The self-learning powertrain: towards smart and green transport

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towards smart and green transport
Inaugural lecture prof.dr.ir. Frank Willems

The self-learning powertrain

towards smart and green transport

Presented on March 24, 2017
at Eindhoven University of Technology
1. Introduction

In today’s modern world, we want to live in luxury. Part of this means easy access to products, such as food, clothing and electronics, from locations all over the world. Consequently, the transport of goods has been growing significantly over the years. This goes hand in hand with an increase of pollutant emissions, greenhouse gas emissions, and the use of increasingly scarcer fossil fuels. Additionally, vehicle-to-vehicle and vehicle-to-infrastructure communication will become available in the near future. This will enable truck platooning and automated driving. To exploit this growing connectivity, mitigate the effects of emissions, and reduce fossil fuel use, there is a need for smart and green transport.

The majority of goods are transported by trucks and ships, which are propelled by heavy-duty powertrains. These powertrains are mainly powered by diesel engines. In the coming decades, internal combustion engines will remain the primary power source, not only in long haul trucks, but also in marine and agricultural applications. When talking about my research field of powertrain control, many people ask me if there is still work to be done, more than 120 years after Rudolf Diesel’s invention of the compression ignited, internal combustion engine. I strongly believe that we are just at the start of a new, exciting chapter for powertrains. Especially when it comes to control.

Powertrain control systems are the brain of the combined internal combustion engine and drivetrain. These electronic control systems give the powertrain its specific feel and characteristics in terms of torque response, fuel efficiency and emissions. The importance of control systems will grow in the future. They play an essential role in minimizing fuel consumption, enabling the use of sustainable fuels, and making vehicle performance insensitive for driving conditions. However, the consequence is an increase in system complexity. With current methods, powertrain control development is moving to a turning point, with unacceptable development time and costs. Self-learning, model-based control systems that automatically determine optimal control settings on the road will become inevitable.
In this inaugural lecture, I will share my vision on next-generation powertrain control systems and my ambitions for the new chair. Future heavy-duty powertrains will include a combination of internal combustion engines, exhaust gas aftertreatment systems and energy recovery systems. Control of these systems requires a profound understanding of the energy conversion and emission formation process. In my research, I follow a system-level approach based on physics-based modeling. This allows on-road energy and emission trading based on sensor and preview information. The multi-disciplinary nature of the research field makes partnerships natural, effective and essential. Moreover, I promote close collaboration with research institutes and industry, especially in the joint use of dedicated, state-of-the-art simulation and experimental test facilities.
Before I start discussing the trends and challenges in powertrain control, first I want to give a sketch of the system to be controlled, the future powertrain, and set the scene in which it has to operate. A powertrain is the combination of engine, transmission, drive shafts, differential and wheels, which generates power and delivers it to the road [1].

Diesel engines are the workhorse of heavy-duty powertrains. They are used in on- and off-road applications, ranging from trucks to ships, agricultural machines and electricity production. Figure 1 shows the layout of a modern European or US truck engine. To meet current emission standards, various engine technologies, such as common rail Fuel Injection Equipment (FIE), turbocharging and cooled Exhaust Gas Recirculation (EGR), have been introduced to reduce engine out nitrogen oxides and particulate matter emissions. Also, exhaust gas aftertreatment systems are installed to further reduce the pollutant emissions to near-zero impact tailpipe levels.

Figure 1
Illustration of a modern European or US truck engine
Typically, these aftertreatment systems consist of a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), urea-based Selective Catalytic Reduction (SCR) deNO\textsubscript{x} system and an Ammonia Oxidation (AMOX) catalyst. Similar layouts can be found in off-road applications.

My research concentrates on the internal combustion engine with aftertreatment system, since it is the main power and emission source, for on-road applications.

### 2.1. Main drivers for future powertrain development

Minimizing air pollution, minimizing global warming and securing the availability of energy sources are three of the major societal challenges for the future. Besides noise reduction and economic drivers, including total cost of ownership, these will be the main factors in future powertrain development. Current legislation for heavy-duty engines is dominated by measures that minimize air pollution. This has been changing. Attention is shifting more and more towards minimizing global warming, as illustrated in Figure 2. In addition to current pollutant emission standards, greenhouse gas (GHG) emissions will be regulated. The scarcity of fossil fuels in the long term also promotes a transition towards alternative and, ultimately, sustainable energy carriers.

