

# Improved Energy Management Using Engine Compartment Encapsulation and Grille Shutter Control

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## ABSTRACT

A vehicle thermal management system is required to increase the operating efficiency of components, to transfer the heat efficiently and to reduce the energy required for the vehicle. Vehicle thermal management technologies, such as engine compartment encapsulation together with grille shutter control, enable energy efficiency improvements through utilizing waste heat in the engine compartment for heating powertrain components as well as cabin heating and reducing the aerodynamic drag.

In this work, a significant effort is put on recovering waste heat from the engine compartment to provide additional efficiency to the components using a motor compartment insulation technique and grille shutter. The tests are accelerated and the cost is reduced using a co-simulation tool based on high resolution, complex thermal and kinematics models. The results are validated with experimental values measured in a thermal wind tunnel, which provided satisfactory accuracy. A control strategy is implemented to actuate the grille shutter according to the specific conditions and a sensitivity study is introduced using the most important parameters affecting energy management performance. Using different conditions (test cycles and environmental temperature), the simulation results reveal a moderate potential fuel consumption reduction of up to 2.5 % on FTP-75 at  $-7^{\circ}\text{C}$ . An analysis of the results shows how the improved aerodynamic properties compare to the warming-up affect on the fuel consumption.

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## INTRODUCTION

Aerodynamic drag force plays an important role in achieving the vehicle energy demand. The airflow through the radiator is extremely inhomogeneous, which can substantially increase the aerodynamic resistance in this area. A control of the airflow rate passing the radiator and entering the engine compartment can provide significant benefits in the warm-up phase with no need to cool the engine. This includes improved fuel economy and better warming-up. The

primary purpose of this study is to evaluate methods of thermally insulating powertrain components in regards to energy required to warm up the vehicle, energy lost to aerodynamic friction force, reduction on fuel consumption, and increase of passenger comfort.

Many papers and projects have focused on modeling the insulation of engine compartments. For example, [1] showed a CO<sub>2</sub> reduction of 2.5g/km for a diesel 4 cylinder engine with simultaneous reduction of exterior noise of up to 5 dB. A reduction of fuel consumption obtained by extending the

cool down time of the powertrain after engine shutoff was discussed in [2] and [3]. In [4] the focus was on the improvement of the air drag coefficient  $c_w$  with 0.014 at 140km/h in comparison to the open grille shutter. A method for actuating an active grille shutter to optimize the total vehicle energy consumption by balancing the power consumption of the A/C compressor and the aerodynamic benefits was developed in [5].

As can be noted, previous research has been done using either engine compartment encapsulation or grille shutter control. However none of the previous research approaches considered both techniques together. Based on this, it was decided to evaluate and combine the benefits of both techniques to achieve optimal fuel reduction.

This study is divided into two sections: initially, engine compartment encapsulation is considered to increase the engine warm-up. In the second part, a grille shutter will be used to show the potential analysis of the aerodynamic forces.

## SYSTEM MODELING

Two conditions must be considered in the vehicle thermal management topics: a longitudinal vehicle dynamics model (closed loop) and a thermal model of the powertrain components (engine and wet dual clutch transmission).

This of course does not only include the thermal modeling of powertrain components in form of thermal equivalent masses with heat transfer relations, but also the modeling of fluid systems, for example detailed oil and coolant circuits, as well as the airflow in the engine compartment. Before discussing the detailed consideration of the focused simulation models, the simulation method used to represent the vehicle model will be briefly discussed.

## FORWARD-LOOKING VEHICLE MODEL

The longitudinal dynamics simulation method for the implemented vehicle models is a forward-looking method. In this case, the driving profile, i.e. the desired speed (command variable) is given to the driver. The driver acts as a regulator and the regulator is generated considering the current actual speed of the vehicle (control variable) and pedal value (actuating variable). This actuating variable is passed to the drive train, where it is converted into a torque command (see Fig. 1).

