International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 10 Issue 5, Sep-Oct 2026 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Study of Electronically Controlled Optimized Direct Injection Systems and Modeling of Injection Systems

Lelo Mwanda Gloire[1,2], Lema Nkwalu Blaise[3], Ngakanga Mukumu Donatien[4], Makengo Lutimba Hubert[5]

[1]Department of Mechanical Engineering, Institute Supérieur de Techniques Appliquées (ISTA), Kinshasa, DR Congo
[2,3,4]Department of Physics and Applied Sciences, Faculty of Science and Technology, Université Pédagogique Nationale (UPN), Kinshasa, DR Congo
[5]Department of Mechanical Engineering, Faculty of Polytechnics, Université de Lubumbashi (UNILU), DR Congo

ABSTRACT

The study of electronically controlled optimized direct injection systems focuses on improving the performance of internal combustion engines through electronic management of fuel injection. Modern systems use sensors, Electronic Control Units (ECUs), and actuators to precisely control the amount of injected fuel, the injection timing, and the injection pressure. This optimization makes it possible to reduce fuel consumption, limit pollutant emissions, and improve engine efficiency.

The modeling of injection systems consists of representing their operation mathematically and numerically in order to analyze their behavior and predict their performance. Simulation software such as MATLAB/Simulink and AMESim is commonly used to study injection dynamics, common-rail pressure, and the electronic control of fuel injectors.

KEYWORDS: *Direct injection, electronic control, electronic fuel injection, internal combustion engine, Common Rail system, modeling, simulation, MATLAB/Simulink, AMESim.*

How to cite this paper: Lelo Mwanda Gloire | Lema Nkwalu Blaise | Ngakanga Mukumu Donatien | Makengo Lutimba Hubert "Study of Electronically Controlled Optimized Direct Injection Systems and Modeling of Injection Systems" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-10 | Issue-5, October 2026, pp.60-69, URL: www.ijtsrd.com/papers/ijtsrd142198.pdf

IJTSRD142198

1. INTRODUCTION

L'évolution des moteurs diesel poids lourds impose aujourd'hui des exigences élevées en matière de performances, de consommation de carburant et de réduction des émissions polluantes. Dans ce cadre, les systèmes d'injection directe à commande électronique occupent une place essentielle dans l'optimisation du fonctionnement des moteurs modernes. Le camion Mercedes-Benz Actros est réseau pour intégrés des technologies avancées de gestion électronique du moteur afin d'améliorer le rendement énergétique et la fiabilité du système d'injection [1].

Unlike older mechanical systems, electronically controlled direct injection allows precise control of injection timing and pressure in the common rail (Common Rail). This precision promotes better combustion, lower specific fuel consumption, and a significant reduction in pollutant gas emissions.

However, despite these advantages, several difficulties persist in the operation of heavy-duty diesel engines: excessive fuel consumption, power losses, injector malfunctions, injection delays, and increased maintenance costs. These problems may be related to poor synchronization of electronic parameters, component wear, or inadequate management of the injection system.

To address these challenges, this study focuses on modeling an electronically controlled optimized direct injection system applied to the Mercedes-Benz Actros. The objective is to develop a model capable of improving injection accuracy and overall engine performance through optimized electronic management [2].

This research also aims to analyze the operation of the electronic injection system, identify the parameters influencing engine performance, and propose an optimization strategy to achieve a better compromise between power, fuel consumption, and compliance with environmental standards.

Thus, modeling the system will not only provide a better understanding of the interactions between the various electronic and mechanical components of the engine, but will also contribute to improving the powertrain technologies used in modern industrial vehicles.

Improving diesel engine performance is currently a major challenge in the field of industrial vehicles. Manufacturers seek to develop injection systems capable of ensuring more efficient combustion while reducing fuel consumption and pollutant emissions.

From this perspective, the electronically controlled direct injection systems used on the Mercedes-Benz Actros represent an advanced technology that enables precise control of engine operation. However, despite the performance offered by these systems, several difficulties remain in their operation, including efficiency losses, excessive fuel consumption, excessive smoke emissions, and malfunctions related to injectors and electronic sensors [3].

