Reduction of Transient Emissions from Internal Combustion Engines through Phlegmatization

Felix von Arnim [1], Marcus Geimer [1]

[1] Institute of Mobile Machines, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

Reducing transient emissions from internal combustion engines in mobile working machines presents a significant challenge, especially in terms of complying with strict environmental regulations. A promising method for reducing these emissions is the phlegmatization, where the internal combustion engine is delayed in adjusting to the new load level after a load step. This allows the air path more time, resulting in lower NO_x and PM emissions.
This paper presents the concept of a hybrid module used for phlegmatization and its approach for an operating strategy. Additionally, the simulation model built to investigate the concept is introduced, with a specific focus on parameterizing and verifying the engine models of two diesel engines. Furthermore, the map area with the highest savings potential for both engines is determined. Finally, the approach for an operating strategy of the hybrid module is outlined.

Keywords: internal combustion engine, phlegmatization, transient emissions, hydraulic hybrid

1 Transient Emissions in Mobile Working Machines

Climate change is driven, among other things, by emissions from internal combustion engines (ICE) powered by fossil fuels. Diesel engines, as a form of an ICE, are the most widely used primary energy converters in mobile working machines [1]. In the Following, diesel engines are referred to as ICE. The most important greenhouse gas in the context of climate change and ICEs is CO_2 [2] [3]. In addition to CO_2, the harmful effects of nitrogen oxide (NO_x) and particulate emissions (PM) from ICE on humans and the environment have been known since the 1960s [4].
As [5] shows in several measurement results, approximately 40% of NO_x and PM emissions are attributable to transient operating conditions, characterized by rapid changes in engine operation. These conditions are particularly common in mobile working machines due to their recurring cycles (e.g., Y-cycle or 90° excavator cycle). Three types of operating conditions lead to transient events: load steps (LS) at constant speed, speed steps at constant load, or cold starts. These conditions can also occur in combination, amplifying their effects [6]. However, this paper only considers the first case.

During steady-state conditions, the air and fuel quantities are balanced to ensure both good power output and low fuel consumption and emissions. In the event of a sudden LS, the desired amount of diesel can be injected immediately, whereas the corresponding boost pressure, i.e., the air quantity, is only available with a significant delay due to turbo lag. [5] [6]

This leads to a reduction in the air-fuel ratio λ, which is the critical factor for the formation of PM. Consequently, many zones in the combustion chamber experience a significant lack of air, which is locally increased by the short mixing time due to the prevalent direct injection in modern ICE. This promotes PM formation. [5]
At the same time, poor mixing during turbo lag results in partially high λ values, leading to locally high gas temperatures and ultimately high NO_x emissions. Additionally, the reduction in the exhaust gas recirculation (EGR) rate to provide the required torque for the LS leads to more fresh air in the combustion chamber, resulting in less PM. However, this fresh air again causes higher gas temperatures and, within the context of the soot-NO_x trade-off, increased NO_x emissions. [5] [6]

In addition to internal engine solutions such as the EGR or adapted injection times, various exhaust gas aftertreatment methods such as diesel particulate filters (DPF) against PM, diesel oxidation catalytic converters (DOC) against unburnt hydrocarbons and systems for selective catalytic reduction (SCR) against NO_x are also used. All of these systems must be tuned to the EGR, if available [7].
Hybrid systems, on the other hand, have so far mainly been used to increase performance and save fuel [8] [9] [10], but less for reducing (transient) emissions [11] [12]. This paper is therefore intended to provide an outlook on the possibilities of a compact hybrid module for reducing primarily transient NO_x and PM emissions from mobile working machines.

2 Concept of a Hybrid Module for Reducing Transient Emissions

The hybrid module (HyM) operates on the same principle as described in [13]. Figure 2.1 illustrates the basic idea using the example of a LS and following load drop (LD). The desired torque M_{des} is distributed between the internal combustion engine (M_{ICE}) and the HyM (M_{HyM}). In the case of a LS in area 1, the ICE builds up M_{ICE} slowly with a constant gradient, depending on the air path ramp-up time t_{AP}. The time required to build up the boost pressure allows for the reduction of transient emissions [14]. The HyM contributes the missing torque M_{HyM} to ensure that M_{des} is achieved at the output. The recharging of the HyM occurs when returning to partial load in area 2 through a delayed decrease of M_{ICE}. The presented principle is a form of phlegmatization characterized by an extremely low degree of phlegmatization according to [15].

