

AN OVERVIEW OF MODERN FUEL INJECTION STRATEGIES FOR AUTOMOTIVE DIESEL, LNG, AND HYDROGEN ENGINES

TOWARDS BETTER PERFORMANCE AND EMISSIONS



SANJOY BISWAS





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About the Author

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He has over 18 years of experience in the Automotive R&D, with expertise spanning Defence Vehicles, Commercial Vehicles, Engine or Powertrain Integration, Electric Vehicles, and Alternative Fuel Vehicles. He started his career as a PGET in 2007 at Tata Motors' R&D, and he served there in various roles for around 15 years. A proven leader, he drives both technology and people - playing a key role in developing world-class products and building a high-performing, motivated, diverse, and inclusive team.

He is an accomplished Author with 26 published research papers across various specialised areas in the Automotive domain. He is Six Sigma Black Belt certified and holds 12 patents (both Indian and European) so far. He is a member of SAE and a life member of the Indian Society of Heat and Mass Transfer (ISHMT). His interests include painting, listening to music, watching football, and social activities.

Preface

The German engineer Rudolf Diesel invented and patented the first compression ignition (CI or Diesel) engine in 1892. Since then, these engine technologies have continued to evolve to meet the performance requirements and emission standards. The use of diesel engines has expanded into various applications compared to Spark Ignition (SI) or Gasoline engines due to better mileage, part-load efficiency, and durability, despite inherent issues like combustion noise and soot emissions.

Now, Internal Combustion Engine (ICE) emissions, fuel economy, and noise significantly impact environmental pollution, especially with on-road or automotive ICE. Therefore, the challenges are multiple for engine developers and R&D engineers, particularly for diesel engines, as they must comply with strict emissions standards [e.g., BS-IV, BS-VI, or Real Driving Emissions (RDE)] while meeting mandated fuel economy norms [such as heavy-duty fuel economy (HDFE) or corporate average fuel economy/efficiency (CAFE)]. Fuel economy standards aim to reduce the carbon footprint or CO₂ emissions (measured in gm/km) to combat Global Warming by improving fuel consumption compared to previous norms. Currently, combustion noise (CN/ radiation) of diesel engines has garnered significant attention because it causes discomfort among passengers and pedestrians, in addition to contributing to noise pollution. Exhaust after-treatment systems play a crucial role in meeting emission regulations but have a limited impact on fuel efficiency, torque, brake thermal efficiency (BTE), and combustion noise (CN). In-cylinder emission reduction methods play a crucial role in shaping combustion characteristics, directly influencing both engine efficiency and the formation of pollutants. Moreover, the combustion behaviour of diesel engines depends on several factors, including the design of the combustion chamber, turbocharger, Exhaust Gas Recirculation (EGR), injector nozzle, fuel injection strategy,

and its parameters—such as Fuel Injection Pressure (FIP), Injection Timing, Start of Injection (SOI), injection dwell, rate shaping, and fuel quantity. EGR is a proven method for reducing in-cylinder NOx emissions; however, it can adversely affect soot emissions. Increasing EGR percentage, depending on engine size and complemented by measures such as adjusting fuel injection characteristics, compression ratio, and air intake, is the simplest approach to achieve low-temperature combustion (LTC), which can simultaneously reduce NOx and particulate emissions.

Multiple fuel injections involve splitting the total injected fuel quantity of each cycle into multiple pulses, thereby achieving better control of spatial fuel delivery and improving air usage in the combustion chamber. In Multiple injections, mainly three types of injection pulses are there, namely a) pre-injections (or pilot injections), b) main injection, and c) post/After-injections. It is known that the combustion process of a DI diesel engine is divided into four phases: ignition delay, premixed burning, diffusion/mixing-controlled combustion, and late burning. The Multiple Injections Strategy plays a crucial role in combustion processes, which ultimately control ignition delay, the premixed and diffusion-controlled phase. Lastly, it controls the combustion chamber inside heat release rate (HRR), combustion pressure, and bulk gas temperature. These are the enablers to control BSFC, Torque, emissions, and combustion noise. Therefore, fuel injection strategy plays a key role in simultaneously reducing emissions and noise without penalising fuel economy due to its better control of the combustion process.