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**Figure 2**

Main drivers for powertrain development
Air pollution

Combustion of fossil fuels results in pollutant emissions. More precisely, nitrogen oxides (NOx), Particulate Matter (PM), carbon monoxide (CO) and unburned hydrocarbons (HC) emissions are assumed to be harmful. Diesel engines are characterized by an unmatched combination of power density, efficiency and durability. On the other hand, inherent to the combustion concept, diesel engines emit relatively large amounts of NOx and PM emissions. To mitigate the effect of these pollutants on human health and the environment, governments introduced legal emission standards to regulate emissions from on- and off-road engines. Over the last two decades, significant progress has been made: current Euro-VI truck engines emit 95% and 97% less NOx and PM emissions, respectively, over a specified test cycle, compared to the Euro-I standards in 1992.

With the recent Euro-VI standards, additional requirements on real-world emission limits and more extensive monitoring of on-road performance are implemented. These measures have to guarantee that reduction levels are found not only during dedicated, type approval tests in the laboratory, but also on the road. In-service vehicle testing confirms that these new standards are very effective [2]. Despite new engines approaching near-zero impact emission levels, more strict emission standards are still foreseen in the future. In Europe, increased emphasis on cold start and city driving conditions is anticipated, whereas an additional 90% NOx reduction is under discussion in the US.

Global warming

Although pollutant emission standards have proven to be challenging, truck manufacturers have to simultaneously meet newly mandated limits on CO2 emissions. For internal combustion engines running on carbon fuels, fuel consumption and CO2 emissions are closely related. For passenger cars, mandatory CO2 standards have already been in place since 2009. The US is the front runner in implementing CO2-related legislation for trucks. Compared to 2010 levels, a gradual reduction of fuel consumption at vehicle level to 40% has to be realized over the period 2014-2027. In Europe, the proposed CO2 reduction targets and testing methodologies are still under debate. Up till now, the focus has been on CO2 emissions, but the future inclusion of methane (CH4), which is now treated as a pollutant emission, and nitrous oxide (N2O) is expected.
Figure 3 clearly illustrates the challenge for manufacturers to control pollutant emissions and fuel consumption simultaneously. This figure shows the historic trend in real-world fuel consumption for 38-40 ton trucks over the period 1966-2014. After a gradual decrease during the beginning of the test period, fuel consumption has stabilized at around 35 liters per 100 km. This stabilization is remarkable, especially, when you keep in mind that approximately 30% of the Total Cost of Ownership (TCO) is related to fuel costs. However, this illustrates that, since the introduction of increasingly strict emission standards in 1992, truck manufacturers have to make substantial efforts to meet these standards, while avoiding fuel consumption increase.

In legislation, the focus is mainly on vehicle or tank-to-wheel CO$_2$ emission. For the transport of goods, the main performance indicator is CO$_2$ emission in grams per ton payload and kilometers travelled. Besides logistics, road infrastructure and vehicle measures, the maximization of powertrain efficiency and the minimization of the use of low-carbon fuels are the main routes for decarbonization at powertrain level.
TNO studies have shown that CO₂ can be reduced by up to 40% in 2025 by combining the measures that are currently known for long haul trucks. These are impressive figures, but will this be sufficient to abate global warming? Figure 4 shows the predicted GHG emissions in the transport sector. Compared to current levels, GHG emissions are expected to have grown by more than 50% in 2050 due to an increasing transport demand. To limit global warming to less than 2°C, the European Commission has defined a target of 60% reduction in 2050 relative to 1990 for the transport sector. Despite the available reduction potential, there will be a substantial gap between the targeted and actual GHG emissions in 2050, as shown in Figure 4.

![Image](image.jpg)

**Figure 4**

Predicted GHG emission development and impact of GHG reduction measures in the transport sector (adapted from [4])

**Energy security**

Sustainable energy carriers, next to measures that limit the growth in transport, have to play an important role in bridging this gap. Examples are electricity and hydrogen from renewable sources and gaseous and liquid fuels produced from biomass. This is also desirable from an energy security point of view, since fossil fuels are expected to be scarce in the long term. Due to their availability and superior energy density, liquid fuels will remain the main energy carrier for heavy-duty applications. For passenger cars, buses and city distribution, the role of electric powertrains and fuel cells will become important.

A transition via alternative, low-carbon fuels towards sustainable fuels is foreseen in the long term. In the literature, various scenarios can be found [4-6], but the following general trends are observed for heavy-duty powertrain applications. For the period up till 2030, the usual suspects will fuel the heavy-duty powertrain:
petroleum-based, liquid fuels (diesel, gasoline) and alternative fuels (natural gas, biofuels) can be made available in sufficient amounts. This is supported by EU directives that set targets for biofuel use and describe the realization of LNG infrastructure along the main European transport corridors. Advanced biofuels and hydrogen are expected to have a significant share in 2050.

2.2. The future heavy-duty powertrain

Having set the scene, I will now discuss in more detail the implications on powertrain design, in terms of required engine and aftertreatment technologies. Internal combustion engines will remain the prime power source for heavy-duty powertrain applications during the coming decades. These powertrains will combine high efficiency with the use of low-carbon and, eventually, sustainable fuels.