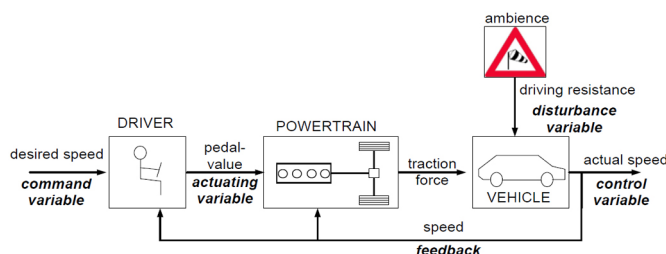


Figure 1. Forward-looking vehicle model

From the drive torque which is applied to the wheel and the driving resistance (disturbance variable) on the vehicle, as a result the vehicle speed is determined. Through the feedback of the current speed, the speed of individual drive train components (from the wheel to engine) is calculated.

There are different approaches for the implementation of a vehicle simulation environment: an integrated approach (only one software product) or a semi-integrated approach. In a partially integrated approach, different simulation tools are linked to each other - this approach was chosen for the simulation.

The coupling of different models is implemented using the cosimulator TISC [6], [7] and [8]. With this software it is, for example, possible to connect MATLAB, KULI, FLOWMASTER and Dymola with each other.

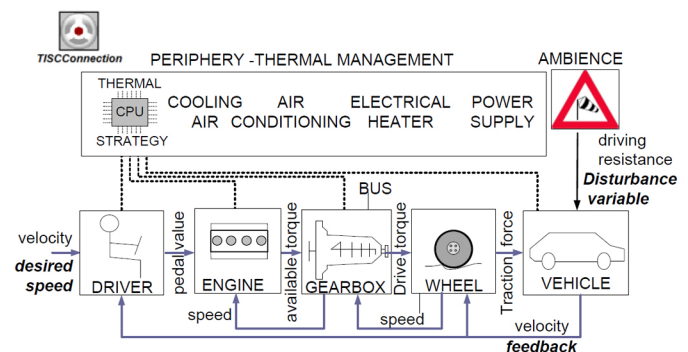


Figure 2. Modules of the conventional powertrain model

Figure 2 shows the detailed full vehicle simulation environment. Here, the conventional drive is divided into driver, engine, wet dual clutch transmission, wheel, vehicle and the periphery models. Peripherals include the rest of the necessary models, for example the thermal management strategy, the electrical system, the HVAC unit and fluid systems (oil, coolant and air).

The drive train models in the simulation environment play an important role, especially for calculation of the fuel consumption. The engine model is created using the equivalent mass method as a representative single-cylinder engine, assuming that the difference in thermal behavior between the individual cylinders is rather low. The modeled four-cylinder diesel engine is therefore implemented by a multiplication of the relevant system parameters (mass flow, heat flow).

The thermal network model of the powertrain consists of 30 thermal masses. The individual equivalent masses are connected with internal or external thermal resistances. The heat transfer from the engine structure to the coolant and engine oil is also implemented. In addition to all exterior components, the heat transfer to the environment is taken into the consideration.

The fuel mass flow is calculated as a map-based table. The stationary map was recorded on a test bench. Input variables here are the engine speed and the mean indicated

**Table 1. Physical properties of the insulator material used for the engine compartment encapsulation [9].**

|                                             |                         |
|---------------------------------------------|-------------------------|
| Thermal Conductivity                        | 0.04 [W/mK]/50°C        |
| Thickness                                   | 13 [mm]                 |
| Density                                     | 96 [kg/m <sup>3</sup> ] |
| Total insulator mass needed for the vehicle | 4 [kg]                  |
| Aluminum coating                            | 0.1 [mm]                |

pressure. Thus, it is possible that the changing engine friction is directly included into the fuel calculation.