These anomalies may be caused by poor synchronization of injection parameters, pressure variations in the fuel circuit, or defects in electronic engine management. In addition, the complexity of electronically controlled systems makes their diagnosis and optimization more difficult. Poor management of injection parameters directly affects combustion quality.

Our general objective is to model and optimize an electronically controlled direct injection system applied to the Mercedes-Benz Actros in order to improve fuel injection accuracy and engine parameters.

Notre étude est constituée des objectifs spécifiques suivants :

A. permettre un meilleur contrôle du débit et du moment d'injection du carburant dans le moteur du Mercedes-Benz Actros ;
B. optimiser des paramètres d'électrocommande et améliorer la qualité de la combustion et les performances du moteur diésel ;
C. correctly model the injection system to facilitate the detection of efficiency losses and engine malfunctions.

To achieve the stated objectives, we will use the analytical method, which consists of an in-depth study of the operation of the Mercedes-Benz Actros electronically controlled direct injection system.

2. PRINCIPE DE L'INJECTION DIRECTE

Direct injection differs from conventional systems in that the fuel is injected directly into the engine cylinder. The fuel is atomized under high pressure into fine droplets, which promotes better combustion. The air-fuel mixture is formed directly in the combustion chamber, improving energy efficiency [4].

ELECTRONIC CONTROL IN INJECTION SYSTEMS

2.1. Definition

Electronic control refers to all electronic devices that operate and control fuel injection in an engine (gasoline or diesel). It relies on an engine control unit (ECU), sensors (temperature, pressure, engine speed, etc.), and actuators (injectors, high-pressure pump) [5].

2.2. Operation

The control unit receives information from the sensors and determines the amount of fuel to inject, the precise injection timing, and the required pressure. The electrically controlled injectors execute these commands with high precision.

2.3. Système Common Rail

This system uses a high-pressure common rail that supplies all injectors. It provides high precision and flexibility in injection control [6].

2.3.1. Injecteurs modernes

A. Electromagnetic injectors;
B. Piezoelectric injectors (faster and more precise).

2.3.2. Avantages

A. Haute précision d'injection ;
B. Réduction de la consommation de carburant ;
C. Diminution des émissions polluantes ;
D. Improved engine performance;
E. Better adaptation to environmental standards.

2.3.3. Inconvénients

A. High component cost;
B. Sensitivity to fuel impurities;
C. Maintenance complexity.

2.4. Le système Common Rail (rompe commun)

Used in diesel engines, the system relies on basic physical relationships, particularly those involving pressure, flow rate, and fuel injection. The following equations are important for understanding its operation [7].

2.4.1. Pression dans la rampe

Pressure is a key element of the system:

$$P = \frac{F}{S} \qquad (2.1)$$

- P= pression du carburant (Pa)
- F=force exerce par la pompe (M)
- S = surface (m²)

In a Common Rail system, pressure can reach 1,000 to 2,500 bar.

2.4.2. Débit d'injection (la de Bernoulli simplifiée)

$$Q = Cd.A\sqrt{\frac{2.\Delta.P}{\varphi}} \qquad (2.2)$$

Q = fuel flow rate (m³/s)
Cd = discharge coefficient (0.6–0.9)
A = injector orifice area
P = pressure difference (rail–chamber)
φ = densité du carburant

The higher the pressure, the more finely the fuel is atomized.

3. LA MODELISATION DES SYSTÈMES D'INJECTION

Modeling injection systems is an essential step in the development of modern engines. It consists of mathematically and computationally representing the operation of the injection system in order to analyze, simulate, and optimize its performance. With the evolution of automotive technologies, particularly direct injection and electronically controlled systems, modeling provides a better understanding of physical phenomena and helps improve key parameters of the injection system. For the Mercedes Actros L, the parameters that directly influence pollution are injection pressure and injection timing. These elements are managed by the engine control unit [8]:

A. Poor injection pressure: pressure that is too low prevents fine atomization of the fuel. This results in poor combustion and increased emissions of fine particles (black smoke).

B. Injection timing: the precise moment at which fuel is injected into the cylinder. If it is incorrectly adjusted, it can generate excess NOx (nitrogen oxides) or unburned fuel.

C. AdBlue injector (SCR system): The Actros L uses the BlueTec system. The AdBlue injector sprays urea into the exhaust to transform NOx into water vapor and nitrogen. If it is clogged or faulty, the truck emits significantly more pollutants and often enters limp-home mode.