Towards 50% brake thermal efficiency and beyond

For internal combustion engines, the brake thermal efficiency (BTE) is the most relevant parameter; it describes the mechanical energy that is available at the engine crankshaft relative to the chemical energy of the fuel. The general industry target is to realize (best point) brake thermal efficiencies of more than 50%. This requires significant development steps, since current Euro-VI engines typically have best point BTE in the range of 46-48%.

Maximizing diesel engine efficiency concentrates on further optimizing the combustion process and on avoiding losses by energy recovery systems and electrification. For efficiency optimization, advanced air management and fuel injection systems are introduced. Together with highly efficient SCR systems, these give extreme flexibility in realizing the desired conditions to fully exploit the trade-off between fuel consumption and engine out NO\textsubscript{x} emissions. In modern diesel engines, approximately 55% of the available chemical energy in the fuel is converted to thermal energy. This waste heat ends up in the cooling and exhaust system. It can be recovered by applying (electrically-assisted) turbo-compounding or systems based on the Organic Rankine Cycle (ORC). With up to 4% points increase of BTE, ORC-based Waste Heat Recovery (WHR) systems are crucial to meet the 50% target. Also, electrification will play a role for long-haul truck applications. First, this will support easy switching-on-demand of auxiliaries, such as air conditioning and steering pumps, to avoid energy losses. Second, it will
enhance the potential of electrically-assisted turbochargers and WHR systems, by using the battery as an energy buffer to separate energy generation and supply.

Alternatively, new highly efficient combustion concepts, such as Partially Premixed Combustion (PPC) and Reactivity Controlled Compression Ignition (RCCI) are under study. Laboratory results show promising results: the combination of high thermal efficiencies with ultra-low engine out NO\textsubscript{x} and PM emissions.

**Transition towards natural gas and biofuels**

In Europe, diesel fuel supplied at the fuel station contains up to 7% volume content of FAME, i.e. the most common type of biodiesel. Diesel engines are becoming more and more robust for wider ranges of biodiesel blends, which supports well-to-wheel CO\textsubscript{2} reduction. Biomass-based fuels have the potential to eventually replace 15-30% of the fossil fuels used in transport [4,5].

If we look purely at caloric values, CO\textsubscript{2} can be reduced by 20%, when natural gas is compared with diesel. As this requires equal thermal efficiencies, there is a similar drive for high BTE in natural gas engines. Direct injection (DI) of natural gas will become the standard, since it has been proven to be an effective means to improve efficiency and reduce methane slip from the engine. Also dual fuel concepts, in which natural gas is ignited by small diesel quantities, are implemented in on-road and marine applications. TNO has demonstrated that highly efficient Diesel-Natural Gas engines can be realized using an advanced RCCI combustion concept that relies on in-cylinder fuel blending. This RCCI concept is not limited to the combination of diesel and natural gas. It allows a mix of a wide range of high-octane (gasoline-like) and low-octane (diesel-like) fuels. This will create fuel-flexible engines and support the use of various (locally available) alternative and sustainable fuels.

Having sketched the future powertrain configuration and its playing field, the system to be controlled and its high-level control objectives are identified. Now, I will move to the core of my research: powertrain control.
3. Towards Self-Learning Powertrains

Starting from a historic perspective, I will first highlight the growing importance of powertrain control systems. Future targets for real-world pollutant emissions and CO\textsubscript{2} reduction set challenging requirements for these control systems. I will then look at current control development approaches for which we will be reaching the limits of development effort and performance robustness. As a result, I will discuss an integrated, model-based approach that combines energy and emission management at powertrain level. This seems to be the logical next step in powertrain control development. By incorporating more and more information of the current and future powertrain state, the role of auto-calibration will increase. This will ultimately lead to the self-learning powertrain.

3.1. Growing importance of powertrain control

Centrifugal governors were the first concepts of feedback control implemented in powertrains. Since their introduction, huge developments have taken place in the field of powertrain control. Over eight decades, diesel engine control was done mechanically and boiled down to the regulation of the timing and quantity of a single fuel injection per combustion cycle.

After this quiet period, control developments and successes happened in quicker succession. Starting in the late 1970s, transient smoke emissions were reduced due to the application of wastegate turbochargers. These systems relied on mechanical feedback of the intake manifold pressure. Around 1990, we entered a new era with the advent of electronic engine control. This was a key enabler for diesel emission control. First, microprocessors control fuel injection parameters (injection timing, injection pressure) as well as air management (EGR valve, Variable Turbine Geometry position) to reduce engine out pollutant emissions. Later, aftertreatment control emerged with diesel injection and urea dosing control for DPF regeneration and NO\textsubscript{x} conversion in SCR systems, respectively. In 2008, the first vehicles with cylinder pressure-based combustion control were introduced. The availability of mass production-type, in-cylinder pressure sensors opened the route to direct control of the combustion process. According to [7],
inaccuracies in fuel injection and the impact of fuel quality variations on emission variations can be significantly reduced by following this control approach. They claim that this technology is an important enabler to meet the strict US standards for diesel-powered passenger cars.