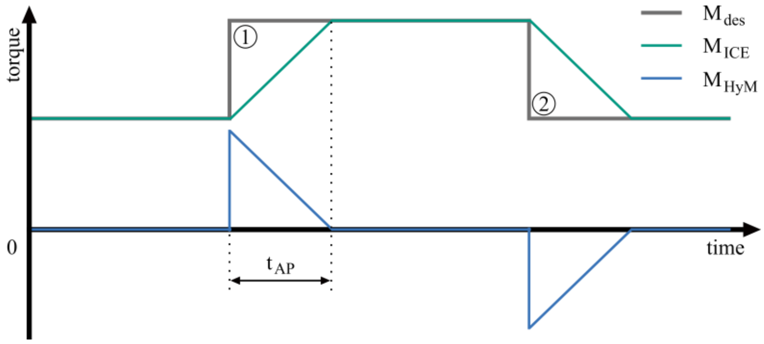

Figure 2.1: Basic principle of the hybrid module according to [13]

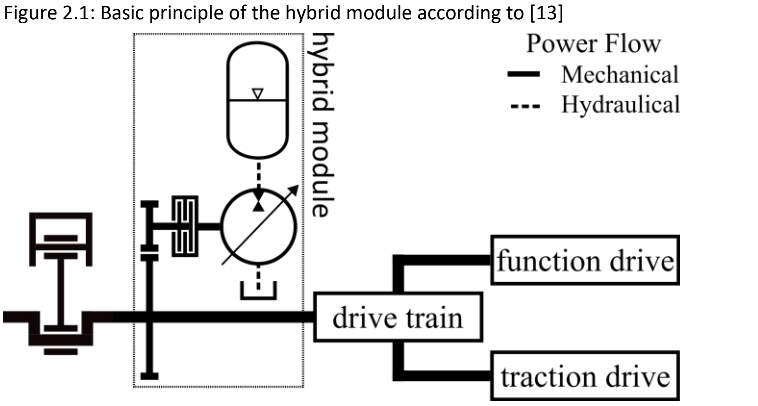

Figure 2.2: Topology of the hybrid module used with clutch [13]

The HyM is designed as a parallel hybrid. As shown in Figure 2.2, an axial piston pump with a

swashplate design (APPSP) is used as the energy converter, and a hydraulic bladder accumulator is used as the power storage. The HyM is located between the ICE and the rest of the drivetrain, as close to the ICE as possible, to better influence its operating points [16].
The APPSP is connected to the entire drivetrain via a spur gear and a clutch only during the transient event. Without the clutch, the constant rotation of the APPSP, even in the neutral position, would generate losses that cannot be neglected [17]. Additionally, the spur gear allows the speed or torque range to which the APPSP is exposed to be modeled.

3 Simulation of the Hybrid Module

The suitability of the HyM for reducing transient emissions is investigated through simulation. For this purpose, a simulation model (see Figure 3.3) is built up. This involves a co-simulation of two simulation environments: Cruise™ M by AVL, where the ICE is simulated, and MATLAB® Simulink®, which considers all other components. In the orange area of MATLAB® Simulink®, the cycle is applied on the far right, which provides M_{des} to the drivetrain via a dynamometer and simultaneously forwards it to the operating strategy (OS). Additionally, n_{des} is passed to the ICE. The HyM is positioned between the dynamometer and the ICE and receives the signal from the OS indicating the torque $M_{HyM,des}$ it needs to generate. Simultaneously, the OS receives the current accumulator status of the HyM in the form of the accumulator pressure p_{acc} and the current ICE speed $n_{ICE,cur}$ to calculate $M_{HyM,des}$.

