New methodology for early injector qualification in real engine.

Dipl. Phys

Johannes Ullrich*

Dipl. Ing.	Dipl.Ing.	Dipl.Ing.
Roland Steininger	Romy Semisch	M.Reke

Hyundai Motor Europe Technical Center GmbH, Rüsselsheim

*Vortragender

1. Introduction

Despite the main stream powertrain technologies such as electrification, sophisticated exhaust after treatment systems and modern transmission concepts, the high pressure fuel injection will be an important component also in the future. The main reason for this circumstance is that while the powertrain technologies have become substantially more powerful, also the legal requirements have become significantly more challenging and so low engine out emissions remain to be also a major development target in the future. This is in line with publications from Daimler and BMW who declare that beside sophisticated after treatment systems and powertrain electrification very good engine raw emissions will be inevitable.

Whereas many different parameters of a fuel injection system can be pre-evaluated either by numerical simulation or by testing on a component test rig, some tasks need to be performed in vehicle or at least in a real engine dyno. In case of an entirely new engine design layout, the decisive question often is which injector concept to be used. Injector concept does not only means piezo or solenoid actuator but also is about the particular nozzle spray hole design, that is of big importance for emissions as well as coking robustness - especially in countries with critical fuel qualities .

To be able to pre-qualify also a totally new injector design not only for its hydraulic performance as it can be done on a component test bench but also for its emission and fuel robustness behavior, a new concept for injector testing on engine was established by Hyundai Motor Europe Technical Center. The new test concept makes use of a well-known base engine as a so called "concept carrier engine". This engine is specially modified to anticipate the main features of the next upcoming engine generation and fitted with a special "injector controller interface" developed by HMETC and VEMAC. This device finally allows to operate any type of injector in that engine as long as it fits design wise into the injector bore of the cylinder head.

After more than one year of concept validation, this new method turned out to be not only cost wise very attractive but also very efficient in terms of engineering resources. However, in the eyes of the authors the biggest advantage is the fact that e.g. the injector fuel robustness, which is strongly linked to customer perceived quality in the field, can now be evaluated already in a very early phase of the engine development rather towards the end of the project. Hence, there is plenty of time to define robustness countermeasures together with the particular injector supplier if needed.

2. Engine Performance

2.1 Parameters influencing engine performance

Regardless of the particular engine use (passenger, truck or off road) there is a common understanding of the major relevant performance parameters to obtain good engine performance as follows:

- **Engine structure:** max. crank speed, max peak pressure, ..
- **Engine sub-systems:** boosting, exhaust after treatment, ..
- **Integration in vehicle:** cooling performance, NVH targets, ..
- **Environmental condition:** altitude, temperature, fuel quality, ..
- **Legal targets:** emission legislation, tax regulation

2.2 FIE impact on engine performance

The Fuel Injection Equipment (FIE) – especially the injector - represents the interface between engine control unit and combustion chamber. Its particular performance decides about engine power (=injection rate), emission (=fuel atomization), engine noise (=injection accuracy) and power, durability and emission stability (=fuel robustness). The ongoing development of Common Rail injection technology during the last 20 years shows some clear trends which allows to identify the key parameter for FIE future technology:

- Rail pressure
  (operation pressure > 2.500 bar)
- Injection pattern
  (hydraulic tuning or split main)
- Short Pilot separation time
  (digital rate shaping)
- Small nozzle spray holes
  (< 100 µm)
- Best hydraulic efficiency
  (leakage → “0”)

FIE performance parameter	Engine performance parameter: Power torque	Fuel economy	Low emission	Low NVH	Endurance reliability
Operation pressure	++	-	+	-	-
Injection pattern	+	+	++	++	+
Short pilot injection separation	o	++	++	+	o
Small nozzle spray holes	-	+	++	+	--
High hydraulic efficiency	+	+	+	o	++

Fig.1 Impact of FIE on Engine Performance

3. FIE System evaluation method

3.1 Impact of FIE on engine emissions

Aside from good fuel atomization, usually realized by high injection pressures combined with small spray holes, low engine out emission also require an excellent, that is homogenous, fuel distribution in the combustion chamber to avoid too rich fuel (< λ) zones where soot as well as HC and CO can form.

