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An example of adoption of the model-based design (MBD) methodology in the development process of an LPG fuelling system

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The research aims to recognize the potential of adopting the model-based design methodology to the development process of an LPG (liquefied petroleum gas) fuelling system. Changing regulations often force the modern development of internal combustion engines (Euro 7, CO_2 reduction measures, etc.). With the definitive ban on new registrations of vehicles powered by internal combustion engines in Europe (planned for 2035), there is still ongoing development of the adaptation of the fuelling system to LPG. There is still market potential in adapting new internal combustion engines, usually equipped with direct injection systems, to reduce customers' cost of ownership of a vehicle. As the engineering process should be accelerated in the face of the variety of direct injection systems offered by OEMs (original equipment manufacturers), the model-based design methodology is proposed to make the development more effective. The article presents the SWOT analysis of this approach in the engineering process and the potential of the method in an LPG system development is concluded.

Key words: *model-based design, LPG, SWOT analysis, direct injection, automotive software development*

1. Introduction

Combustion engines are still the most popular power source in passenger cars globally. For about a decade, the market share of ICE-powered (internal combustion engine) passenger cars has been decreasing in favor of alternative powertrains (hybrid, battery electric, and others). This trend is becoming clearly visible in recent years, as it was presented in the chart in Fig. 1 for the EU (European Union) market.

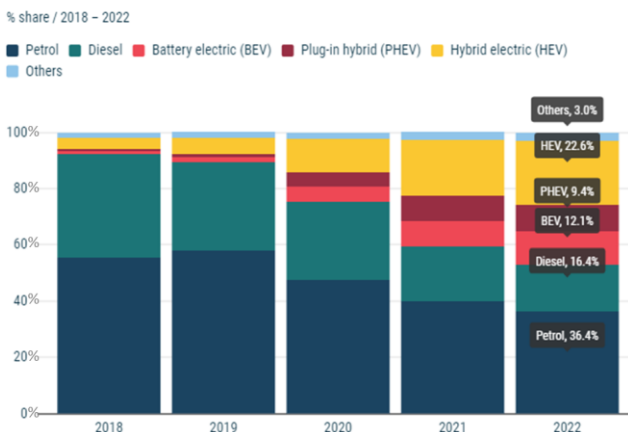

Fig. 1. New cars in EU by the fuel type [10]

The changing situation in the passenger car market globally is mainly caused by the efforts to decrease CO_2 emission reduction from the transportation sector.

Despite the fact, that only around of the 50% passenger cars are powered by the classical powertrains (ICE only, petrol or diesel), the ICE remains a component of the powertrain of almost 85% of new cars (petrol, diesel, HEV – hybrid electric vehicle, and PHEV – plug-in hybrid electric vehicle). The majority of these ICEs can be easily converted to be partially or completely LPG-powered.

LPG, as a fuel to power vehicles, is regarded not only as a cheaper alternative to petrol or diesel fuel but also as a more environmentally friendly combustion [2]. It is also the most widely used alternative fuel in Europe, although other alternative fuels are present in the market. Theoretically, the engines which can be fuelled by the LPG can also be fuelled by the CNG (compressed natural gas), with small modifications to the conversion system. However, due to the still limited network of CNG filling stations [25], it is not as popular as the LPG.

Stelmasiak et al. [26] presented the potential of utilizing methanol as an alternative fuel. However its high toxicity prevents ~~the~~ further study on expanding the supply network of this fuel, especially in the current legislative situation in Europe.

Ethanol is another alternative fuel, which can replace petrol in powering ICEs [5]. Currently, it is used as an addition to petrol, since its ability to form a homogeneous mixture. The engine control algorithms provided by OEMs already take into consideration the addition of ethanol, thus no conversion kit is needed for ethanol combustion in ICEs.

LPG conversion kits are being manufactured by many automotive companies. Most of them are based in Europe and offer conversions of engines powered by petrol, diesel and those included in a hybrid powertrain.

The development of an LPG conversion kit dedicated to modern ICEs mostly consists of software modification to control the LPG dosage by reducing or switching off the original fuel supply. To keep pace with OEM powertrain development, the manufacturers of LPG kits need to invest in engineering resources. One of the means to improve productivity in software development is to adopt the model-based design methodology (MBD). This article focuses on recognizing the potential of adopting MBD in software development for an LPG conversion kit.