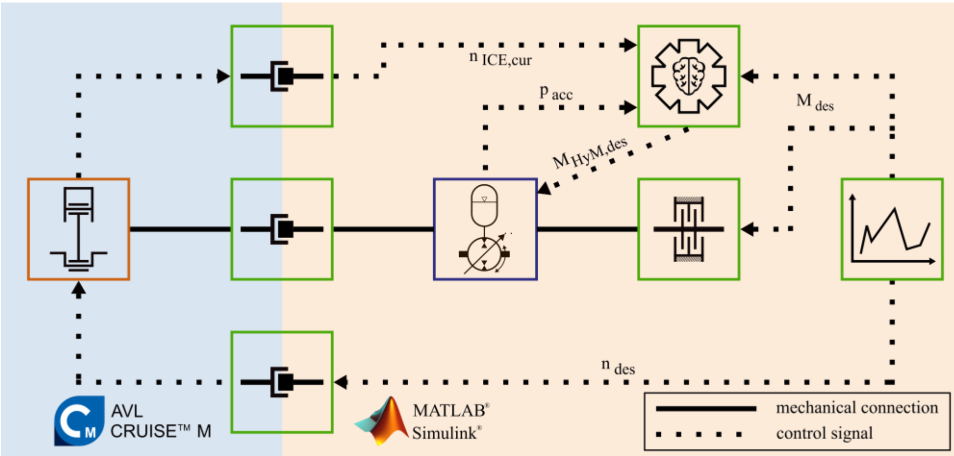

Figure 3.3: Overview of the basic structure of the model

The ICE in Cruise™ M is a semi-physical model of the cylinder block and a physically implemented air path using a 0D simulation approach [18] [19] [20]. Here, a PID controller based on n_{des} and $n_{ICE,cur}$ determines the load signal, which, together with $n_{ICE,cur}$, is used to read all important parameters such as injection quantity and timing, EGR rate, etc., from maps. This allows the engine model to simulate the combustion and thus the emissions for the required torque M_{des}.

Based on map measurements, two engine models have been developed that have different performance ranges and are used in both trucks and mobile working machines. Their technical data can be found in Table 3.1.

Table 3.1: Technical data of the two simulated ICE

	ICE 1	ICE 2
cylinders	inline, 6	inline, 6
displacement in l	12,8	7,7
$M_{ICE,max}$ in Nm	2600	1400
$P_{ICE,max}$ in kW	390	260
EGR	yes	yes
turbocharging	VTG	Bi-Turbo

3.1 Parameterization of the Engine Models

The models are parameterized using map measurements according to the definition in [21]. For evaluation, both a graphical method and a feature-based method are used as in [22]. Both methods utilize the 12 parameters shown in Figure 3.4 and Figure 3.5. The results of the measurements, represented by the blue solid lines, are compared with the corresponding simulation results (green solid line).

Each model is considered parameterized according to the graphical evaluation method when the measurement and simulation of the individual parameters match as closely as possible. The calculation of the deviation $\mathrm{r_z}$ in the upper left corner of each parameter diagram and thus the evaluation according to the feature-based method is carried out using the method from [23], which is further detailed in [22]. The better the agreement between measurement and simulation, the smaller $\mathrm{r_z}$ is [24]. Analogous to [22], $\mathrm{r_z}$ less than 10% is considered very good. If $\mathrm{r_z}$ is less than 20%, the parameterization is still considered good. $\mathrm{r_z}$ up to a value of 25% is considered satisfactory.

The parameterization of ICE 1 in Figure 3.4 shows that simulation and measurement agree well both qualitatively and quantitatively at most measurement points. Only for the exhaust manifold pressure $\mathrm{p_{31}}$, the EGR mass flow $\mathrm{MF_{EGR}}$, and PM are there quantitative deviations, which slightly increase the values of $\mathrm{r_z}$, but still remain in the good range with a maximum of 16.4%. The deviations of these three variables are all due to $\mathrm{p_{31}}$, as $\mathrm{MF_{EGR}}$ and PM indirectly depend on $\mathrm{p_{31}}$. In the simulation $\mathrm{p_{31}}$ is always about 0.5 bar below the measured values. This is due to the processes in the combustion simulation