Pour la Mercedes Actros L, le principal paramètre du système d'injection qui influence la pollution est le calibrage du débit et de la pression d'injection, géré par le calculateur. Une pression trop basse ou des injecteurs usés pulvérisent mal le carburant, entraînant une hausse des particules fines et des oxydes d'azote (NOx).

Other components associated with the injection and emissions-control systems have a major impact on emissions:

A. AdBlue dosing (SCR system): The dosing module injects urea into the exhaust. If the injection parameter for this fluid is incorrect (or the system is disabled), NOx are no longer removed and are released into the air.

B. Exhaust gas recirculation (EGR valve): This system recirculates part of the burned gases into the intake to cool combustion and reduce NOx. A clogged valve drastically increases pollution.

C. Fuel quality: the use of poor-quality fuel (common in some regions) rapidly contaminates the injectors (often unit-pump injectors on the Actros), causing incomplete combustion and high black-smoke emissions.

The injection pressure of Mercedes Actros L engines (equipped with OM 471 or OM 473 engines) reaches up to 2,700 bar (2,500 bar on early versions) thanks to the X-Pulse high-pressure common-rail injection system. The X-Pulse architecture amplifies the basic common-rail pressure (approximately 900 to 1,160 bar) to ensure ultra-fine atomization [9].

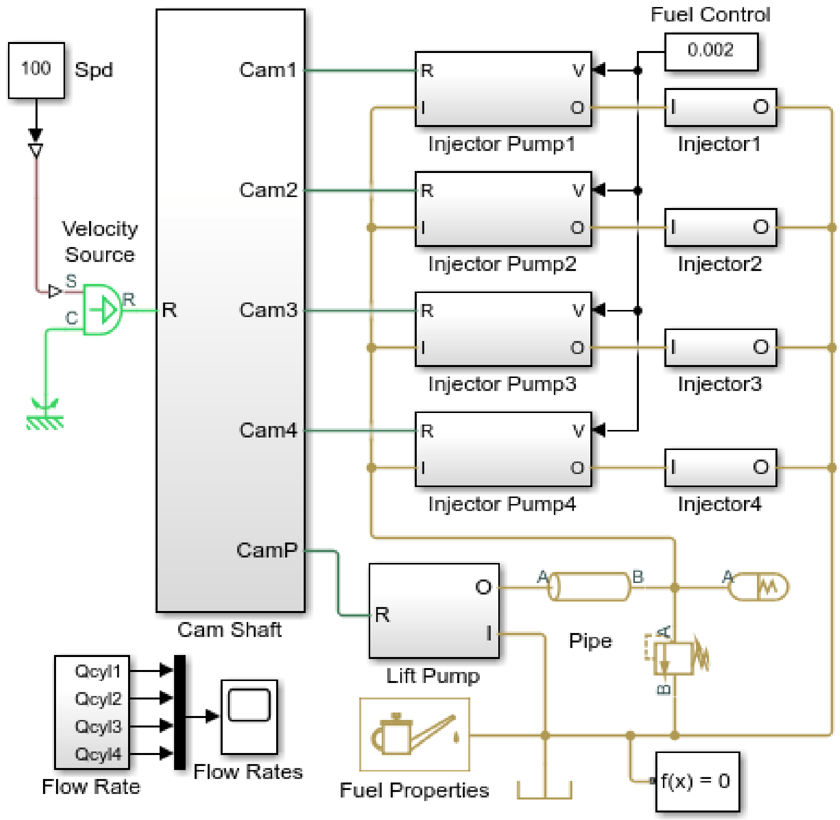

Fig. 3.1: Model of the injection system of Mercedes Actros L engines in MATLAB.

Figure 3.1 presents the numerical model developed in MATLAB/Simulink to represent the operation of the X-Pulse high-pressure Common Rail injection system fitted to Mercedes Actros L engines. This model reproduces the dynamic behavior of the injection pump, injectors, and fuel flow in the supply circuit. The model makes it possible to simulate the hydraulic phenomena occurring between the high-pressure pump and the injectors. The different blocks represent the physical subsystems of the circuit:

- the injection pump;
- the fuel lines;
- the injectors;
- the pressure sensors;
- the control actuators.