1.1. Current situation of a passenger vehicle powered by an ICE

The current development of the automotive industry struggles with many issues related to economic, ecological, political, legal, and technical aspects. Some of them are:

– banning new fossil fuel vehicles (planned on 2035 on leading markets and 2040 globally [5, 17])
– introducing more stringent emission standards, such as Euro 7 in EU [24]
– weak supply chains affected by events with the global range, such as the war in Ukraine or COVID-19 pandemic
– high engineering costs and long development time of projects in the automotive industry.

The ever-changing environment around the development of ~~the~~ new passenger vehicles enforces changes in the operation of all automotive companies. It concerns the OEMs, Tier 1-3 suppliers, and the aftermarket equipment producers.

Manufacturers of automotive LPG kits enable with their products the means to convert the powertrains powered with petrol to use the LPG as a partial or a complete replacement fuel. LPG is considered cheaper and more environmentally friendly fuel than gasoline [2].

Currently (2022), 36.4% of new cars in the EU are powered with gasoline [10]. For around a decade, there has been a visible rising trend of equipping the engines in new petrol cars with a DI system [19].

The modern LPG conversion kits allow applications on the new ICEs with sophisticated DI systems. However, the variety of the combustion systems and features applied in the currently available DI engines (SPCCI – spark-controlled compression ignition, VVT – variable valve timing, SCE – stratified charge engine, etc.) enforces the individual approach in the development of the LPG fuelling system for each engine application.

This paper introduces the potential approach of accelerating the development of the software of a modern LPG system with the deployment of the model-based design.

1.2. Model-based design

Model-based design is an established approach to developing efficient solutions to complex engineering problems. In this method, complicated systems can be created ~~by~~ using mathematical models representing system components and their interactions with their surrounding environment [1]. The modeled phenomena can be simulated by system engineers and applied in the production software code by the automatic code generation toolchain. The behaviour of the model can be easily validated and verified on various testing benches (MiL – Model-in-the-Loop, SiL – Software-in-the-Loop, HiL – Hardware-in-the-Loop).

Embedded software development is a continuously developing engineering branch. The progress made in the field of control algorithms include the adoption of modern applications, such as artificial intelligence (neural networks, machine, deep, reinforced learning, etc.) [21], digital twins [13], Internet of Things (IoT) [27]. The specific feature of the MBD is the significant improvement of ~~the~~ software development efficiency.

The main advantages of MBD are that modelling and simulation enable engineers to quickly try many ideas without the need for expensive prototypes, testing and validation are done early and continuously rather than at the end of the process so that errors are found and corrected before hardware testing, and software source code can be generated from the system models, which reduces effort and eliminates hand-coding errors [11].

In general, the MBD approach in automotive software development is applied due to its positive impact on the development time, which influences the engineering cost significantly. An example of the implementation of a system in the MBD methodology applied in the MATLAB/Simulink environment is shown in Fig. 2.

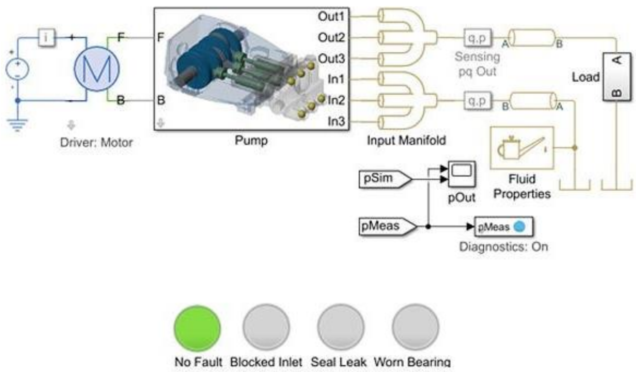

Fig. 2. Example of the MBD model in MATLAB/Simulink [15]

The main content in the MBD is the mathematical model of the system for which the software is being developed. The literature proves that an LPG system has been successfully modelled mathematically [7, 12, 20]. An example of a top-level model for software architecture for an LPG system is presented in Fig. 3.

