Injection Optimization of Spark Ignition (SI) Engines

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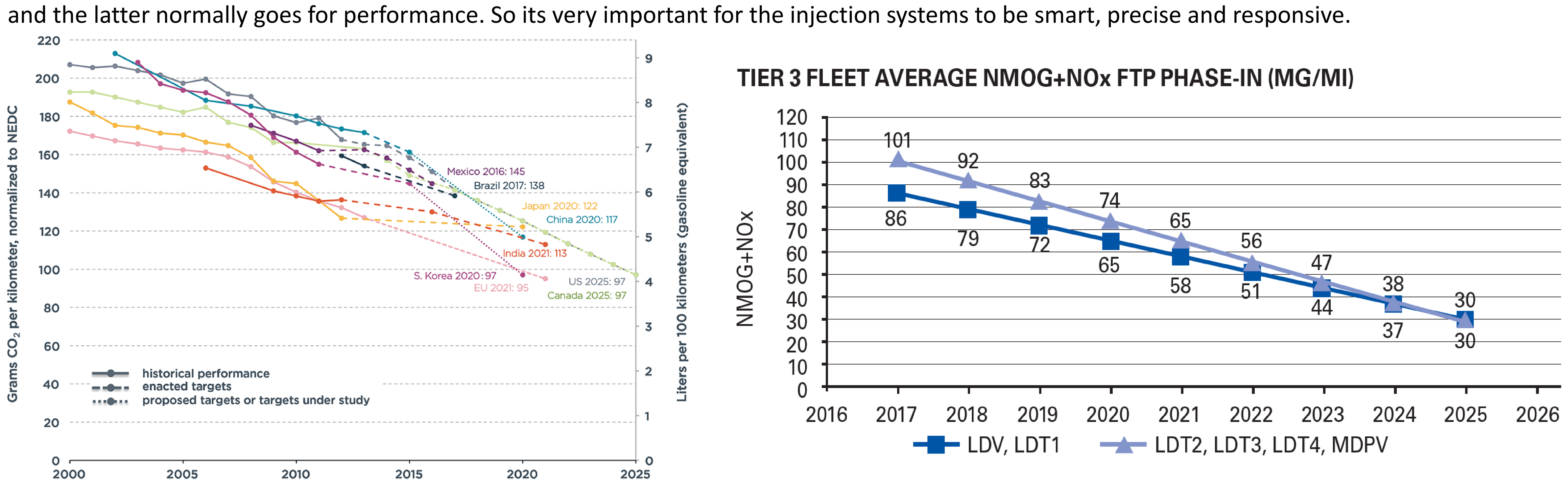
SIGNIFICANCE OF THE INJECTION SYSTEM

The injection system in SI engines is responsible for meeting the requirements coming from customers and environmental legislations. The main objectives of the Engine Management System (EMS) that are linked to the injection system include: **Emission, Fuel Consumption, Performance, Drivability and Component protection**. Optimized injection is a matter of hardware and software, the former is the provided accuracy and responsiveness of the sensors and the actuators of the injection system and the latter is the smartness of the control strategy.
Internal Combustion Engines are nonlinear complex plants with a variety of disturbances and uncertainties, which make their control task to be difficult. Legislations and customer requirements are getting more and more demanding, where the former aims the emission and fuel consumption and the latter normally goes for performance. So its very important for the injection systems to be smart, precise and responsive.