The purpose of this book is to provide comprehensive insights into modern fuel injection strategies of diesel engines and their impact on performance (BSFC, Torque, BTE), emissions, and combustion noise, with a strong focus on vehicle-level performance. Aimed at engineering students (Mechanical and Automobile), researchers, and automotive professionals, it brings a rare combination of the author's PhD research, scholarly knowledge and real-world hands-on R&D experience. A key

highlight is the detailed analysis of the Quadruple Injection Strategy—comprising double pilot, main, and post injections—combined with high EGR and Low Temperature Combustion (LTC) in a medium-duty Common Rail Direct Injection (CRDI) engine. It also presents the effects of different multiple fuel injection strategies on fuel economy and noise at the vehicle level.

Further, Hydrogen and LNG-based engines are gaining significant attention globally for their potential to reduce emissions and support the automotive industry's decarbonization goals. This book includes two chapters dedicated to dual-fuel (Diesel-LNG and Diesel-Hydrogen) compression ignition (CI) engines, their fuel injection strategies and high-level vehicle configurations. Both engine types employ High-Pressure Direct Injection (HPDI) technology. These engines utilise the Quadruple Injection Strategy featuring double post-injections and a diesel pilot fuel pulse.

The book is arranged in eight Chapters and four sections. Chapter One covers the basic insights of the Diesel engine, including cycles, combustion mechanism, emission formation, and emission control technologies. Chapter Two focuses on the fuel injection system and strategies, providing a summary of existing research on fuel injection strategies, and an outline of the objectives. While Chapter Three focuses on the study objectives, experimental setup, procedure, engine specification, instrumentation details, vehicle details, and noise measurement schematic and method. This also shows the uncertainty analysis of the measurement. All the information provided in this chapter applies to all experimental investigations (Chapters Four to Six). Chapter Four is to assess three different multiple injection strategies at different loads and speeds. An estimation was done for soot/smoke emission, BSFC, torque, and combustion noise. Another study in Chapter Five evaluates the effectiveness of quadruple injections over triple injections with different SOI Main injection timing experimentally at wide operating conditions.

Furthermore, Chapter Six represents a comprehensive assessment of the quadruple injection strategy (epMa) over two different (pMa, eMa) triple injections at fixed main injection timing (SOI) and wide operating conditions on the Rig and vehicle level for fuel economy, emissions, and noise. Chapters Seven and Eight cover the insights of HPDI-LNG engines and the HPDI-H2 engines, as well as their fuel injection strategies and challenges. In the last chapter (Chapter Nine), the author summarises the studies and future study scope in this domain. Furthermore, a Questionnaire section is available in this book.

Sanjoy Biswas, PhD

Endorsements from Leading Industry and Academic Experts

A must-read for someone working on shaping the future of engine technologies. This book masterfully unpacks the science behind fuel injection strategies with a focus on both performance and efficiency of IC engines. From traditional diesel systems, transitioning to the latest trends in LNG and hydrogen injection techniques. Sanjoy, leveraging his research findings, captures the evolution of clean combustion with clarity and precision. Packed with insights of regulatory interventions like CAFE norms, emission control, and noise regulations, he explains how innovative fuel injection techniques help optimise engine design. It is an essential guide for powertrain engineers, researchers, and leaders pushing the boundaries of sustainable mobility.

Kishan Sreenath

VP Powertrain Engineering

Volvo Group India R&D Centre, Bangalore, India

<https://www.linkedin.com/in/kishansreenath/>

“This book is useful for both academic (Mechanical and Automobile Engineering) and the Automotive industry. This provides good insights into the modern fuel injection strategies of CI Engines.”