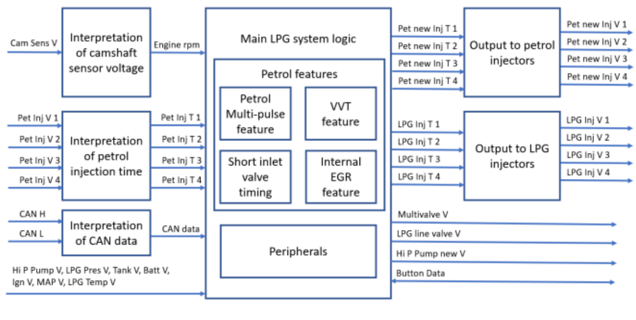

Fig. 3. An example of a top-level architecture model for an LPG system software

1.3. Novel autogas systems

Although petrol engines are currently considered as the legacy constructions, with limited focus on development from the OEMs' side, they are still the most frequent chosen powertrain type in the new passenger cars in Europe [10]. Many car owners choose to convert the classical, petrol powered engines to bi-fuel ones, which can be powered with LPG. Their decision is made mainly due to lower fuel costs.

LPG vapor phase injection systems utilize the signals from the gasoline system controller, where they intercept the gasoline injector control signal at the start of the injection and its duration [23].

Modern SI engines often utilize DI (direct injection) systems in combination with advanced features in the mixture formation and combustion processes, such as SPCCI, VVT, Miller cycle, internal EGR (exhaust gas recirculation), charge stratification, etc. These features are possible to apply to a high extent, mainly due to the deployment of DI. However, most ~~of~~ modern LPG systems still use LPG vapor injection into the intake manifold. The issues related to the dependency of the LPG injection on the intake timing (which direct petrol injection does not meet) are resolved by influencing the petrol-LPG composition for individual combustion cycles, depending on the engine operating range and its power demand. Schematics of the Prins LPG vapor injection system applied on a DI engine is presented in Fig. 4.

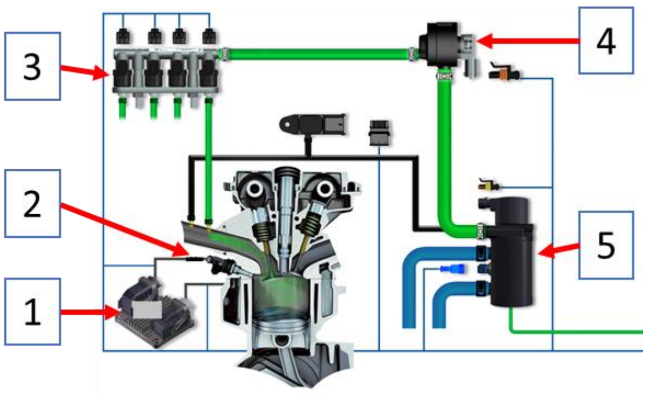

Fig. 4. Schematics of the LPG vapor injection system applied on a DI engine [28]: 1 – petrol engine ECU, 2 – ICE equipped with DI, 3 – LPG injectors, 4 – LPG filter, 5 – LPG evaporator

Controlling both fuel dosages is difficult in terms of software and hardware. The controller needs to take into consideration rapidly changing engine operation points, measurement of original petrol dosages, and adapt to the current petrol direct injection accordingly. Each OEM applies different strategies to meet the power demand in various engines, whereas the LPG kit manufacturers are focused on covering ~~the~~ most of the engine applications on the market. This creates a high demand for engineering resources, which are costly.

2. Analysis aim and goal

The aim of the analysis is to assess the potential of applying the MBD methodology for software development of the modern LPG conversion systems.

The automotive industry knows many success stories related to the deployment of the MBD approach in developing the production software code. Toyota claims that the MBD is a measure to deliver more complex systems with quality and improved productivity [18]. Stellantis developed the new generation of its gasoline Engine Control System using MBD [8]. VW and MathWorks successfully collaborated to craft an MBD process that is targeted towards reaching compliance with important industry quality standards [4]. MAN successfully applies the MBD approach in the embedded software development for more than 15 years [7].

This valuable experience in the development of the software controlling the functionality of automotive powertrain systems can possibly be transferred to companies manufacturing LPG conversion kits.

The goal of the analysis is to prove the above argument by analyzing the strengths, weaknesses, opportunities, and threats of adopting the MBD processes into the embedded software development for LPG system controllers.

3. SWOT analysis

The SWOT analysis is a simple method that can provide a realistic interpretation of the strengths and weaknesses of a business [3]. Mostly, organizations carry out SWOT analysis at a strategic planning stage, try to identify and examine the existing resources, both internally and externally, investigating their trends and patterns that may have either positive or negative impacts on businesses [16]. The presented analysis focuses on the aspect of adopting the MBD in the development process of ~~a~~ modern LPG system software.

3.1. Strengths

Rapid development of software: MBD process is highly efficient compared to the classical embedded software development. The addition of model-based systems engineering to the traditional approach delivers a 55% reduction in total development cost [14]. Not only does it concern the LPG kit manufacturers, but all the companies developing the control algorithms for complex systems.