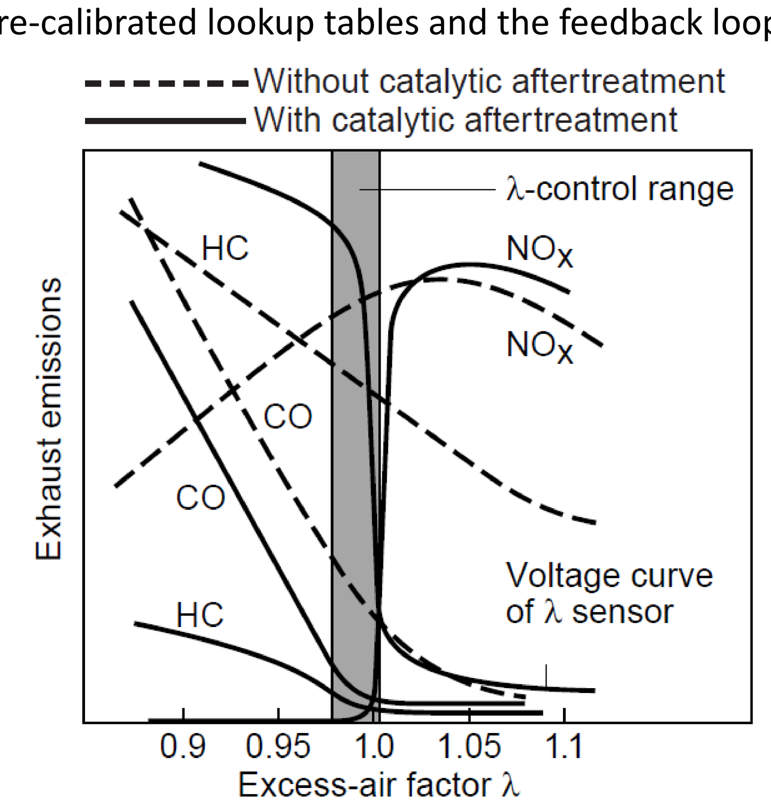


Year	LDV, LDT1	LDT2, LDT3, LDT4, MDPV
2017	86	101
2018	79	92
2019	72	83
2020	65	74
2021	58	65
2022	51	56
2023	44	47
2024	37	38
2025	30	30