Manish Bakshi

Joint General Manager (JGM)

Head of Engine Testing

Sonalika, International Tractors Limited, India

<https://www.linkedin.com/in/manish-bakshi-aa3086115/>

Your book is an outstanding contribution to the field of internal combustion engine research. This book presents a comprehensive exploration of modern fuel injection strategies—ranging from conventional diesel to emerging LNG and hydrogen-based systems. Dr. Sanjoy Biswas skillfully connects academic research and industrial practice, offering an in-depth analysis of multiple injection strategies. This volume serves as an essential reference for researchers, Students, and practicing engineers working on engine combustion.

Akhilesh Shukla

Vice President – Engine Design and Development

VE Commercial Vehicle Limited, Pithampur

<https://www.linkedin.com/in/akhilesh-shukla-ba82937/>

This book by Dr. Sanjoy Biswas provides a deeper understanding of modern fuel injection strategies for diesel and HPDI (dual-fuel – LNG and Hydrogen) engines. This is a useful reference book for both automotive professionals and academic communities. Dr. Biswas has used his long experience in research and development of diesel engines to compile this extremely useful book.

Dr. Achintya Mukhopadhyay

Professor, Department of Mechanical Engineering

Jadavpur University, Kolkata

West Bengal. Pin Code: 700032, India

<https://jadavpuruniversity.in/faculty-profile/achintya-mukhopadhyay/>

“The comprehensive exploration of modern fuel injection strategies – including advanced concepts like quadruple injection, EGR-assisted combustion optimization and high-pressure direct injection (HPDI) for alternative fuels -makes this volume a timely and valuable resource for engineers, researchers and students alike.”

Dr. Ajoy Kumar Pandey

Associate Professor & Head of the Department
Department of Metallurgical & Materials Engineering
National Institute of Technology, Warangal
Warangal - 506004, Telangana State, India
<https://sites.google.com/nitw.ac.in/ajoy>

“This book has a fine blending of fundamentals related to academic and industry expertise in the domain of modern Fuel Injection system of CI engines, and it is recommended as a good reference material for Industry professionals as well as academia.”

Dr. Santanu Das

Professor and Head, Department of Mechanical Engineering
Kalyani Govt. Engineering College, Kalyani- 741235, West Bengal, INDIA
Website: <http://lnkd.in/-2tW86>, www.kgec.edu.in

“This book provides in-depth insights into modern fuel injection strategies and their impact on the performance and emissions of Diesel engines. It also provides an overview of the current trend—HPDI dual fuel technology (Diesel-LNG & Diesel-Hydrogen). This is a highly useful book for both academic courses (Mechanical and Automobile Engineering) and the automotive industry.”

Dr. Sudip Dey

Associate Professor, Department of Mechanical Engineering
National Institute of Technology, Silchar
Assam. Pin Code: 788010, India
<https://me.nits.ac.in/faculties/sudip-dey>

This book offers a comprehensive understanding of CI engine fuel injection technologies, bridging theory and application effectively. Its lucid explanations make it equally valuable for students, researchers, and practising engineers.

Dr. Sirshendu Mondal

Assistant Professor (Dept. of Mechanical Engineering)

Associate Dean (Academic) /My Homepage

NIT Durgapur, West Bengal, India

“This book will effectively bridge institutional knowledge with industry practices and contemporary research on fuel injection systems in diesel engines.”

Dr. Bijan Kumar Mandal

Professor and Former Head (Dept. of Mechanical Engineering)

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<https://www.iests.ac.in/IEST/Faculty/mech-bijan>

A well-structured and insightful volume, this book bridges theory and real-world applications of modern fuel injection strategies across Diesel, LNG, and Hydrogen engines. Dr. Sanjoy Biswas combines deep research and industrial experience to explain multiple and quadruple injection strategies, EGR-LTC, and HPDI technologies with remarkable clarity. It is a valuable resource for researchers, students, and practicing engineers working toward cleaner and more efficient powertrains.