Advantage over the competition: deployment of MBD is not a common practice among manufacturers of LPG conversion kits. Implementing the MBD process can enable releasing the applications more often than other competitors on the market.

Potential of the development of the new technology products: due to its ease of use, MBD can shift the engineering focus on the system development instead of being put on mundane implementation details. MBD also enables fast simulation and validation techniques with convenient integration of the measurement data.

3.2. Weaknesses

High initial cost: implementing MBD can be costly, especially in the initial phase, when the results are not yet visible. The costs include framework licenses, consulting, and support.

Foreseen limited growth in the particular product range: MBD applied only to the LPG kit development process is risky in the face of the threats related to the internal combustion engines mentioned in the introduction. However, this risk can be mitigated by extending the product range, where MBD can also be successfully adopted (companies like AC or ALEX already extend their product portfolio with photovoltaic systems).

3.3. Opportunities

Quick expansion on the market: applying MBD to the engineering process can provide a chance to cover a broad range of engine applications, not only petrol powered with DI, but also PFI-DI or diesel.

Satisfying "here and now" demand: until the complete removal of internal combustion engines from the streets, there are decades of their presence. Converting as many engines as possible to be LPG-powered can be regarded as environmentally friendly, with the means currently available. MBD can be a way of reducing air pollution in the near future.

3.4. Threats

Changes in legislation: investing in the further development of LPG conversion systems can be risky in the face of the continuous change of the regulations. Even the rules defining the installation of LPG systems in cars are not free from the changes (vide new project of changes in R115 homologation proceeded in Poland [22]).

Variability of fuel prices: uncertainty of profitability of an LPG system installation influences the customers' decisions. Currently, the fuel prices are not forecastable long term.

3.5. Interpretation of the SWOT analysis

In the SWOT analysis process it was recognized, that adopting the MBD methodology to the software development process of an LPG conversion system has more strengths than weaknesses. However, the analysis did not take into consideration the individual business development plan of an LPG kit manufacturer. Provided the company focuses on the further development of its products in order to cover the most of the ICE applications, adopting the MBD is a reasonable step to take.

Introducing the MBD is not free from risks. However, they can be mitigated in the following ways:

- high initial cost can be reduced by applying for external funding (e.g. from the EU) or hire external freelancers or consultants
- limited growth in the LPG conversion kit's market is inevitable, regardless of the adoption of MBD. However, if a company adopts ~~the~~ MBD for the currently offered product range (LPG kits), the methodology can be easily applied to other technology products offered in the future.

Table 1. SWOT analysis of the potential of adopting the MBD methodology in the software of LPG powering system

Strengths	Weaknesses
1) Rapid development of software 2) Advantage over the competition 3) Potential of the development of new technology products	1) High initial cost 2) Foreseen limited growth in the particular product range
Opportunities	**Threats**
1) Quick expansion on the market 2) Satisfying "here and now" demand	1) Changes in legislation 2) Variability of fuel prices

Despite the potential drawbacks of adopting the MBD, it ~~is~~ cannot be forgotten that this methodology is a modern process to develop software for automotive applications, and its advantages outweigh the threats. The detailed calculation of the profitability of introducing MBD cannot be performed within this article due to the individual situation of each company.

4. Conclusion

Adopting the MBD methodology in the development process of the embedded software used to control a modern LPG conversion system can be advantageous for the company, which would decide to do so. The biggest strength of this method is its potential for cost savings. The decision to introduce MBD in the company is not free from risks, ~~which were~~ described in the SWOT analysis.

The decision to adopt the MBD process in the development of the software to control the LPG system is to be made individually by a company, however in the face of an ever-changing situation with ICEs, it can be a decent starting point to modernize the development process for future products.

Nomenclature

CNG	compressed natural gas
DI	direct injection
ECU	electronic control unit
EGR	exhaust gas recirculation
EU	European Union
HEV	hybrid electric vehicle
HiL	Hardware-in-the-Loop
ICE	internal combustion engine
IoT	Internet of things
LPG	liquified petroleum gas
MBD	model-based design
MiL	Model-in-the-Loop
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
SCE	stratified charge engine
SiL	Software-in-the-Loop
SI	spark ignition
SPCCI	spark-controlled compression ignition
SWOT	strengths, weaknesses, opportunities, threats
VVT	variable valve timing

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