This architecture makes it possible to study the influence of operating parameters on:

- injected flow rate;
- injection pressure;
- atomization quality;
- specific fuel consumption;
- pollutant emissions.

The model therefore constitutes a tool for analyzing and optimizing the diesel engine injection system.

3.1. Fine Particles (PM)

Soot formation (Particulate Matter) depends on the air-fuel ratio. Mathematically, particle mass is modeled by an exponential law as a function of injection pressure and combustion temperature (Tcomb) [10]:

$$M_{PM} = A_{PM} \cdot \left(P_{inj} \right)^{-n_{inj}} \cdot \exp\left(-\frac{E_a}{R \cdot T_{comb}} \right) \quad (3.1)$$

Where (APM) is a constant related to the design of the combustion chamber, and (ninj) (often between 0.5 and 1.5) represents the effect of atomization.

3.1.1. Carbon Monoxide (CO)

Since CO is a product of incomplete combustion, it decreases as injection pressure allows better homogenization of the mixture. The model is written as [11]:

$$M_{CO} = \frac{C_{CO}}{P_{inj}} \cdot \exp\left(-\frac{E_{CO}}{R \cdot T_{comb}} \right) \quad (3.2)$$

3.1.2. Nitrogen Oxides (NOx)
NOx formation is governed by the extended Zeldovich mechanism and requires a high combustion temperature (> 1800 K). Since increasing injection pressure promotes this phenomenon, the emission rate is modeled by:

$$M_{NOx} = K_{NOx} \cdot (\ P_{inj}\ )^{m_{inj}} \cdot (O_2)^{\beta} \cdot \exp\left(-\frac{E_{NOx}}{R \cdot T_{comb}} \right) \quad (3.3)$$

Where (minj) is the exponent representing the impact of fine atomization on local temperature (often positive), (O2) is the oxygen concentration in the cylinder, and (ENOx) is the activation energy of the NOx formation reaction.

3.2. Simulation
Figure 3.2 shows the time evolution of the position of the pump-injector assembly and the volumetric flow rate of injected fuel during an operating cycle.

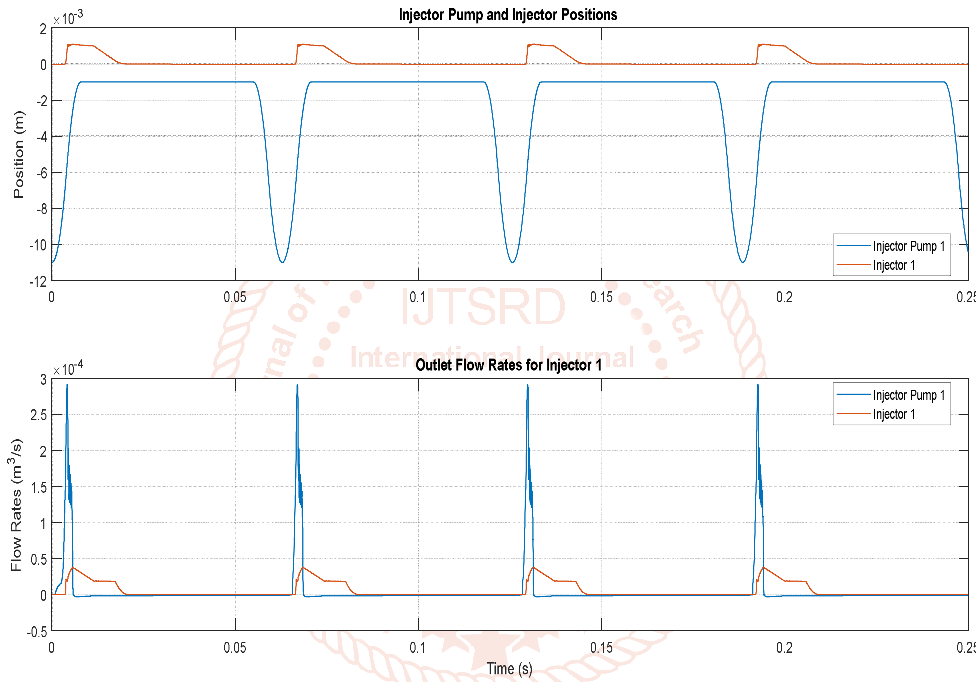

Fig. 3.2 : Position et débit du combustible du système d'injection des moteurs Mercedes Actros L.