Research in spray chambers and on engine dyno has shown that good spray symmetry is not only mandatory for the main injection but in particular also for the pilot injection phase because during this part of the combustion the boundaries are set to have an homogenous oxygen distribution for the latter main injection. In addition poor spray symmetry at pilot injection usually goes in parallel with insufficient fuel atomization in the near of those spray holes were only little amount of fuel passes through and thus conflicts the wish of an overall good fuel atomization.

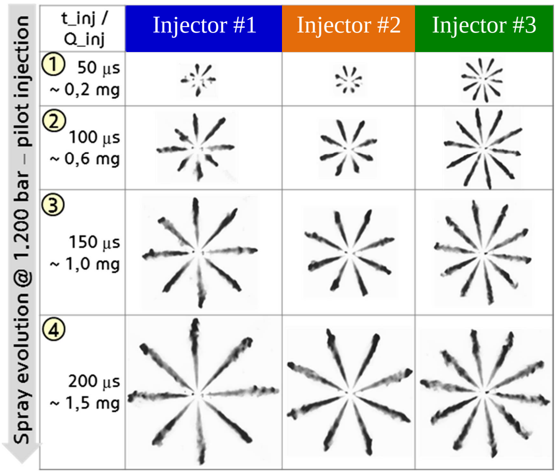


Fig.2 Spray Symmetry of different Injector Concepts

3.2 Impact of FIE on engine efficiency

A totally different aspect of fuel injection system is its impact on fuel consumption. Here, two different phenomena should be separated for its effects and test methods:

Firstly, the indirect impact of the FIE system on fuel efficiency by enabling a good combustion. Secondly, the direct impact of the FIE system on fuel efficiency through is mechanical power consumption.

Whereas first item requires a real engine on a dyno to perform the analysis (also here the new HMETC test concept can give advantages for better testing efficiency), the second item can be evaluated on so-called FIE component test benches with good correlation to the full engine. The task here is just to measure the total power consumption of the FIE system and to identify the particular areas that have room for efficiency improvement.

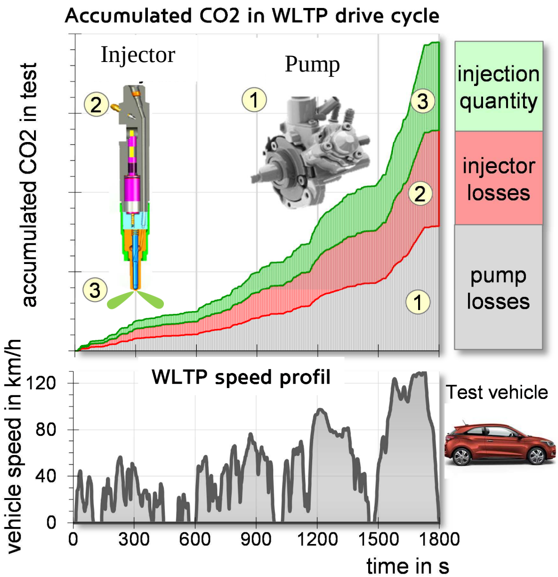


Fig.3 Impact of FIE power consumption on CO2

3.3 Impact of FIE on fuel robustness

As long as fuel robustness is seen with special focus on fatigue or wear testing, FIE component test benches can be used reliably. When it comes to fuel deposits tests (internal or external injector deposits) it is obvious that an engine dyno or a real vehicle is required because the FIE system (especially the injector) must be operated under most realistic conditions. In particular for buildup of spray hole deposits, which are caused by special combustion effects (temperature, gas chemistry) but also by nozzle design (spray hole geometry) it is necessary to operate the

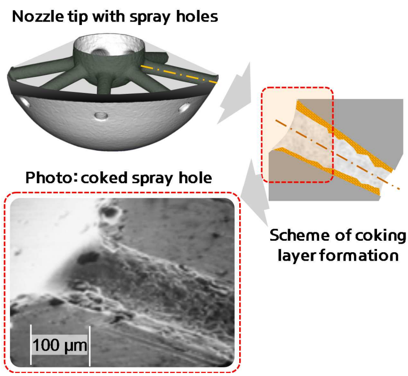


Fig. 4 Nozzle spray hole coking

injector in real engine. This is also one of the main reasons why the newly developed testing concept described here was firstly applied for the evaluation of different injector designs with special focus on their robustness on critical fuel qualities with special attention on the spray hole coking that is one of the major limiting factors for the spray hole diameter reduction for future clean diesel applications.

