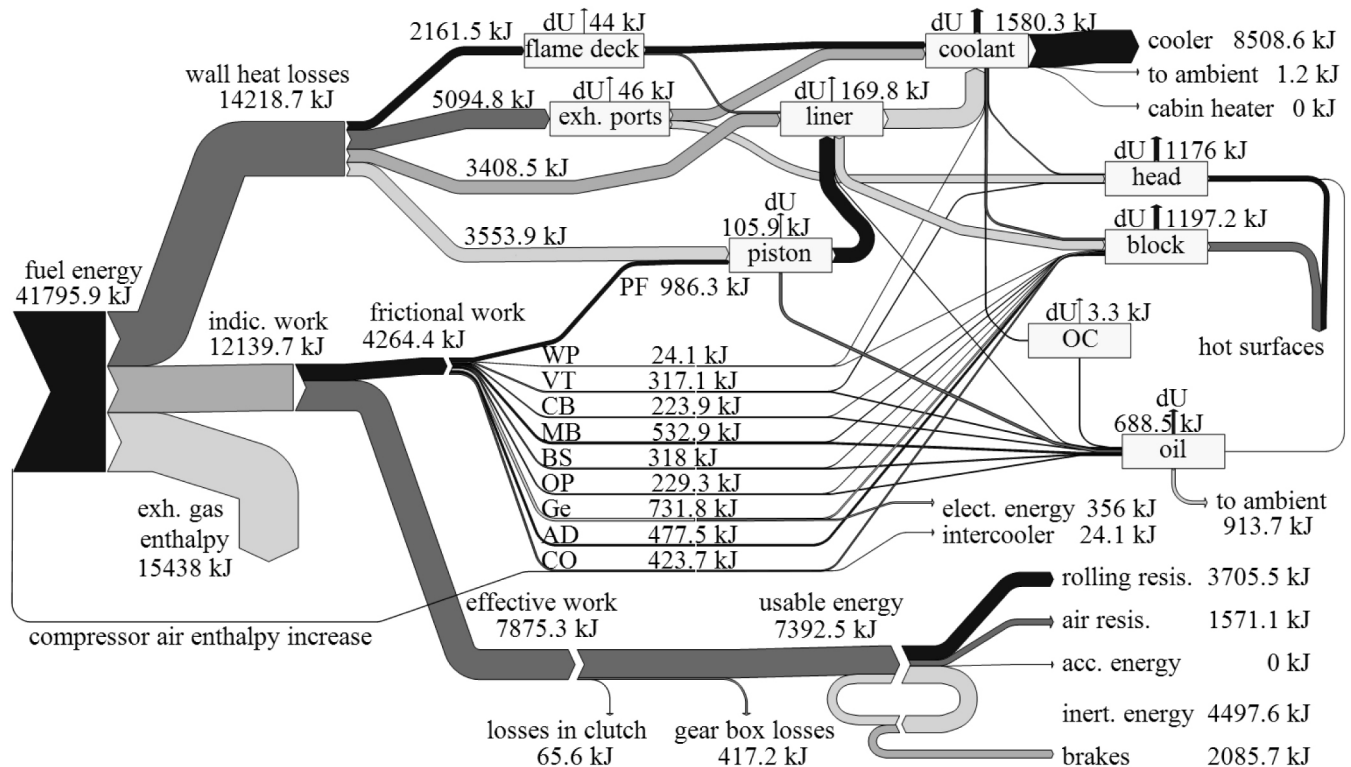


Figure 1. Simulated accumulated energy flows at the last time step of a cold started FTP75 test cycle

Table 1. Selected data of investigated Mercedes M271 KE

Displacement	1796 cc
Stroke	85 mm
Bore	82 mm
Connecting Rod	143.5 mm
Compression ratio	8.5:1
Maximum power output	135 kW @ 5500 1/min
Maximum torque	250 Nm @ 2800 1/min
Super charger	Eaton M45 compressor

The accumulated input fuel energy of $\sim 41,800$ kJ corresponds to a mileage of 7.4 l/100km (31.7 MPG) and is converted into exhaust gas enthalpy, wall heat losses and piston work called indicated work. Effective engine power output to be directed into the gear box via dry clutch makes up about two-thirds of the indicated work - one third is used to overcome engine friction. The mechanical engine efficiency is rather low, since the FTP75 in here is started at room temperature and therewith shows high friction. The frictional work itself is broken down into ten components whose friction energy is simulated according to their respective dependencies. Water pump friction for instance is simulated in a hydraulic circuit depending on its speed, coolant temperature and engine thermostat position, whereas valve train friction is derived from measured maps according to the main gallery oil temperature and engine speed. A detailed description of the simulation model and break down

of all components can be found in [6]. Abbreviations in Figure 1 are given in Table 2.