3.3. Interpretation
3.3.1. Pump and Injector Position
The first curve represents the displacement of the injection-pump actuator.

The following can be observed:
- periodic motion;
- oscillations synchronized with the engine cycle;
- a relatively small amplitude corresponding to the mechanical movement of the system.

These variations reflect the successive opening and closing of the injectors.

3.3.2. Fuel Volumetric Flow Rate
The second curve represents the injected fuel flow rate.

The following can be observed:
- a rapid increase in flow rate when the injector opens;
- a peak corresponding to the main injection phase;
- a gradual decrease during closing.

This behavior confirms the typical pulsed operation of modern Common Rail systems.

The stability of the flow-rate peaks indicates good regularity of the injection system.

Figure 3.3 shows the evolution of pump plunger extension as a function of cam rotation angle.

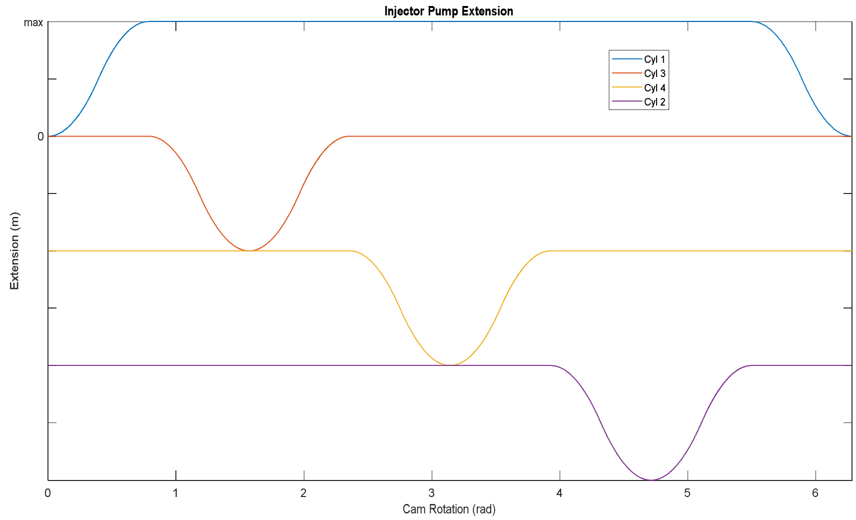

Fig. 3.3: Timing of each injection pump as a function of cam rotation.

The four curves correspond to the four simulated cylinders.

It can be noted:
- an angular offset between the cylinders;
- sequential activation of the injectors;
- identical periodicity for each cylinder.

This distribution ensures:
- regular combustion;
- engine torque balance;
- reduced vibration.

The observed phase shift confirms that the injection order is correctly reproduced in the model.

Figure 3.4 presents the main dynamic parameters of the injector:
- number of zero crossings;
- dynamic opening area;
- instantaneous flow rate;
- pressure drop.

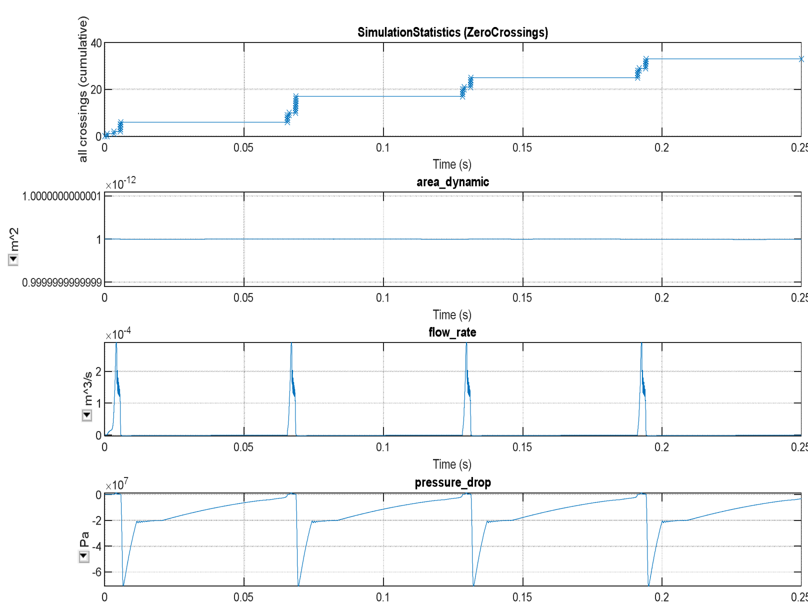

Fig. 3.4: Actuation period, dynamic area, fuel flow rate, and injection pressure for each injector.