The engine model includes a friction model, which calculates the engine friction as a function of engine speed, oil temperature, coolant temperature and engine load. If thermal management measures are evaluated, it is necessary that the effect of the increased coolant temperatures, on engine friction is taken into account. The integration of the coolant temperature in the friction model is therefore very important because it has a massive influence on the friction of the piston group.

To calculate the important parameters for fuel consumption and passenger comfort with different thermal management concepts, a set of interacting simulation models is required. The simulation models are designed so that the overall models can be well organized and allow the integration of other simulations models. Using identical variable interfaces, the simulation models can be used for different vehicle types. The thermal losses of the powertrain components are determined from interpolation of maps that are derived from measurements and analytical equations. At the end of the engine warm-up phase, the main thermostat is involved. The transmission losses are directly input into mechanical moving parts, transmission case and oil sump.

## ENGINE COMPARTMENT ENCAPSULATION MODEL

Engine compartment insulators can be made of different materials, but there are several factors that must be considered to design the encapsulation of the engine compartment. The requirements are:

1. High temperature stability at normal and extreme operating temperatures (−50°C up to 200°C) that occur in various standard tests in terms of resistance to thermal shock and flammability.
2. The thermal conductivity of the insulator should be very low
3. The insulator materials should be lightweight in order not to increase the vehicle mass and therefore the fuel consumption.
4. The insulator should cover the whole surface of the engine compartments to prevent direct exposure of the powertrain surfaces to the cold outside air or to the cold surrounding surfaces, which would in turn influence the temperature of the hot air inside the engine compartments.

Besides heat protection, some additional functions are taken into account, such as increasing the acoustics

absorption of the powertrain components. The selected insulating matting has a 0.1 mm aluminum foil installed in the surface with non-fuming and incombustible inorganic adhesive. In addition to the above condition, the OEM's selection of such material depends on whether acceptable costs and compatibility with manufacturing and maintenance processes are achieved [2].

The physical properties of the used insulator material are listed in the following table:

A basic requirement to generate a new model is measurements. Measurements were evaluated by equipping a vehicle in the climatic wind tunnel in order to answer the question: how many temperature levels actually exist in the engine compartment. For this purpose, eight temperature sensors were installed in the engine compartment. [Figure 3](#) shows the different temperature levels in the NEDC cycle at an ambient temperature of 20 °C.

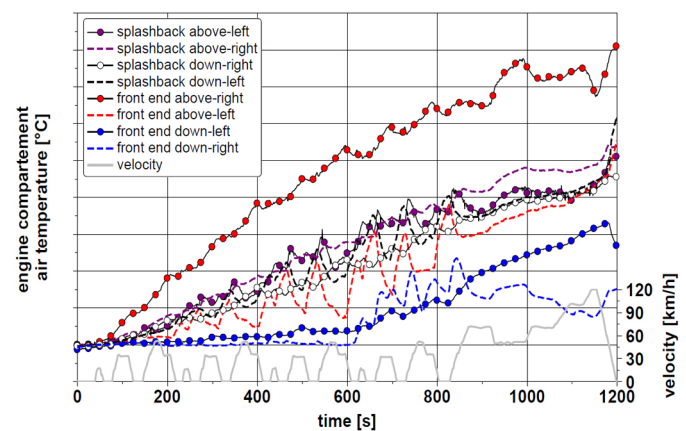


**Figure 3. NEDC cycle: measured temperature profiles of the cooling air in the engine compartment in an equipped test vehicle in the climatic wind tunnel at an ambient temperature of 20 °C**

Based on these data, two different temperature levels were identified. The lowest values are close to the lower floor base in the engine compartment area and the higher values in the upper part of the engine compartment. As a consequence, the cooling air model has to calculate two air temperatures. The arrangement of the heat transfer in the engine compartment can be seen in [Figure 4](#). For example, the cylinder head exchanges heat with the air at the higher level (cooling air upper) and the engine oil pan with the air at the lower level (cooling air lower). The air mass in the engine compartment