These examples demonstrate the growing importance of control systems. These control systems are the brain of the powertrain and largely determine its performance, environmental and economical characteristics. Its role is expected to increase even further in the future. Control systems are seen as an integral and essential part in future system integration. Moreover, these systems will play a crucial role in getting highly efficient combustion concepts and fuel-flexible engines on the road. More precisely, the introduction of advanced combustion concepts, such as PPC and RCCI, need closed-loop combustion control for stable and safe operation.

3.2. Challenges for powertrain control systems

Figure 5 shows a diagram of the control architecture for future heavy-duty powertrains. Based on sensor information, the powertrain control system determines the optimal settings for all actuators. These settings have to realize the driver’s requested torque with minimal fuel consumption within emission limits, and in all driving conditions. In addition, the safe and proper functioning of various subsystems, including engine and aftertreatment, is continuously monitored. If a malfunction is detected, the driver is warned by a light on the dashboard to avoid damage or failure.

![Control architecture for future heavy-duty powertrains](image)
Need for robust performance

Over the years, various subsystems with their low-level control systems were gradually added. Most low-level controllers consist of map-based feedforward controllers that optimize powertrain performance mainly by dedicated calibration of the maps. Calibration engineers typically start from trade-offs between fuel consumption and pollutant (NO\textsubscript{x} and PM) emissions. These trade-offs are measured on the engine test-bed under ambient reference and stationary operating conditions. In this way, the desired control settings for each engine speed-brake torque combination are determined and implemented in the maps.

Contrary to nominal laboratory conditions, real-world driving emissions are strongly affected by:

- **System uncertainty**, related to production tolerances, component ageing and wear;
- **External disturbances**, e.g. varying fuel quality, ambient conditions, and driving conditions (including pay load, duty cycle, driver behavior and traffic flow).

This results in a wide variation of tailpipe emissions. To mitigate these effects, the controller has to show excellent robust performance. For dynamic driving conditions, transient compensations are often introduced, whereas non-optimal margins in the calibration of the maps have to account for system uncertainty. Also, the map-based feedforward controllers are extended with feedback controllers. This makes, for instance, air management more robust to altitude effects.

A major disadvantage of the control design methodology outlined above is its non-systematic and rigid structure. Final performance largely depends on the calibration expertise of the control engineer. Moreover, not all relevant conditions are foreseen and tested. Just recently, we observed the first steps towards supervisory control for emission management: mode switching controllers are in production. When the actual SCR NO\textsubscript{x} reduction capability allows higher engine out NO\textsubscript{x} emissions, these controllers switch to a corresponding engine map with more fuel-efficient settings. Analogously, switching between different combustion modes is introduced. In all cases, the combined engine-aftertreatment system still has to meet the real-world NO\textsubscript{x} emission targets. However, this requires extensive testing, since each mode corresponds to a large set of engine maps.

On the other hand, energy management for hybrid-electric drivetrains evolved into a mature field. Supervisory control strategies coordinate the torque split between engine and electric motor/generator to minimize fuel consumption. In [8], we
showed that focus only on energy management can lead to unacceptably high tailpipe NO\textsubscript{x} emissions.

**Growing system complexity**
With the further increase of actuators and sensors, the complexity of the powertrain control system will grow exponentially. On the actuation side, this is mainly attributed to the increased flexibility in fueling (multiple injection and rate shaping capabilities) and in air path (Variable Valve Actuation), the introduction of WHR systems, and the introduction of various combustion modes [9]. In a similar way, the number of sensors will grow, since the performance of new systems has to be monitored and information for control is required.

This increase in system complexity implies that the number of independent control parameters will grow from six, in 2010, to 25 by around 2030. According to [9], for map-based control, the number of labels to be specified increase by a factor ten for each added control parameter. This will lead to unacceptable development time and costs. He estimates that full factorial testing will explode to 95000 years of engine testing in 2030. Also, manually performance optimization for these complex powertrains is no longer feasible, especially during transients. Consequently, by continuing this map-based approach, we will reach a turning point, where control system development is no longer straightforward.