Table 2. Used abbreviations in Figure 1

PF	piston friction
WP	water pump
VT	valve train
CB	connecting rod bearings
MB	main bearings
BS	mass balancing system
OP	oil pump
Ge	generator
AD	accessory drives
CO	compressor
dU	increase of internal energy
OC	oil cooler
exh.	exhaust
resis.	resistance
indic.	indicated
acc. energy	acceleration energy
inert. energy	inertial energy
to ambient	conduction and radiation

Wall heat losses in this indirect simulation approach as pre-simulated with GT-POWER and validated with engine test bench measurements covering the entire engine operating range are subdivided into four paths and input into 3D finite

elements. Indirect simulation approach means that two simulations are conducted one after the other. The results of the first simulation are input as data point maps into the second simulation. A direct simulation approach in where both simulations run simultaneously is more time consuming. The roughly discretised 3D finite elements cover the engine structure close to the combustion chamber and therefore absorb only small amounts of energy while their internal energy content rises with a simulated evolving 3D temperature profile. Most of the energy spent to increase the systems internal energy is to be found in the fluids coolant and oil and two more lumped masses describing the remaining engine structure of head and block. All heat flows between structure, fluids and environment for instance via the main cooler are defined by numerous heat transfer laws or measurements of real specific engine components converted to mapped look ups in the simulation in detail presented in [6].

Drive Train Quality Criteria

Efficiency as being a quality criterion can be defined in different ways. Vehicle mileage or fuel consumption respectively, is a common performance criterion. For any instant of time while driving a vehicle, the accumulated useable mechanical energy acting on the driving wheels can be set into correlation with the accumulated fuel energy. Thus, a general degree of utilisation η_{sys} can be defined as

$$\eta_{sys} = \frac{\int_0^t P_{wheel} d\hat{t}}{\int_0^t \dot{m}_F \cdot H_u d\hat{t}}. \quad (1)$$

In here P_{wheel} is the mechanical power acting on the driving wheels which becomes negative in overrun phase with decreasing vehicle speeds. $\dot{m}_F$ represents the actual fuel mass injected into the engine and H_u the fuel lower heating value.

Following the path of mechanical energy in [Figure 1](#) flowing through clutch and gear box, the accumulated usable mechanical energy acting on the driving wheel is quantified to be only $\sim 7,400$ kJ at the last time step in a cold started FTP75 test cycle. With this the general degree of utilisation becomes only ~ 18 %. It is obvious that an improvement of system efficiency and with that an improvement of the general degree of utilisation goes along with a better vehicle mileage, if and only if the same cycles are compared with each other. For different cycles, an increase in system efficiency can mean a worsening of vehicle mileage. It depends on the ratio of energy to overcome rolling resistance, aerodynamic drag, acceleration and energy wasted directly in wheel brakes. This can easily be seen by comparing steady state vehicle rides at different speeds.

Vehicle mileage is given by the distance travelled over the used fuel volume or mass, respectively by

$$\frac{d}{V_F} = \frac{v}{\dot{V}_F} = \frac{\rho_F \cdot v}{\dot{m}_F}. \quad (2)$$

With distance d , vehicle speed v , density ρ , volume V and mass m of fuel (index F). Fuel mass rate in steady state conditions can be described with the general degree of utilisation η_{sys} and the resulting force of all resistances F_{wheel} such that it follows

$$\frac{d}{V_F} = \frac{\eta_{sys} \cdot H_u \cdot \rho_F \cdot v}{P_{wheel}} = \frac{\eta_{sys} \cdot H_u \cdot \rho_F \cdot v}{F_{wheel} \cdot v} = \frac{\eta_{sys} \cdot H_u \cdot \rho_F}{F_{wheel}}. \quad (3)$$

The resulting force of all resistances is strongly dependent on vehicle speed, with the conclusion that vehicle mileage is a function of vehicle speed, too, even if the general degree of utilisation stays constant.

This can be seen by comparing mileage values and general degrees of utilisation for different cycles with different speed profiles as depicted in [Figure 2](#).

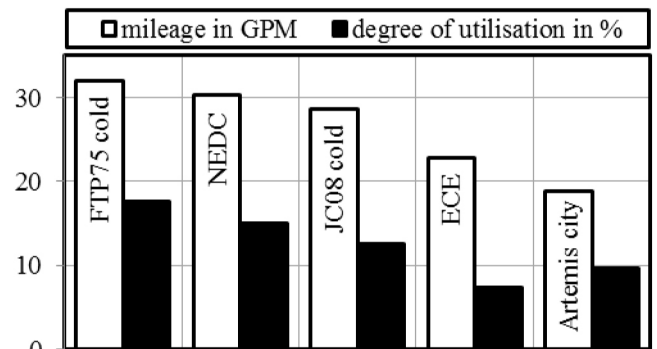


Figure 2. Mileage and system efficiency in comparison for different driving cycles

Shown are legislation driving cycles for the U.S., Europe (NEDC [7]) and Japan (JC08 [8]) started at room temperatures and the two city cycles ECE, as being the city part of the NEDC until time step 780, and Artemis city [9], a drive cycle often used to come close to real world driving. Despite the fact that all legislation cycles show different mileage and efficiency values mostly due to their different load levels, their trends lead into the same direction. A worsening in consumption goes along with a worsening in system efficiency. This does not account by comparing the city cycles. The ECE shows a better mileage, but a lot lower system efficiency.

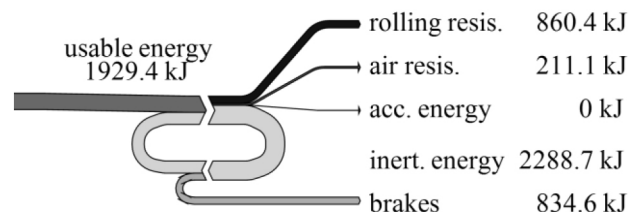


Figure 3. Driving resistance breakdown Artemis city