Dr. E Vijayaragavan

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This book provides consolidated and authentic experiential knowledge related to modern fuel injection system strategies, in combination with Exhaust Gas Recirculation (EGR), of modern compression ignition engines and its implications on performance, emissions, and combustion noise, to the engineering students, researchers, and professional community in the Automotive industry. The book also covers LNG and hydrogen-based engines. In short, a must-read textbook for those aspiring to become masters of the art and science of combustion in internal combustion engines.

Dr. Pramod Sreedharan

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This book is an indispensable resource for navigating the complexities of modern automotive powertrains. It masterfully bridges foundational diesel engine and combustion fundamentals with the stringent realities of contemporary emission standards. The text provides exceptional detail on advanced control strategies, including injection strategies, exhaust gas recirculation (EGR), and the critical implementation of modern low-temperature combustion (LTC) modes. Crucially, it looks toward the future, offering timely and thorough analysis of alternative fuels and their applications, with dedicated sections on liquefied natural gas (LNG), hydrogen internal combustion engines (H₂-ICE), and direct-injection hydrogen technology. A must-read for graduate students, researchers, and practising engineers seeking a complete, forward-looking view of diesel engine and next-generation propulsion systems.

Dr. Mohamed Ibrahim M

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School of Mechanical Engineering
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“This book covers a deeper understanding of modern fuel injection strategies for automotive diesel, dual-fuel (Diesel-LNG and Diesel-Hydrogen) engines and their vital role towards cleaner emissions and higher performance. It is a nice reference book for the R&D professionals of the automotive industry and the academic community.

Dr. K.C Vora

Director at NAMTECH, Former Sr Dy Director at ARAI, Former
CEO of COEP Bhau Institute,

Chair-ASDC Expert Group on EV, Advisor-BAJA SAEINDIA;

Working on Road Safety, Hydrogen,

ACES & MET (Manufacturing Engineering Technology)

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Chapter - 2

Fuel Injection System and Available Research

2.1 Fuel Injection System

The fuel injection strategy or system and its parameters have a significant effect on the combustion mechanism, which affects the emissions and performance of DI diesel engines. A few key research areas are discussed in the forthcoming sub-sections.

2.1.1 Overview of Fuel Injection System

The previous section clearly indicates that there are two possible methods used for emission control: either by engine design changes or by treating the exhaust using after-treatment techniques. To achieve both fuel economy and emissions goals, both in-cylinder and after-treatment techniques are adopted simultaneously. Fuel injection system optimisation is an attractive technique that can improve the desired combustion process with major changes in engine design. A modern electronic fuel injection system is key to achieving the desired combustion environment, enabling combustion management to attain the required outcome. There are four types of fuel injection systems: 1. Inline (PLI), 2. Distributor or Rotary, 3. Unit injection (EUI), and 4. Common rail direct injection (CRDI). Among these, CRDI is superior. CRDI technology enables precise control over injection strategies by allowing adjustments to parameters such as injection pressure, fuel quantity, and injection timing, all of which play a critical role in managing engine combustion. A CRDI system operates at constant pressure throughout the injection period, with control of injection timing independent of engine speed. A common rail injection system comprises a high-pressure supply pump, common rail injectors, fuel metering, various sensors, and an ECM/ECU (Electronic Control Module/Unit) to map and control the different engine components, as shown in Fig 2.1. A typical common rail system and high-pressure pump are shown in Fig 2.2.