Trends of worldwide emission standards for passenger cars

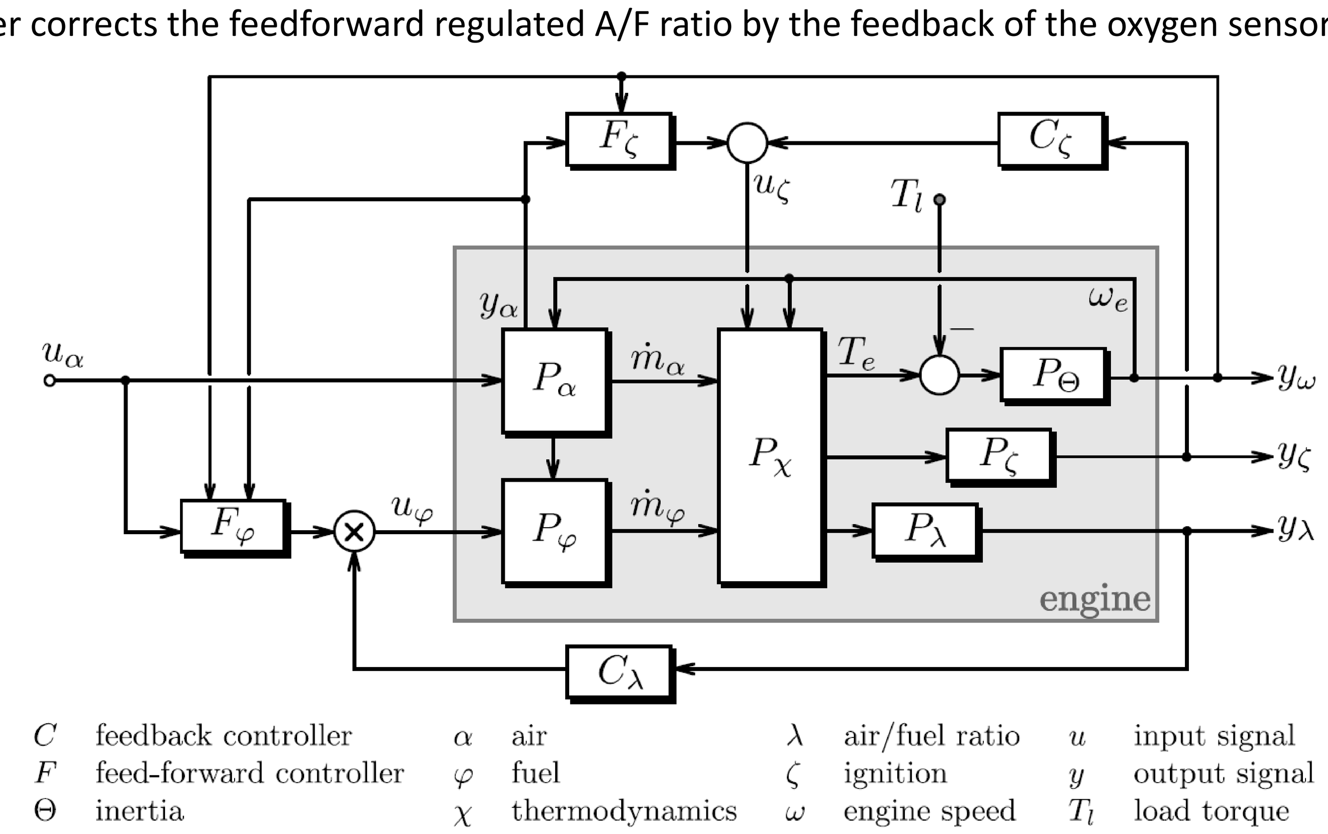
HOW THE INJECTION SYSTEM WORKS

Three Way Catalysts (TWC) are the most popular devices for controlling the emissions of the SI engines. Their conversion efficiency is very much dependent on their temperature and the **Air to Fuel ratio** of the mixture in the combustion chamber. Air to fuel ratio must be kept in the **stoichiometric value ($A/F \approx 14.7$) for gasoline fuel** to have a good conversion efficiency of the TWC and this is the main task of the injection system. There is a big time delay between the point of actuation (fuel injection) and the point of measurement (Oxygen sensor) in the exhaust line. This causes the injection system to require both feedforward and feedback control loops. The feedforward loop is fast and compensates the effects of the delays via pre-calibrated lookup tables and the feedback loop further corrects the feedforward regulated A/F ratio by the feedback of the oxygen sensor.



Effect of A/F ratio on engine emission

Ref: Robert BOSCH GmbH



Block diagram of SI engine with injection FF and FB control loops

Ref: L. Guzzella, C. H. Onder -Introduction to Modeling and Control of Internal Combustion Engine Systems

WHY OPTIMIZATION?

The objectives associated with the injection system are contradictory i.e. the better performance degrades emission and fuel consumption and vise versa. So there should be a **trade-off** between the required objectives, which means that a **multi-objective optimization** is required. Optimization techniques like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are useful for such problems provided that the candidate solutions and the objective functions are well defined. It means that the system should be well understood to determine the affecting parameters on the desired attributes that are supposed to be optimised. This approach works efficiently at the points where the feedback signal is not available (**during cold start and transient modes**) and can remedy the poor emission control functionality of current injection systems during such critical operating modes.