3.3.3. Zero Crossings
The cumulative number of zero crossings increases progressively.

This indicates:
- normal dynamic activity;
- good numerical convergence of the model;
- the absence of significant instability.

3.3.4. Dynamic Opening Area
The dynamic area remains close to:

$$1\times(10^{-12})m^2$$

This value represents the effective opening of the injection orifice.

Its stability shows that the injector operates consistently.

3.3.5. Fuel Flow Rate
The flow rate reaches values on the order of:

$$2\times(10^{-4})\ m^3/s$$

These values are consistent with a high-pressure injection system.

The flow rate directly follows the evolution of injector opening.

3.3.6. Pressure Drop
Pressure drops momentarily during the injection phases.

This decrease is normal because:
- fuel leaves the common rail;
- part of the hydraulic energy is converted into the kinetic energy of the jet.

The pressure nevertheless remains high enough to ensure proper fuel atomization.

3.4. Injector 1
Figure 3.5 shows the time evolution of:
- mass flow rate;
- volumetric flow rate.

These parameters directly determine the amount of fuel injected into the combustion chamber.

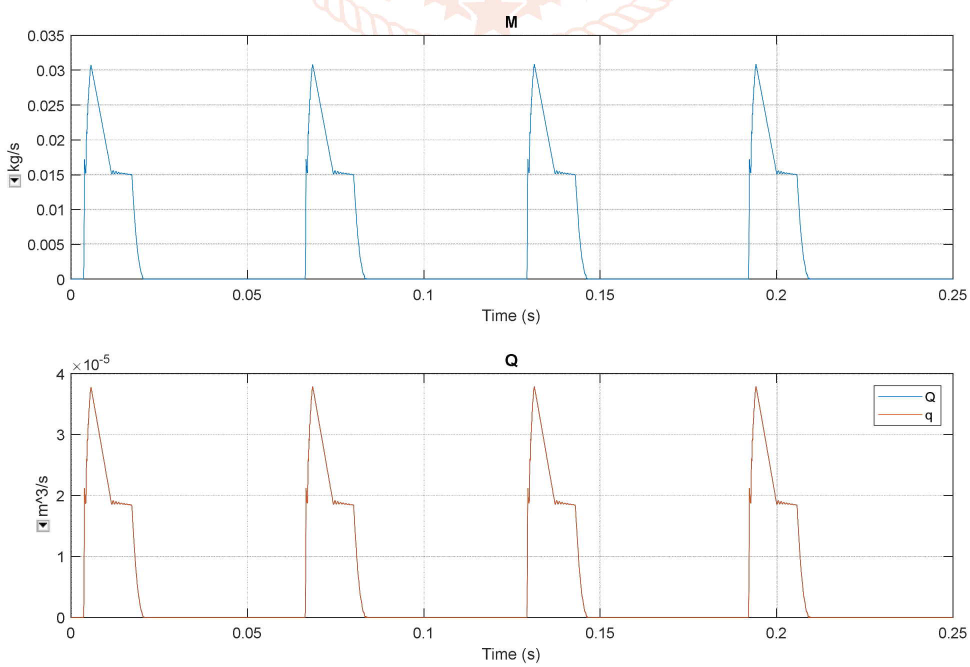

Fig. 3.5: Mass and volumetric fuel flow rate of each injector.

3.4.1. Interpretation
3.4.1.1. Mass Flow Rate
The mass flow rate reaches approximately:

$$0{,}035 \text{ kg/s}$$

This value varies periodically according to the injection commands.

An increase in mass flow rate results in:
- ➢ an increase in engine power;
- ➢ a potential increase in fuel consumption.