3.4 Impact of FIE on engine power

There are a variety of FIE parameters that influence the engine performance. However, one of the major criteria that is relevant to the engine power output while maintaining low exhaust gas temperatures is the injection rate profile or more precise the injection quantity that is injected per time.

Only high quantity injected in short time (figured by high rate) in conjunction with small spray hole diameters (as well as high pressures) assures a high engine power, a durable exhaust manifold and turbocharger and also low emissions of the powertrain.

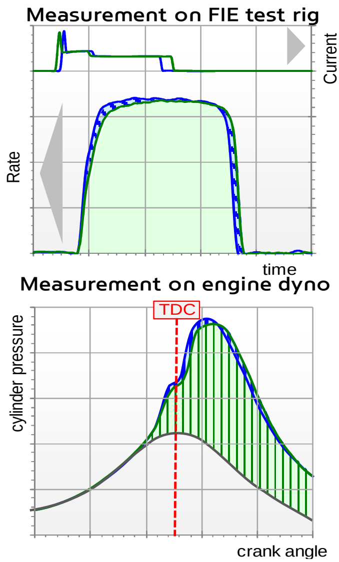


Fig. 5 Impact of Inj. Profile on Combustion

4. FIE Supplier Technologies (focus ⇔ injector)

During the last two decades of common rail system development, many innovative concepts have been published whereas those with direct piezo actuation, closed loop control and also rate shaping option belonged to the most innovative ones.

However, as technological progress is not only about “features” but more about reliability and product cost, those concepts have not be successful in the market – moreover cheaper, robust and similar powerful servo driven injectors operated by a solenoid or a piezo actuator are in use in combination with sophisticated fueling controls.

Physical analysis of…	Engine/drivetrain inertia		Ignition or combustion		Pressure drop in rail	Engine friction
No.	#1	#2	#3	#4	#5	#6
Used sensor	crank sensor	crank sensor *	knock sensor	p_cyl. sensor	rail press. sensor	crank sensor
Pilot error [mg/str]	± 0.35	± 0.30	± 0.45	± 0.30	± 0.19	± 0.20
Speed [km or h]	> 5.000 >35	>350 >3	>1.200 >15	>800 >9	> 500 >3.5	>„0“ >0.5
Operation mode	Overrun of engine/vehicle		In all engine operation area			engine idle
Application effort	0	0	-	-	--	+
System robustness	0	+	0	-	+	+
Individual pilot inj. control	no	no	no	yes	no	no

Fig. 6 Concepts for injector quantity life time drift control (different suppliers)

4.1 Injector actuator concepts (solenoid/piezo)

One layout example for a modern CR-Injector is given in below table, where a typical Euro 6 passenger injector is presented. At this point it would not mean a big difference to show alternatively the data of a piezo injector as – aside from the actuator spec. – it would be more or less the same figures.

For future and even more challenging engine applications, servo injectors can be performance wise enhanced by sophisticated control functions but also by continuous design refinements for higher efficiency or for better production quality and lower tolerances.

Engine data	
Engine	U2-1.6
Performance	93 kW @ 4000 rpm
Spec. power	58 kW/l
Injector data	
Rail pressure [bar]	2,000
Needle seat coating	C2-coated
Hydraulic flow rate [ccm/min]	725
Spray hole diameter [µm]	119
No. of spray holes	8
sac hole type	Micro w/o SNG
K-factor	ks 1.5
Length of spray hole [mm]	0.75

Fig.7 Injector Specification Table (Example)

4.2 Injector design features (nozzle design)

As stated in the beginning, the injector – in particular the nozzle – is the inference to the combustion chamber and so it is no wonder that this parts is of special interest for the engineer.

Especially the nozzle tip design (mainly of spray hole) is not only most relevant for fuel preparation such as atomization and distribution (= emission) but also for the formation of fuel related deposits that can hamper the free movement of the nozzle needle by internal deposits but also influence the fuel flow inside the spray holes by outer deposits.

Whereas the inner deposits influence typically the armature and needle dynamics in the pilot injection phase, the outer deposits show a dominant effect mainly during the main injection phase and can cause substantial reduction of fuel flow of the nozzle so even the engine power output can be affected critically.

To counteract especially the issues of external deposits in spray holes, all FIE makers have developed their own design strategy to offer most robust system to their customers. As nozzles are usually not interchangeable between the different supplier injectors, the task for the HMETC engineers was, to be able to test any kind of injector in an arbitrary engine - the methodology was developed exactly for this purpose.