METHODOLOGY

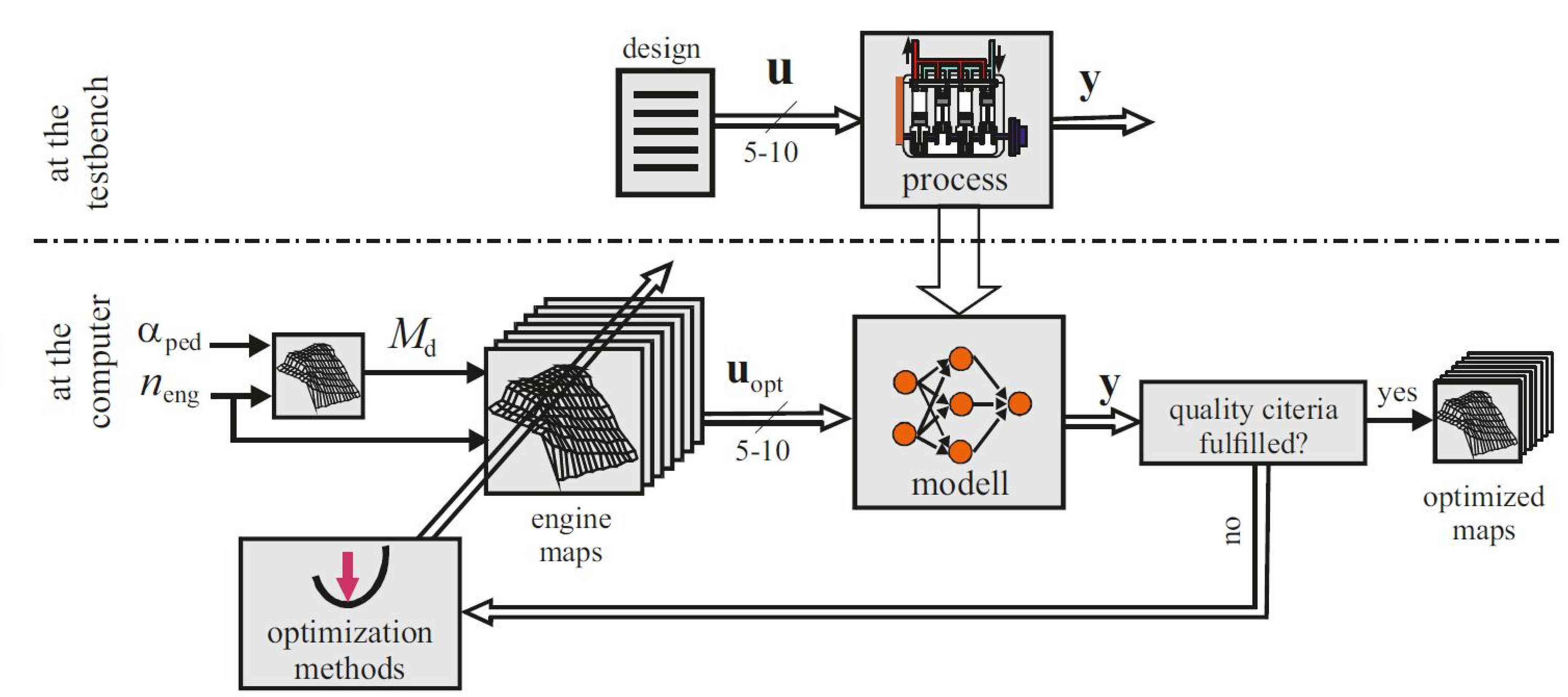
There are different approaches of injection map optimization varying from **conventional trial and error** to the novel **model based** approaches. The former is done by the powertrain engineers on the engine dyno and is very time consuming. The latter however is much faster but may suffer from the inappropriateness of the developed models. The main tasks of an injection optimization project are:

Engine modeling: The engine model in any optimization problem must be able to reflect the effects of the contributing parameters selected as the candidate solutions. Mean Value Engine Model (MVEM), which has been proven to be a proper choice for control problems may work for optimization problems dealing with the overall objectives of the engines specially those linked to performance. Discrete Event Models (DEM) are used for attributes dealing with subsystems of the engine that are not continuous i.e. ignition, injection and gas exchange process of individual cylinders. Some phenomena may require more detailed models like 3D CFD models with the ability of modeling emission formation, thermodynamics events and fluid dynamic properties. Black box models are proper choice of systems with extreme levels of complexity.

Injection Optimization: Any modification of the injection system resulting in more accurate air to fuel ratio control while keeping other objectives within their proper range can be a matter of optimization. This can be done through air mass estimation improvement especially during transient modes, accurate fueling, precise feedforward control and robust and accurate feedback control. Assuming the estimated air mass flow to be accurate during steady state condition, the candidate parameters for the optimization can be the number of the injection pulses in each cycle and timings of the injection pulses with their own upper and lower limits.

Verification Tests: To verify the effects of optimization on the plant outputs, engine dyno tests are conducted to check the engine performance and emission attributes. The new **Gen3 Ford Coyote engine** is used in this research at CMHT engine dyno lab.

Ford Coyote engine



Model based optimization approach

Ref: Rolf Isermann, Engine Modeling and Control

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