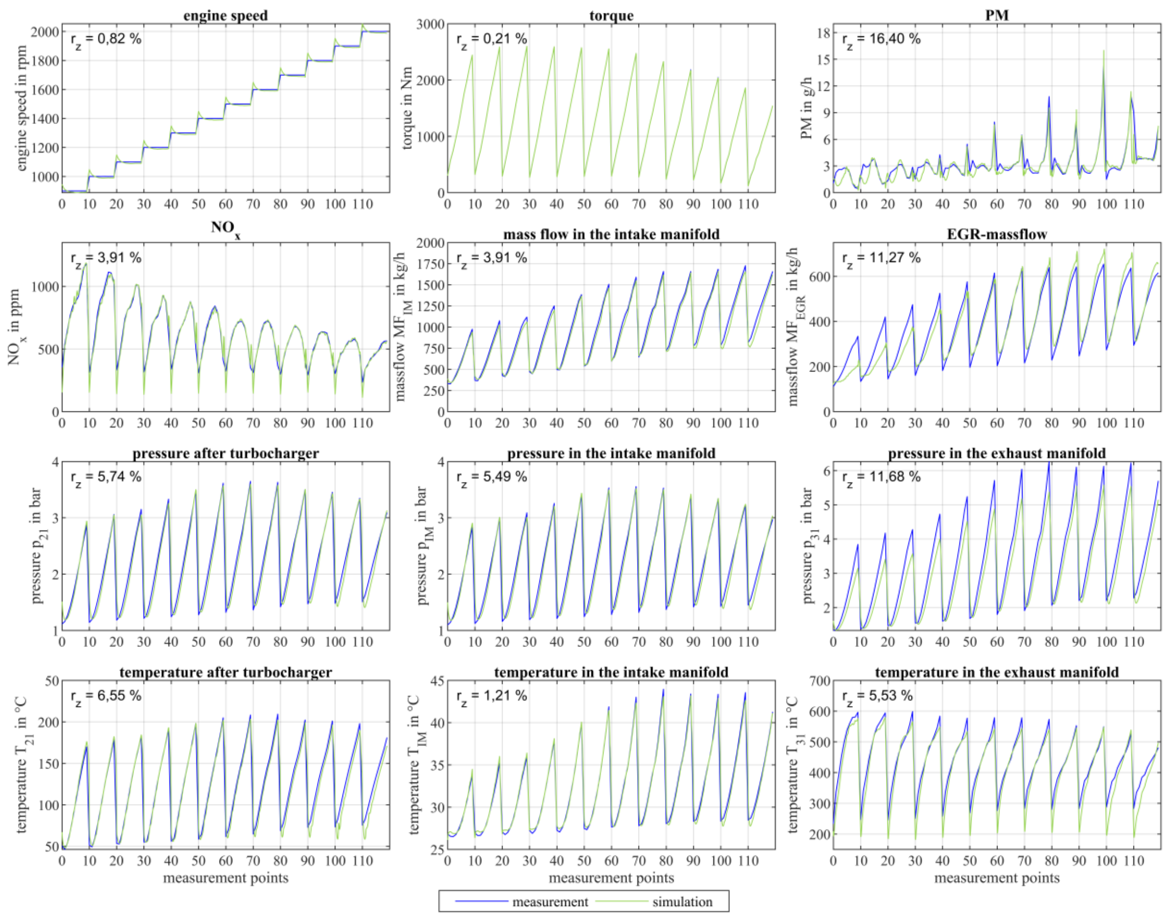

Figure 3.4: Result of parameterization of ICE 1

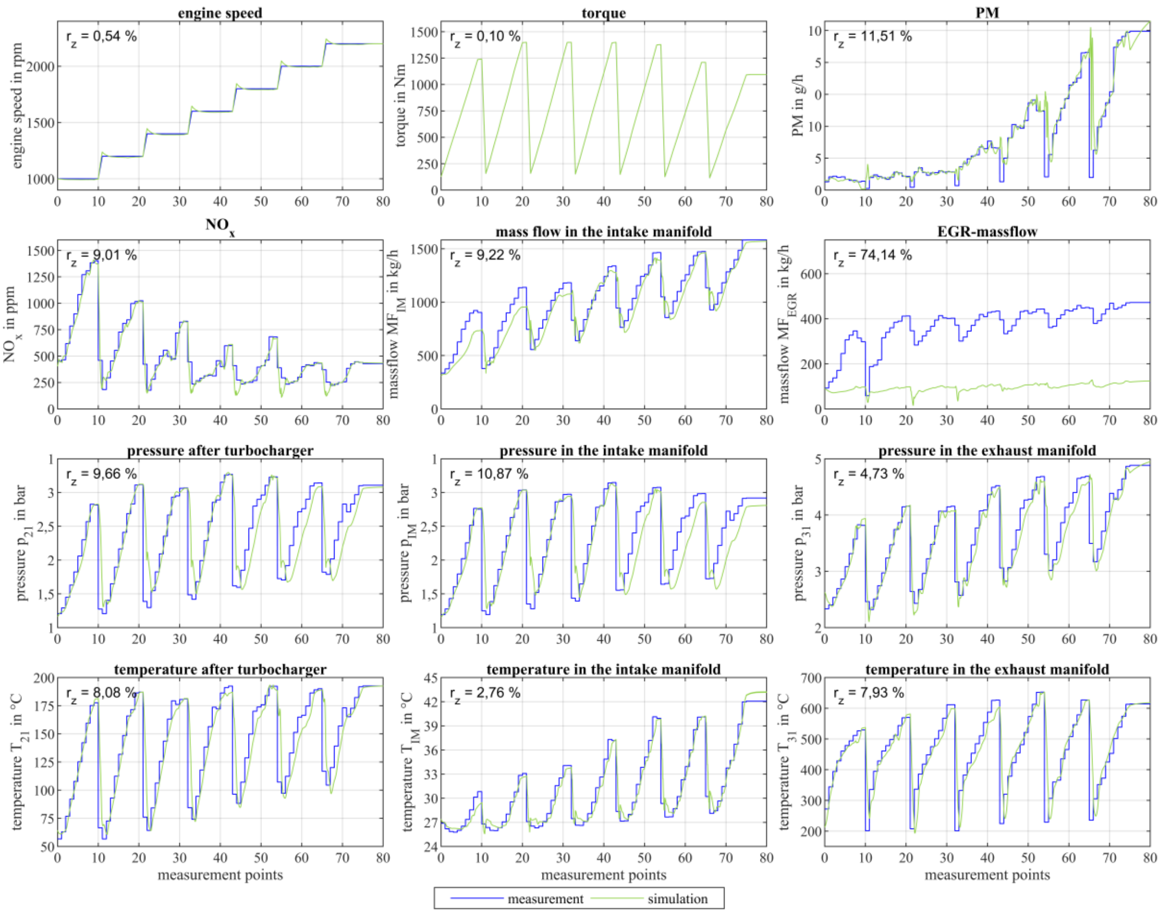

Figure 3.5: Result of parameterization of ICE 2

within the engine block, as all simulation values before and after match the measurement data very well. However, the engine block is a black box, so the influence on internal engine processes is very limited. Parameters such as the pressure at the start of injection are adjusted as much as possible to raise p_{31} while still ensuring a stable simulation process. MF_{EGR} flows along Δp from the exhaust manifold to the intake manifold when the EGR valve is open. If $p_{31}$is too low, this affects MF_{EGR} and thus directly the PM.

As shown in Figure 3.5 measurement and simulation also agree well for ICE 2 for most parameters. Only for MF_{EGR}, simulation and measurement differ by about a factor of 4. This is because the control of MF_{EGR} in the simulation, according to the state of the art [6], aims to achieve both the performance and emission values of the measurement simultaneously. However, the approach to control MF_{EGR} in the measurement is unknown and can only be derived from assumptions. All other parameters agree good to very good.

In summary, it can be noted that all parameters have deviations in the good to very good range. Thus, the presented models of ICE 1 and ICE 2 are defined as successfully parameterized.

3.2 Verification of the Engine Models

A verification compares an analytical solution with a numerical one. If both solutions agree to a certain extent, the numerical solution is considered verified [25]. For the validation of a simulation model, measurement data must be used. Without this measurement data, validation is not possible [21]. But this validation measurement is not available for the considered ICE. Therefore, this paper omits validation and instead conducts a more extensive verification focusing solely on NO_x and PM.

The literature does not present any clear trends regarding engine behavior, either stationary or transient. Based on this, a method is developed using LS as shown in Figure 2.1, which first compares the stationary level after the LS in the simulation with measurements from the literature or map measurements. If a comparison is possible, the stationary behavior is verified. Then, for NO_x and PM, the resulting peak and the level after the LS, and thus the transient behavior, are examined individually. The literature indicates that, except for PM peaks, there are no trends for various ICE. But a peak was always observed for PM after the LS.