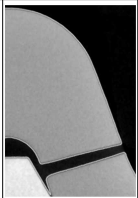
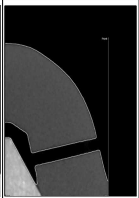
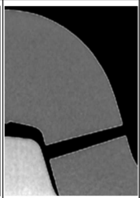
	Supplier #1	Supplier #2	Supplier #3	Supplier #4
Nozzle spray hole design by CT-Scan				
Inlet Diameter	108 µm	107 µm	129 µm	105 µm
Outlet Diameter	89 µm	100 µm	100 µm	97 µm (490 µm)
K-factor	1.9	0.7	2.9	0.8
Hole Length	750 µm	620 µm	720 µm	590 µm

Fig. 8 Spray hole geometries of different nozzles

5. Testing Mixed-Supplier-FIE-Systems

5.1 Mechanical integration

As a key element of the new methodology is the mixing of different injection system hardware components, an essential part is the proper physical interaction of all parts. Aside from making sure that the injectors fit into the cylinder head and the high pressure pipes have a suitable layout in terms of length and volume, it must be guaranteed that the high pressure pump can deliver sufficient pressurized fuel for the fuel injection but also for the servo control quantity (static & dynamic leakage). Hence, to perform a fuel quantity-balance calculation for all pump-injector combinations and operation points and to select a properly sized pump is one of the first steps.

5.2 Electrical integration

Another key target of the new method when using a well-known standard engine is to avoid any kind of substantial re-calibration effort in order to get the engine running. As a consequence, the most effective way to succeed here is to carry over using the original ECU and software of the base engine that is field proved million times.

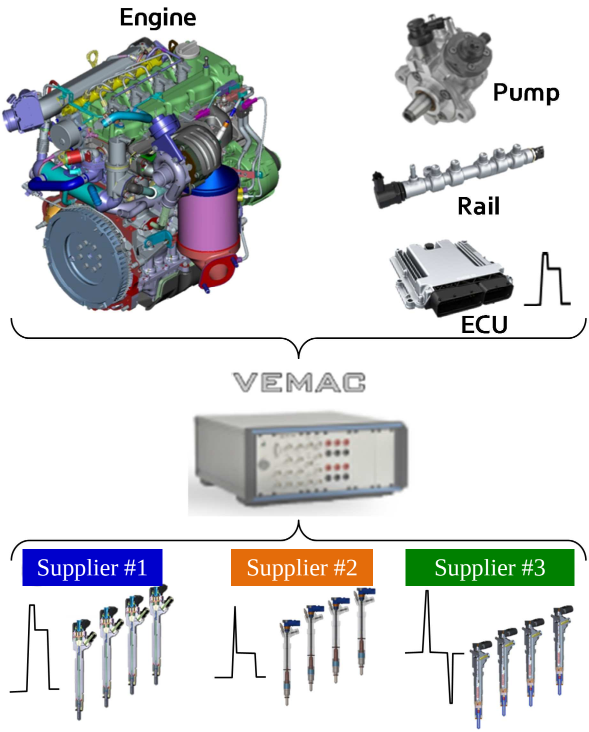


Fig. 9 Concept Carrier Engine Concept w. Interface

Under those circumstances, the electrical integration of the various injector types is of course one of the more challenging issues, because the new test method should by applicable to any injector types that are on the market. Here not only different profiles of different solenoid injector are targeted but also the operation of piezo actors with a sophisticated energy control of the piezo stack must be covered.

A solution for this task was found in an "injector control interface module" developed together with partner "VEMAC" that is installed between ECU-injector-power-stage and injector. This interface module utilizes the output signal of the generic ECU just as a digital "ON/OFF" switch information and generates the very particular injector driver profile for each injector individually. As the interface used here has a twin-processor-core, it can handle any kind of solenoid but also piezo injector variants with same hardware.