### 3.3. Integrated Powertrain Control

To overcome the limitations associated with map-based control, a model-based approach, as illustrated in Figure 6, is inevitable. This enables a systematic, time-efficient development process. Models are applied in the control development process in different ways. First, by combining subsystem models, a virtual powertrain and simulation environment is built. This allows for system optimization by concept, configuration and component-sizing studies. Second, these models are used for control design. At the moment the control strategy is selected, third, model-based calibration of control strategies is feasible. This includes off-line tuning of the control parameters and performance validation in simulation for various cases. Finally, real-time models can be embedded in the control system. This supports the development of smart sensors, which estimate variables that cannot be measured directly, and of model-based predictive control strategies.
A system-level approach is essential to maximize overall powertrain energy efficiency and simultaneously keep emissions within legal limits. Until recently, emission and energy management were treated separately and powertrain performance was mainly based on off-line optimization in laboratory conditions, as illustrated in Figure 7. This results in sub-optimal solutions, which also lack robustness to varying driving conditions. To tackle these issues, we presented the Integrated Powertrain Control (IPC) concept, which integrates energy and emission management. By following a model-based control approach, we developed a cost-based optimization strategy, which minimizes fuel consumption or total operating costs on-line and explicitly deals with emission constraints. This supervisory control strategy fully exploits the synergy between subsystems. Based on real-time model information about the actual powertrain state, the optimal actuator settings and controller set points are determined on-line. A detailed discussion of this IPC approach can be found in [10,11].

Initial laboratory results show that Integrated Powertrain Control is a promising concept; 2.1% fuel consumption reduction has been demonstrated for a Euro-VI engine [11]. However, for on-road application we have to bring this concept to the next level by dealing with real-world emission limits and exploiting the growing connectivity. The ultimate goal is the realization of a self-learning powertrain, see Figure 7.

**The self-learning powertrain is the way to go**

In the context of this lecture, the term self-learning refers to the ability of the powertrain control system to adapt control settings, based on smart sensor information, and realize the desired powertrain behavior. This is also referred to as...
The self-learning powertrain: towards smart and green transport

Adaptive control, optimal control and auto-calibration. As illustrated in Figure 7, we want to avoid off-line optimization and aim to rely mainly on on-road optimization. The envisioned control architecture for the self-learning powertrain is shown in Figure 8.

Currently, on-road energy and emission trading is done using smart sensor information of the momentary powertrain status. With the large-scale introduction of vehicle-to-infrastructure communication and truck platooning, increasing amounts of preview information will become available. This includes information on external disturbances, such as road load and traffic ahead. With autonomous driving, we can take the driver out-of-the-loop, which helps to reduce the uncertainty in the predicted propulsion power, and maximizes the flexibility to vary vehicle speed and acceleration in a wide range. These developments allow further performance optimization, further shift towards on-road optimization, and will feed the need for predictive control.

In the optimization, the system level will gradually move from powertrain towards vehicle, fleet and traffic system. At powertrain level, this multi-level system optimization will generate a need for varying, on-road tailpipe emission set points for individual vehicles. First, manufacturers increasingly collect real-world fleet data to monitor vehicle performance and operation. Smart use of this data can ultimately lead to further optimization of the vehicle performance. For a specific route or mission, they can perform off-line optimization using fleet data from various vehicles. Based on this off-line optimization, the control calibration can be fine-tuned to achieve the lowest fuel consumption. Second, the introduction of truck platooning is anticipated, starting around 2020. Depending on the vehicle

![Figure 7](image-url) Evolution of powertrain control towards the self-learning powertrain

location in the platoon, this can lead to up to 8% fuel consumption reduction. With a platoon approach, further reduction seems feasible by handling energy efficiency and emission constraints at platoon level. This approach is supported by varying emission targets on vehicle level. This will also create the need for new business models in which benefits are shared equally by all platoon participants. Third, regional emission zones will require varying tailpipe emission limits; e.g. supportive measure to current vehicle speed limits to reduce smog. Similarly, targets on fleet or traffic level can be specified.

Up till now, real-world tailpipe emissions are monitored only in dedicated tests. A Sensor-based Emission Measurement System (SEMS) is found to be an effective emission screening tool, which provides real-time information on the in-use emission performance [2]. In this way, robust performance and reliability of the controlled powertrain system can be proven. Consequently, this smart emission sensor is a crucial enabler for the implementation of control strategies that adapt tailpipe set points on-line.
4. The Integrated Powertrain Control chair

In support of the self-learning powertrain concept, my research concentrates on emission-constrained energy management for heavy-duty powertrains. The combination of energy and emission management gives this chair a distinctive position in international engine and control research. Furthermore, a dedicated chair on powertrain control is new. This also illustrates the growing importance of this field as well as the need for a multidisciplinary approach. Control research has become integral part of advanced combustion and powertrain research. Similar trends are observed in the field of nuclear fusion and mechatronics for the adjoining chairs of Prof. de Baar and Prof. Vermeulen, respectively.