3.4.1.2. Volumetric Flow Rate
The volumetric flow rate oscillates around:

$$4\times10^{-5} \text{ m}^3\text{/s}$$

The observed profile closely follows that of the mass flow rate.

This consistency confirms the validity of the continuity equations used in the simulation.

Figure 3.6 analyzes the effect of injection pressure on:
- ➢ specific fuel consumption;
- ➢ fine particles (PM);
- ➢ carbon monoxide (CO);
- ➢ nitrogen oxides (NOx).

The simulated results are compared with experimental measurements.

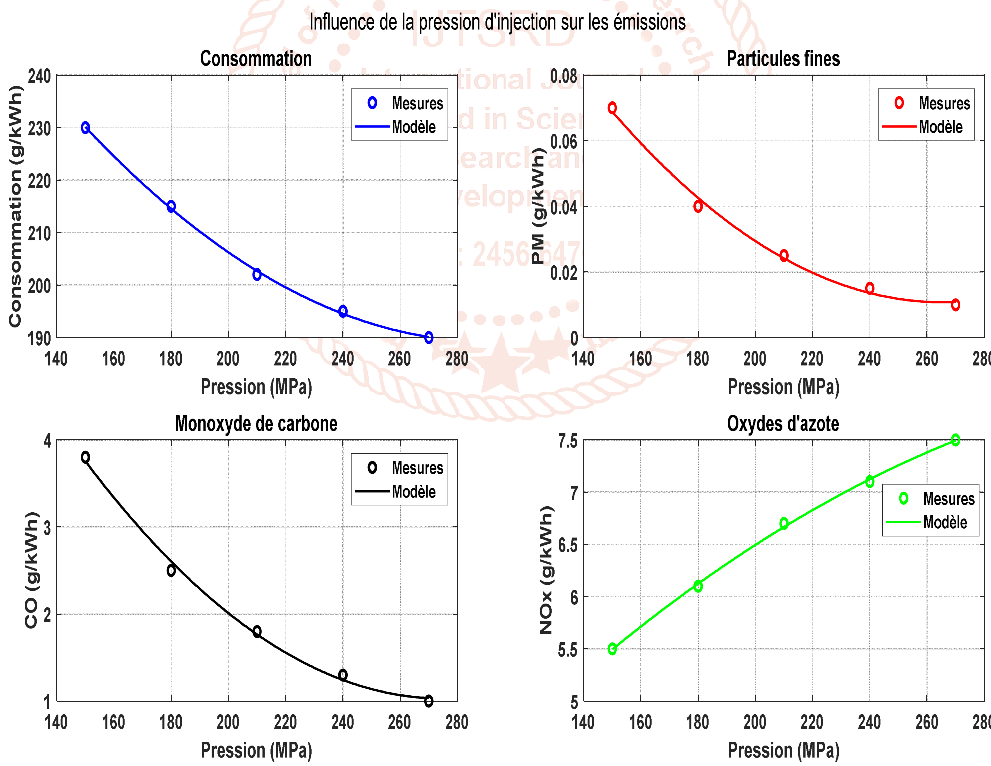

Fig. 3.6: Influence of injection pressure of the injection system of Mercedes Actros L engines on emissions.

3.4.2. Interpretation
3.4.2.1. Specific Fuel Consumption
When injection pressure increases:
- ➢ fuel consumption decreases slightly;
- ➢ combustion becomes more efficient.

Improved atomization promotes better fuel utilization.

3.4.2.2. Fine Particles (PM)
PM emissions decrease significantly with pressure.

Increasing pressure produces:
- finer droplets;
- more complete combustion;
- less soot.

3.4.2.3. Carbon Monoxide (CO)
CO decreases progressively. This decrease indicates better oxidation of the carbon contained in the fuel.

3.4.2.4. Nitrogen Oxides (NOx)
Unlike PM and CO, NOx increase slightly. This phenomenon is explained by:
- a higher combustion temperature;
- greater oxygen availability.

The results obtained are consistent with the scientific literature on Common Rail diesel engines.

Figure 3.7 summarizes the overall impact of injection pressure on the main environmental indicators of the Mercedes Actros L engine.