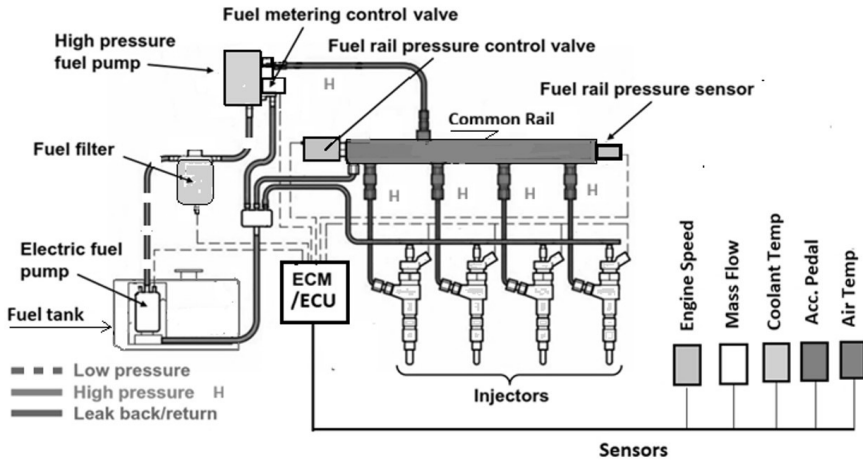


Fig 2.1:- Schematic of Common Rail Diesel Fuel Injection System

The inline and distributor (rotary) types are the most common and conventional fuel injection systems (PLI - Pump Inline Injector) of DI diesel engines. These types of systems generate fuel pressure for each injection repeatedly. In the case of a unit injection system, the pump and nozzle are combined in a single housing. Each cylinder is provided with one of these injectors. Fuel is brought up into the injector using a low-pressure pump, and the rocker arm activates the plunger at the proper time so that fuel is injected into the cylinder. In CRDI, Fuel injection pressure is not dependent on engine speeds like other types of injection systems.

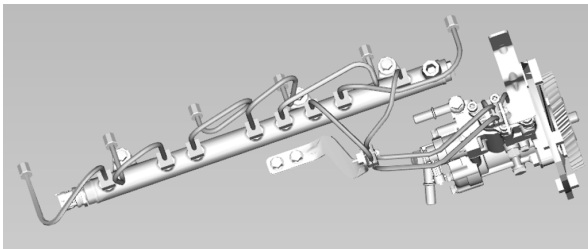


Fig 2.2: Typical Common Rail and high-pressure fuel pump

The increase in Fuel injection pressure enhances the atomisation quality and air entrainment in the combustion process, and as a consequence, there is an enhancement in fuel consumption level and a reduction in soot formation. However, it increases the injection

rate as well, which ultimately increases the rapid burning premixed combustion phase. This leads to an increase in NO_x emissions and high peak pressure inside the combustion chamber, which is transformed into high combustion noise. Primarily, a common rail direct injection system has the following injection parameters.

1. Fuel Injection Pressure (FIP) - Modern days suitable up to 300 MPa
2. Injection timing (SOI, Dwell, Energising time)
3. Injector parameters like nozzle hole diameter, position, and number of holes
4. Injection rate shaping
5. Number of injection pulses (single/Multiple/Split injection)

The design of injectors is very important for the better performance of engines equipped with the CRDI fuel system. Modern diesel engines have long relied on two main types of injectors to ensure precise fuel delivery. This ensures precise delivery of fuel with correct quantity, duration, pressure, and timing. In modern days, Fuel Injectors are electronically controlled, especially for the CRDI. It is classified as a solenoid-type and a piezoelectric-type (Piezo) based on the actuation mechanism. Solenoid injectors are the most used injectors. Piezo injectors are considered the next generation of diesel fuel delivery systems.

Table 2.1: Modern Injectors for CRDI Diesel Engines

Solenoid Injectors	Piezoelectric injectors
1. It relies on an electromagnetic coil/plunger to open and close the injector, allowing fuel spray into the combustion chamber.	1. It uses a stack of crystals that expands and contracts when an electric charge is applied and controls fuel delivery.
2. Proven Technology and Cost-effective	2. Advanced technology and costly
3. It can work on moderate pressure and robust	3. Can work at very high pressure
4. Moderate speed of operation and precision	4. Faster and more precise.
5. Operational noise	5. No operational noise

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