As argued, the importance and need of control for heavy-duty powertrains will continue to grow. Many challenges related to CO₂ reduction and use of fuels have been pinpointed in this field of research, which gives it a solid base for long-term, scientific research. In order to give the chair an international position, it is important to focus and to create critical mass on a few, innovative topics. That brings me to one of the most important parts of my lecture: which scientific challenges have I identified for my research and what are the essential areas for collaboration? In the following part, I will give a brief overview of the research and education ambitions for the chair. It is noted that low-level controllers, such as combustion, aftertreatment and WHR controllers are important building blocks in integrated energy and emission management, and are also topics of research. However, in this lecture I mainly concentrate on supervisory control strategies.

4.1. Powertrain control research

In my research, I follow a model-based control approach. Based on physics-based models, new control methodologies and concepts are being developed. In contrast to data-driven or black box modeling approaches, these models give a profound insight in the systems and processes studied, give information on internal system states and do not require extensive data sets for each combination of powertrain configuration and operating conditions to be studied.
Within the scope of the chair, I will concentrate on the following three scientific challenges.

**Control-oriented modeling of the combustion process**
First, I aim to understand the energy conversion and emission formation processes from a control point of view. In other words, I want to grasp the powertrain behavior in terms of dominant dynamics, system characteristics and the relationship between actuator settings and disturbances on the one hand, and controlled outputs, on the other hand. This results in control-oriented models, which can be embedded in model-based controllers and can run real-time on standard control hardware. In recent studies, we have put much effort into the modeling and control of the air path, SCR $\text{deNO}_x$ system and WHR system. However, a deep understanding of the combustion process, which is an essential cornerstone in energy and emission management, is still lacking. In particular, we want to model the effect of multiple pulse fueling strategies, of intake and exhaust timing strategies of VVA systems, and of ambient and fuel conditions on energy efficiency and emission formation. This applies to both conventional diesel and advanced combustion concepts.

For all these combustion concepts, tracking of optimal in-cylinder conditions per combustion cycle is the ultimate research objective for combustion control. This is also called in-cycle combustion control. This requires the relationships between actuators, in-cylinder conditions and controlled outputs, such as emissions, to be known. At the moment, control-oriented models that accurately describe these concepts are not available. Moreover, in-cycle control sets very demanding requirements on the combustion control system, since control actions have to take place within 0.1-0.5 ms. Today, next-cycle control of (multiple) combustion parameters that characterize the combustion process is state-of-the-art in combustion control research.

**On-road energy and emission trading**
The second challenge is to maximize the powertrain’s overall energy efficiency, while explicitly dealing with tailpipe emission limits set by legislation. More precisely, how to determine on-line the optimal control settings based on available information on actual and future powertrain status? In earlier research, this control problem was formulated as a cost-based optimization problem [8,10,11]. However, determination of optimal solutions is still an open problem for the cases in which emissions and exhaust gas aftertreatment are included. So far, real-time implementable approximations experimentally tested for two control inputs have given promising results for a Euro-VI engine configuration: 2.1% fuel consumption
The self-learning powertrain: towards smart and green transport

reduction compared to a production strategy [11]. Extension to larger number of control inputs is not straightforward. Current proposed strategies solve the optimization problem momentarily or for a few second control horizon and only consider emission limits for the type approval cycle. New methodologies are required that can guarantee optimal performance for varying tailpipe emission limits. These methodologies should lead to real-time implementable solutions, which explicitly take care of real-world emission limits for a work-based window or preview window.

Robust performance
Thirdly, we want to realize optimal performance in real-world varying operating conditions. This means that we have to deal with disturbances and system uncertainties. Although numerical analyses have proven that the implemented approximations are close to the optimum for specific test cycles, this cannot be guaranteed for all operating conditions. Recent studies have shown that operational costs and real-world emission variations can be further reduced if the control settings are adapted [12]. An interesting direction is the development of new, self-learning feedforward control strategies that use mission or preview information.

4.2. Applied and multidisciplinary research

Powertrain control research is at the intersection of various research domains, as illustrated in Figure 9. Therefore, we team up with experts from different research areas, including combustion, catalyst and energy technology. This multidisciplinary approach is required to create a profound understanding of the processes to be controlled and of their interactions. This is input for our physics-based, control-oriented models.
Experimental facilities

Modeling of the combustion process is complex. This especially holds for emission formation. Moreover, it is difficult to create representative models of disturbances and system uncertainties. Typically, data and validated models are lacking to study various scenarios. Therefore, numerical and experimental work is combined. Various experimental set-ups are available in the combustion technology laboratory at TU/e. This allows us to study fuel sprays and emission formation in detail and validate our models, see Figure 10. A wide variety of fuels can be tested. For combustion control research, a single cylinder test set-up is equipped with dedicated rapid control prototyping hardware. Starting from hardware-in-the-loop testing, engine demonstration is essential in the end since practical challenges related to real-time implementation of smart sensors and controllers have to be covered. This is particularly true for in-cycle combustion control concepts.