The verification shows that the simulation data regarding the stationary level after the LS are comparable to the results from the map measurements. Additionally, the peak after the LS for PM can be demonstrated for all examined cases. An example of such a typical PM peak for LS from 1500 to 2250 Nm at 2200 rpm is shown in Figure 3.6. Since the ICE models do not need to exactly replicate their underlying originals but should primarily reflect real engine behavior, the verification is successfully completed. Thus, the simulation results are usable within the defined boundary conditions, i.e., within the measured maps during stationary and transient states.

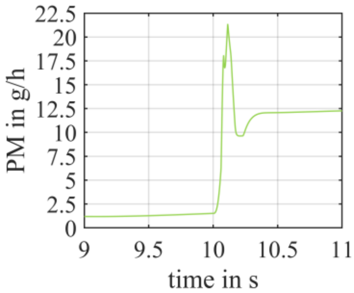

Figure 3.6: Typical PM peak after a LS

3.3 Potential Identification

Before developing operating strategies (OS) for phlegmatization, it is crucial to identify the areas in the engine map where the OS can actually achieve a reduction in transient emissions. For this purpose, LS similar to those in Figure 2.1 are used. At a constant speed, the engine map is traversed concerning the starting torques and speeds to cover every possible speed-torque (s-t) combination. The transient behavior with $t_{AP} = 0$ s is used as a reference. The phlegmatized steps are run with a torque gradient of 100 Nm/s. The reduction can be calculated for NO_x and PM using formula (3.1). For each examined s-t combination, a field is created in the engine map, with its color reflecting the reduction in Figure 3.7 to Figure 3.10. In the fields colored white, the engine stalled due to excessive throttling.

$$\text{reduction} = \frac{\int_{LS_{Start}}^{LD_{End}} NO_{x,trans} - \int_{LS_{Start}}^{LD_{End}} NO_{x,phleg}}{\int_{LS_{Start}}^{LD_{End}} NO_{x,trans}} \quad (3.1)$$

ICE 1 shows a significant clustering of NO_x reduction in the torque range of $M \leq 250$ Nm with a maximum reduction of 4.2 % in Figure 3.7. This potential for reducing NO_x is likely more usable than the distributed potential for reducing PM in the engine map shown in Figure 3.8.
In contrast to ICE 1, ICE 2 shows a significant clustering of PM reduction in the lower speed range (1000 to 1100 rpm) in Figure 3.10. Only there is a reduction in PM with values of up to 29.3 % promising. A reduction in NO_x does not seem particularly worthwhile in any area of the engine map in Figure 3.9, with a maximum reduction of 4.1 %. Based on these findings, the OS can subsequently be developed.