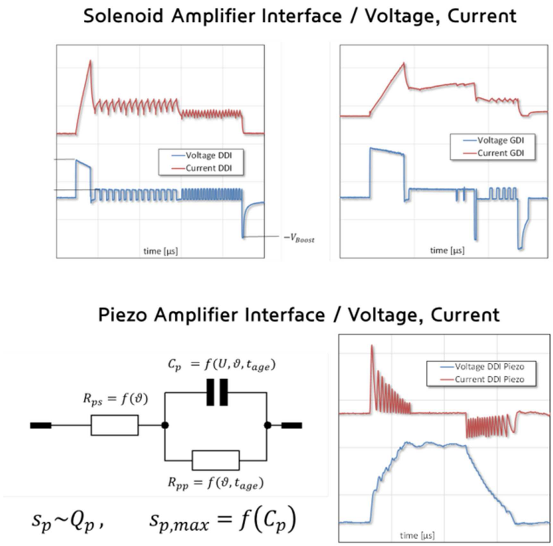


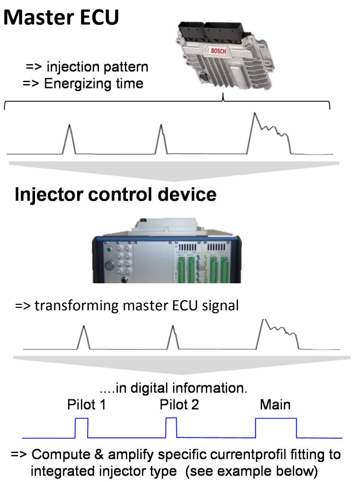
Fig.10 Electr. System Layout of Carrier Engine

5.3 Control logic aspects

The concept of using the generic engine ECU and the injector interface module in a "server-client" mode eases many FIE control items. Only the very particular injector driver pulses must be "matched" to obtain the same physical fuel injection quantities and timings, whereas almost all the remaining engine calibration maps can be utilized further on without changes. Especially the performance and the emission related calibration areas can be carried over fully and as a consequence the effort to perform injector tests with this concept is about 5% the effort compared to the usual way making a completely new and own engine application.

5.4 Matching and monitoring

When operating totally different injectors characterized by different mechanical behavior but also different hydraulic flow properties, it is clear that the fuel injection timing and fuel metering relevant maps to not fit without some minor modifications Nevertheless the entire effort is extremely low compared to establishing a fully new application as only the so called injector base map (correlation of energizing duration, pressure and quantity) and the physical timing correction maps (correlation between start of energizing and start of hydraulic fuel injection) have to be checked or slightly modified. Based on many years of experience in this field, HMETC handles these tasks in a fully automated hardware-in-the-loop cycle, using an FIE component bench equipped with the particular FIE components and controls.



Application	Current profil	ET µs	Q mg/str
Supplier #1 (solenoid, hi-voltage)	ET	557	50
Supplier #2 (solenoid, 12V max.)	ET	855	50
Supplier #4 (solenoid, hi-voltage)	ET	681	50
Supplier #3 (Piezo, energy controlled)	ET	776	50

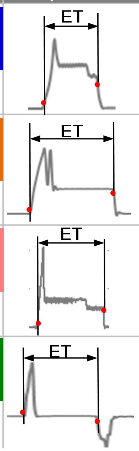


Fig.11 Conversion and matching master ECU pulse to client (=injector) pulse

6. Advantages & Conclusion

6.1 Increase of development efficiency

The new testing concept has big potential to increase the development efficiency as the fuel robustness evaluation of a new injector concept can be done even before or at least in parallel to the “normal” project activities. Only from time to time it might become necessary to integrate the latest findings from the main project development line into the fuel robustness tests done with the “concept carrier engine”.

6.2 Shortage of development time

Also the overall development time can be substantially reduced by the new method as – due to the very early start of the injector robustness qualification – less injector design loops have to be performed in order to find the best nozzle design compromise between emission and robustness. Additionally the “fuel robustness validation team” does not have to wait for late pilot engines to perform their tests – instead the suitably modified “concept carrier engine” can do the job.

6.3 Saving of prototyping costs

As typically a modified regular mass production engine (“concept carrier engine”) is used instead of an expensive and rare prototype engine the material cost of the fuel robustness test mainly reduce basically to fuel and injector sample cost – this equals a cost saving of around 45.000 € per test (50.000 € for proto engine vs. 5.000 € for a serial engine).

6.4 Most trustworthy results

One of the biggest advantages of the new test concept is finally the trustworthiness of the results. In case the evaluation a novel injector concept is done in an engine that is still under development, the results must be critically reviewed with respect to the question to what extend the outcome is due to the new engine and/or the injector.