For Integrated Powertrain Control concepts, current proof of concept relies mainly on simulation studies with validated powertrain models; initial engine tests are done in [11]. In order to demonstrate and validate their actual performance and to test for a wide range of practical scenarios, it is important to implement these control strategies in multi-cylinder experimental set-ups, which can also vary ambient conditions.

Running engine test facilities requires close collaboration with research institutes and industry. This not only gives access to state-of-the-art engine hardware,
experts and practical support, but also helps to focus and define relevant, practical cases. The first results of this collaboration are already visible. PhD studies have resulted in, e.g., the application of control-oriented combustion and WHR models in TNO simulation tools and application of a systematic design method for air path control within DAF. For advanced combustion control research, a multi-year research program with a focus on PPC and RCCI control is in place. This is supported by international partners from the automotive industry. We want to further expand this research program and upgrade TU/e test facilities. Facility sharing will also play an important role. First, this creates opportunities for the partners to perform dedicated tests at TU/e. Second, we have access to joint multi-cylinder test and development platforms and we can validate robust performance for varying ambient conditions in, e.g. TNO’s climatic altitude chamber. Third, tools for mixed testing can become available for testing.

Powertrain control research at TU/e concentrates on engine demonstration. By using virtual vehicle and traffic simulations, we can perform engine-in-the-loop tests, see Table 1, while validating the controller performance in on-road driving conditions. This also supports research on truck platooning and automated driving.

<table>
<thead>
<tr>
<th>System level</th>
<th>Software-in-the-loop</th>
<th>Engine-in-the-loop</th>
<th>Vehicle in-the-loop</th>
<th>On-road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>Model</td>
<td>Model</td>
<td>Model</td>
<td>Real</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Model</td>
<td>Model</td>
<td>Real</td>
<td>Real</td>
</tr>
<tr>
<td>Engine</td>
<td>Model</td>
<td>Real</td>
<td>Real</td>
<td>Real</td>
</tr>
<tr>
<td>Ambient conditions</td>
<td>Model</td>
<td>Real</td>
<td>Real</td>
<td>Real</td>
</tr>
</tbody>
</table>

Table 1

Various integration levels of virtual simulation in mixed testing

4.3. Powertrain control education

Future powertrain control engineers ideally combine detailed control knowledge with knowledge of subsystem behavior, such as engine, aftertreatment and energy recovery systems. Starting from their control specialization, they are able to oversee the complete field and to work with connected areas and experts. Model-based control development will become the standard in the future. This requires expertise ranging from control development in simulation environment to implementation of controllers in rapid control prototyping tools.
Future control engineers have to be familiar with development tools that integrate the various stages in the development process. This includes Software-in-the-loop (SIL), Hardware-in-the-loop (HIL), and Engine-in-the-loop testing. Mixed testing will attract more and more attention.

Powertrain control research directly contributes to the Automotive Technology program at TU/e. Education concentrates on concepts and methodologies for model and control development. On the modeling side, physics-based modeling approaches together with design of experiments and model identification methodologies are taught. In addition to these models, knowledge on how to design and calibrate optimal controllers is important. Here we do not want to focus on text book examples, but define practical use cases. Experience with real engines has to become an essential and integral part of the education. This clearly illustrates practical issues like CAN communication, actuator drift and constraints, and measurement noise. Students can perform model identification and develop and implement advanced combustion control strategies on the single cylinder engine platform. Moreover, a production-type, three-cylinder diesel engine has been modified such that the studied model and control development methodologies can be implemented in practice.

Various student projects on modeling and control of engine and aftertreatment systems are done within my network of collegial universities and industry partners. This gives students the opportunity to experience a different environment, apply their knowledge to real-world applications, and access state-of-the-art testing facilities.

With this, we are confident that we can educate control engineers for the future and fulfill the increasing need for control experts in the automotive industry.
5. Conclusions

Before I finalize, let me first summarize the main messages of this inaugural lecture.