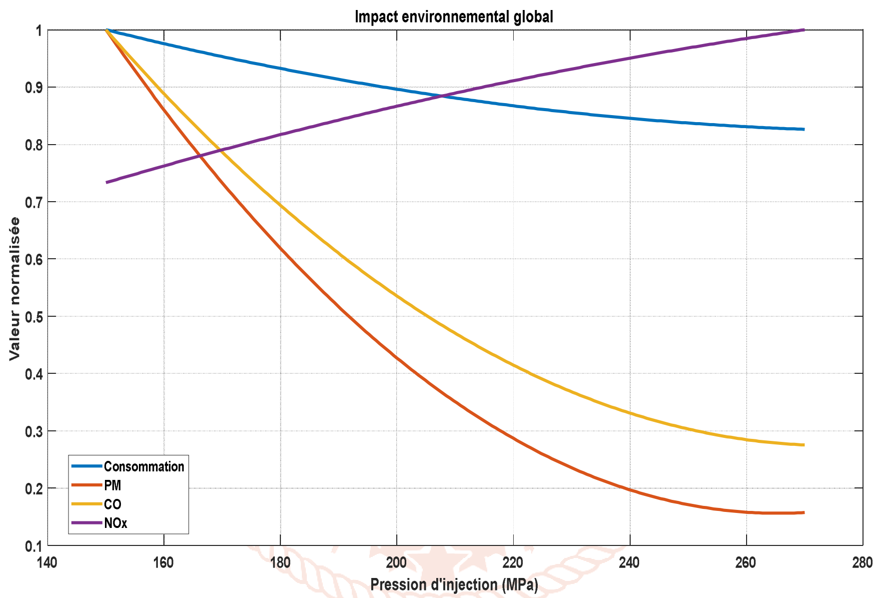

Fig. 3.7: Overall environmental impact of emissions as a function of injection pressure in the injection system of Mercedes Actros L engines.

1° Interprétation
The normalized curves show that:
- fuel consumption decreases as pressure increases;
- fine-particle emissions decrease significantly;
- CO emissions also decrease;
- NOx emissions increase slightly.

The analysis highlights a classic environmental trade-off in diesel engines:
- higher pressure improves combustion;
- it reduces smoke and CO;
- but it promotes NOx formation.

The optimal range appears to be between: 220 MPa and 250 MPa

Within this range, the following are obtained simultaneously:
- low fuel consumption;
- low PM emissions;
- low CO emissions;
- a moderate increase in NOx.

This range therefore constitutes the best technical and environmental compromise for the injection system studied.

4. CONCLUSION
The modeling shows that the electronic injection system is more efficient and more precise than the mechanical system. However, the mechanical system remains simpler and less expensive to maintain.

Technological development currently favors electronic systems because of their energy efficiency and low environmental impact. Injection-system modeling is an essential tool in modern engineering. It makes it possible to design engines that are more efficient, more economical, and more environmentally friendly. Thanks to advances in numerical simulation, engineers can now more easily predict injection-system behavior accurately and even support their manufacturing.

ACKNOWLEDGEMENTS
At the end of this work, we would like to thank all those who contributed to the preparation of this article, particularly Professor MAKENGO LUTIMBA Hubert and Professor LEMA NKWALU Blaise, whose availability and advice were invaluable.

REFERENCES

[1] Springer Vieweg, (2018). Diesel Engine Management. 5th Edition. Wiesbaden.

[2] Butterworth-Heinemann, (1999). Vehicle and Engine Technology. 2nd Edition.

[3] Robert Bosch GmbH, (2018). Automotive Handbook. 10th Edition. Stuttgart.

[4] Springer Vieweg, (2015). Common Rail System for Diesel Engines.

[5] Springer Vieweg, (2014). Fuel Injection System. 3rd Edition. Wiesbaden.

[6] Robert Bosch GmbH, (2018). Diesel Engine Management: references on modern diesel injection systems (Common Rail, injectors, sensors, ECUs).

[7] Tom Denton, (2021). Automotive Electrics and Electronics: operation of vehicle electronic systems.

[8] Wiley, (2014). Modeling and Control of Engines and Drivelines.

[9] McGraw-Hill, (2018). Internal Combustion Engine Fundamentals. 2nd Edition. New York.

[10] John B. Heywood, (2024). Internal Combustion Engine Fundamentals.

[11] SAE International, (2002). Advanced Engine Technology.