With the new concept presented here, it is obvious that all data – especially when compared to field data obtained from the known mass production engine – represent 100% the influence (=impact) and the performance of the tested injectors. In addition it can be judged clearly if the new injector concept has to be seen as a step forward in terms of better fuel robustness or if there is room for improvement compared to the robustness of the existing combination that is produced in big numbers.

Conclusion

HMETC Competence Center for Fuel and Injection Systems developed a new and innovative methodology which allows for the integration of any Diesel fuel injector type from any supplier in a Hyundai engine in very fast and efficient way. It furthermore has been already successfully proven in an HMETC project where injectors of four different FIE suppliers were tested in one and same Hyundai engine. The special "injector interface module" that is mandatory for the new testing concept was developed in close cooperation with company VEMAC that is known for their rapid prototyping ECU and control logic. The related tests and especially all FIE mapping has been done at and by the nearby University of Applied Science Giessen-Friedberg where HMETC looks back on several years of successful co-work.

As the idea is tailored to obtain a most early FIE qualification process for advanced injection systems, the entire engine pre-development can be simplified and speeded up which means on the other hand also time and cost saving. Furthermore a well-known engine technology linked to a big stock of reference data from development and field experience offer are a trustful work base to Hyundai engineers. In this way one can evaluate most advanced injection system concepts (i.e early injector proto-types), as well as competitive technology (state of the art) fast and with reliable and trustful results with only low efforts.

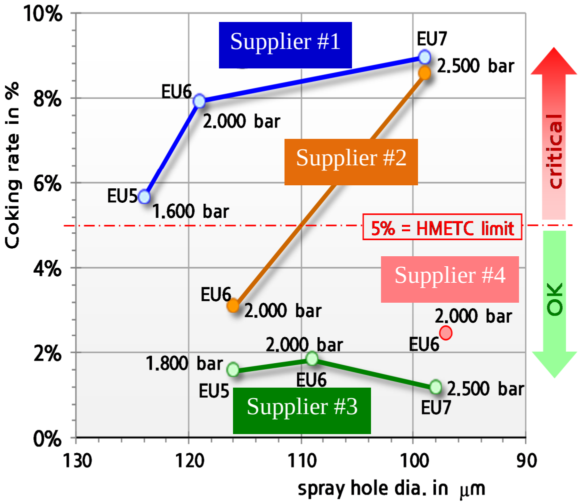


Fig.13 Nozzle Coking Robustness of different Injectors

As in the case shown here, the entire injector robustness information is based on a highly mature base engine design, it can be expected that the all observed performance aspects are fully related to the injection system that is under evaluation.

Hence the tests can be utilized to discriminate between the various performance features of the injection systems. Also the overall experience of the particular supplier can be rated regardless if it is for its knowledge on making a hydraulically powerful injector or a highly fuel robust nozzle design.

First but still conservative estimations on efficiency improvement of the method lead to typical time saving of 9 months as the test engineer does not have to "wait" for latest ECU-control software and a cost saving of at around 300.000 € as a special proto-engines will not be needed and also the engineering effort to setup a "base calibration" reduce from about 16 weeks to approx. 2 weeks.

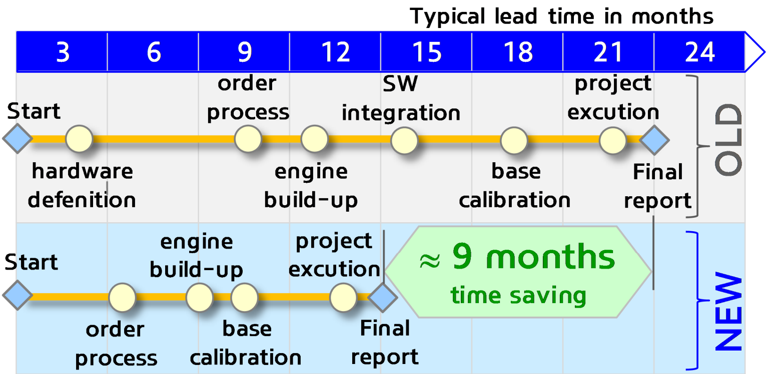


Fig.14 Typical engine development schedule

HMETC Competence Center for Fuels and Injection Systems strongly believes that this new testing methodology for early FIE component evaluation on full engine will substantially support to enhance Hyundai Powertrain Development Processes in order to save cost and development time.

Furthermore it facilitates to make an even more reliable decision when new FIE-components have to be selected for the next engine development step – especially when the focused technology does not yet exist in the current technology portfolio.