- **Internal combustion engines will remain the main power source for future heavy-duty powertrains.** These engines have to combine brake thermal efficiencies beyond 50% with zero-impact emissions and support the transition from diesel to natural gas and biofuels. Due to additional actuators and subsystems, the complexity of future powertrains will grow exponentially;

- **The importance of powertrain control will grow and control development will face a turning-point in the near future.** Due to robust performance requirements and growing system complexity, development time and costs will reach unacceptable levels with current map-based methodologies. Model-based control development will become the industry standard;

- **The self-learning powertrain is the way to go.** By applying self-learning concepts, optimal control settings that maximize overall powertrain efficiency are automatically determined on-line using sensor and preview information. Real-time emission monitoring systems are a crucial enabler for these self-learning concepts;

- **My research concentrates on integrated energy and emission management for heavy-duty powertrains.** By following a system approach, we aim to develop physics-based, control-oriented models for on-road energy and emission trading. This ultimately has to lead to self-learning control strategies that deal with real-world emission limits and guarantee optimal powertrain performance in varying driving conditions;

- **Close collaboration with adjoining research fields and with research institutes and industry is key for this multidisciplinary research field.** This applies to knowledge transfer as well as facility sharing. There is a special focus on integrating the test facilities of TU/e with industry to create a world-class, experimental environment and on integration of virtual and experimental testing.
With this lecture, I aimed to give you a glimpse of the drivers, requirements and challenges in the field of powertrain control. I believe that this clearly illustrates my earlier claim: after 120 years of diesel engine development, we are just at the beginning of a new generation of super-efficient and fuel flexible powertrains. Electronic control will play a crucial role in getting these powertrains on the road. My ambition is to develop innovative control methodologies which make smart and green transport solutions feasible.
Acknowledgements

This inaugural speech landmarks a personal milestone in a long and exciting journey. Many colleagues, students, family and friends have contributed in their own way and helped me to reach this point. Thank you all. Although it is impossible to name everyone individually, I want to take this opportunity to especially express my gratitude to the following persons.

As various colleagues from academia and industry have enviously confirmed, with the combination of my positions at TNO and TU/e, I have the greatest job in the world. It allows me to research innovative concepts with international expert teams, demonstrate these concepts on engines and vehicles, and educate the next generation automotive control engineers. First, I am extremely grateful to TNO for their confidence and creating this opportunity. Especially, I want to acknowledge the stimulating support of Peter Werkhoven, Hugo Vos, Casper Lageweg and Paul van den Avoort. Working with many TNO colleagues from various disciplines has been a great and valuable experience. Over the years, the collaboration with Rik Baert and Peter van Gompel has been especially uplifting and energizing. I want to thank them for introducing me to the field of automotive powertrains and being enriching sparring partners. I thank Rutger Beekelaar for his valuable and motivating advice during the preparation of the inaugural lecture.

Moreover, it is my honor to work at TU/e, which is the world’s number one university in collaboration with innovative industry. At this university, I started my mechanical engineering study more than 25 years ago. By offering me a PhD position, Jan Kok and Bram de Jager stood at the cradle of my academic career. I want to thank both for their enthusiasm, inspiration, and giving me the freedom to explore many novel ideas. After I moved to TNO, Maarten Steinbuch played a crucial role in re-uniting me with TU/e. I am extremely grateful to Maarten that he gave me the opportunity to further develop my academic career in his internationally renowned group. He has been an inspirational sounding board and role model, who combines ambition and leadership with attention for people. Like an F1 team, success relies strongly on the support of the management team, team members and sponsors. Especially, I want to thank the executive board and department of mechanical engineering for their confidence over the years.
Moreover, I want to thank the industrial and university partners, scientific and supporting staff, and associated MSc, PdENG and PhD students. They have been large contributors to my research, challenging me, and making it fun. Particularly, I want to thank my colleagues Thijs van Keulen, Bram de Jager, Bart Somers and Xander Seykens along with the (ex-)PhD students Chris Criens, Emanuel Feru, Xi Luo, and Robert van der Weijst.

Making this journey without family and friends is difficult to imagine for me. I want to thank my parents for their unconditional love, encouragement and assistance, and for giving me opportunities that were not available to themselves. Anke, thank you for your patience, the space that you give me, and for keeping me aware of the celebrations of life. You are the rock of our family, who always creates a warm and relaxing home. Noortje and Tijs, of all people mentioned, you are the persons that teach me most. It is a pleasure to explore the world together, literally during holidays, as well as listing to your questions, ideas and views on the world. All this fuels me up and gives me energy for another day in the “Walhalla”, as I use to refer to my work.
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Prof.dr.ir. Frank Willems was appointed part-time professor of Integrated Powertrain Control at the Department of Mechanical Engineering of Eindhoven University of Technology on January 1, 2016.

Frank Willems gained his MSc and PhD degrees in Mechanical Engineering from Eindhoven University of Technology (TU/e), in 1995 and 2000, respectively. Subsequently, he joined the Powertrains group of TNO Automotive, where he is currently a senior technical specialist in powertrain control. He has been involved in various industrial research projects on clean engine technologies. Since 2007, he has been a part-time staff member at the Control System Technology group, Department of Mechanical Engineering at TU/e in various roles. Following his Assistant and Associate Professorships, he currently holds a position as part-time full professor in this group. His main research interests are modeling of internal combustion engines and aftertreatment systems, cylinder pressure-based combustion control, and integrated powertrain control.
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