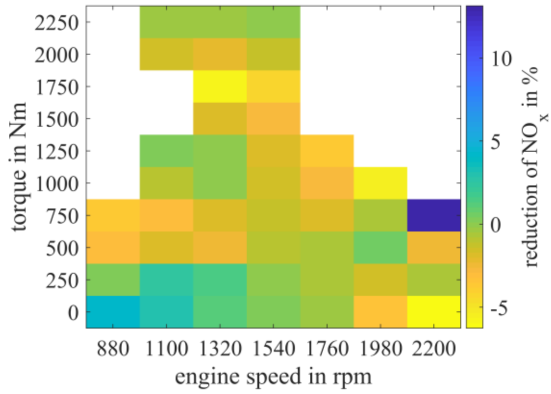

Figure 3.7: NO_x reduction for ICE 1

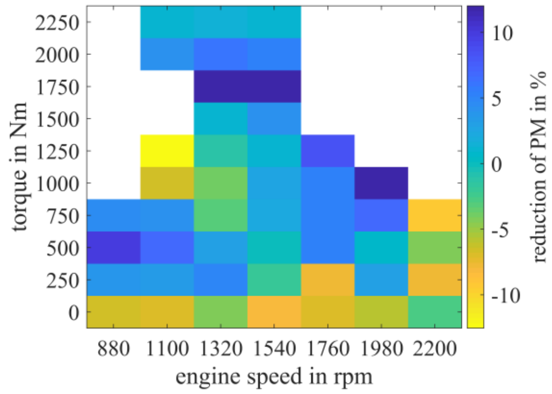

Figure 3.8: PM reduction for ICE 1

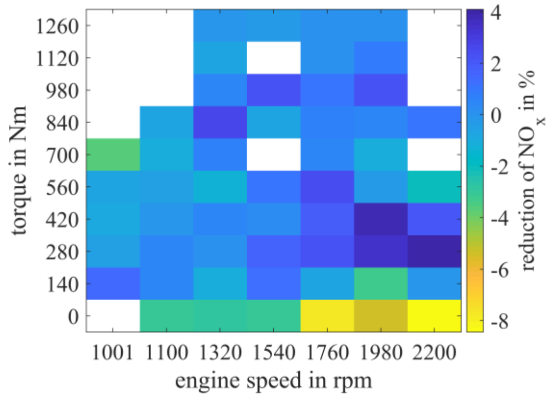

Figure 3.9: NO_x reduction for ICE 2

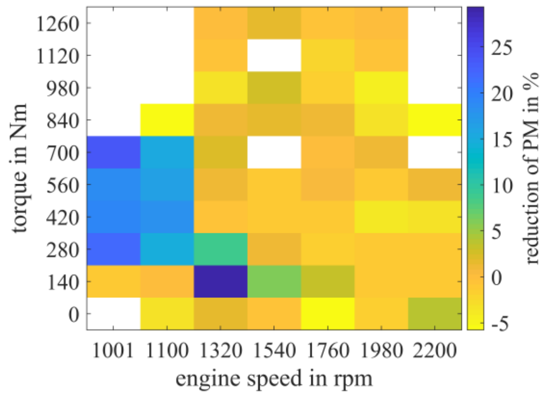

Figure 3.10: PM reduction for ICE 2

4 Operating Strategies

The goal of each developed OS is to control the APPSP, considering the current accumulator level and the current s-t combination, so that the ICE is only loaded to the extent that minimal transient NO_x and PM emissions are produced. Thus, the engine should operate in a phlegmatized manner during transient operating conditions.

Chapter 2 already described the concept of the hybrid module with control via constant gradients. The OS must now determine the optimal gradient for each s-t combination. [26] and [27] show that simulated stationary emissions in transient operating points can be converted into transient emissions by multiplying with the coefficient "c-factor" for defined map areas.
The approach of the OS used here is roughly the inverse of this procedure. Although the coefficients are also called c-factors, but here they are the gradients from Chapter 2 that need to be defined and determined for each of the s-t combinations from Chapter 3.3. For this purpose, LS across the entire engine map of both ICEs are simulated with varying c-factors, and then the optimal c-factors are determined using a cost function. The goal is an optimum of low NO_x and PM emissions and the shortest possible t_{AP}.
To provide a reference for the cost function, a ramp-up time of $t_{AP} = 5$ s is defined as optimal concerning emissions [5] [13]. LS are simulated as in Chapter 3.3, resulting in emission maps similar to those in Figure 3.7 to Figure 3.10. These emissions, optimally phlegmatized by definition, can be compared with the emissions of the various OS developed in order to determine the best OS.

The determination of the OS and the verification of their suitability for controlling the hybrid module is the subject of current research.

5 Summary and Outlook

This paper presents a concept for a hybrid module designed to reduce transient emissions from mobile working machines through phlegmatization. In addition to the basic principle, the simulation model of the hybrid module is also presented. This includes a detailed engine model of two internal combustion engines. Both engine models are parameterized and verified. The paper also identifies areas where NO_x and PM emissions can be reduced.
Finally, the planned approach for the operating strategies is presented. The result should be a map with maximum gradients (c-factors) for each s-t combination, based on which the hybrid module phlegmatizes the internal combustion engine.
The finalized operating strategies and the complete evaluation of the simulation results to determine the best strategy and its emission reduction potential are planned to be published in a PhD work by the end of 2025.

The completed hybrid module, with an OS tailored to the engine and the mobile working machine, aims to provide another option for sustainably reducing transient raw emissions from mobile working machines in the future. Especially in energy-intensive industrial sectors outside urban areas, where internal combustion engines will remain the state of the art for the foreseeable future, this technology can help counteract the ongoing air pollution.
It is conceivable to not only install the hybrid module in new machines but also retrofit older existing machines with it. Due to its simple design and compact dimensions, it is often possible to find space for installation despite the spatial constraints of mobile working machines.

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