

DESIGN AND PERFORMANCE ANALYSIS OF A HYDRO-PNEUMATIC BRAKING SYSTEM FOR LIGHT PASSENGER VEHICLES

Submitted by

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ABSTRACT

Brakes are arguably the most important safety feature on any vehicle. Most everyday passenger cars use standard hydraulic brakes, which depend entirely on the physical force a driver applies to the pedal. The issue is that in an emergency, a driver's foot pressure alone might not create enough force to stop the car in time. To address this problem, this study looks at the design and analysis of a compact "hydro-pneumatic brake intensifier" specifically made for lighter vehicles like sedans. The idea is simple: the system uses compressed air to increase the existing hydraulic pressure, resulting in a much stronger clamping force at the brake callipers. The research process started with creating a detailed digital blueprint of the device using CAD software. Next, analytical calculations were performed to determine how much extra force and pressure the device could produce. To make sure the design was solid, it underwent thorough ANSYS computer simulations to assess how the components would manage internal stress, high pressures, and possible deformation. Finally, the system's real-world braking performance was tested at speeds of 80, 90, and 100 km/h. The results were very promising. The intensifier effectively raised an initial air pressure of 6 bar to about 42 bar of hydraulic pressure. This significant increase in braking power led to a noticeable reduction in stopping distances compared to a standard, unassisted braking setup. In the end, this research shows that adding a hydro-pneumatic assist is a practical and effective way to improve passenger vehicle safety.

1. INTRODUCTION

1.1 Automobile Braking Systems

When it comes to vehicle safety, the braking system is your first line of defense. Its main job is simple but relies heavily on physics. It takes the forward momentum, or kinetic energy, of your car and turns it into heat through friction. This process allows you to slow down or stop completely. Mechanically, this usually happens in one of two ways. Either brake pads clamp down hard on a spinning rotor in disc setups, or brake shoes push outward against a rotating drum in drum setups. Both methods create the strong drag needed to stop the wheels. However, a good braking system must do much more than just bring a car to a stop. To keep the driver safe, it needs to keep the vehicle stable and pointing straight. It must also prevent the tires from locking up and distribute the stopping power evenly across all four wheels. Additionally, we expect today's brakes to work perfectly in the toughest situations. Whether that means panic-braking at highway speeds, navigating slick and uneven roads, or riding the brakes down a steep hill, the system needs to handle the heat without losing its stopping power.

Classification of Automotive Braking Systems

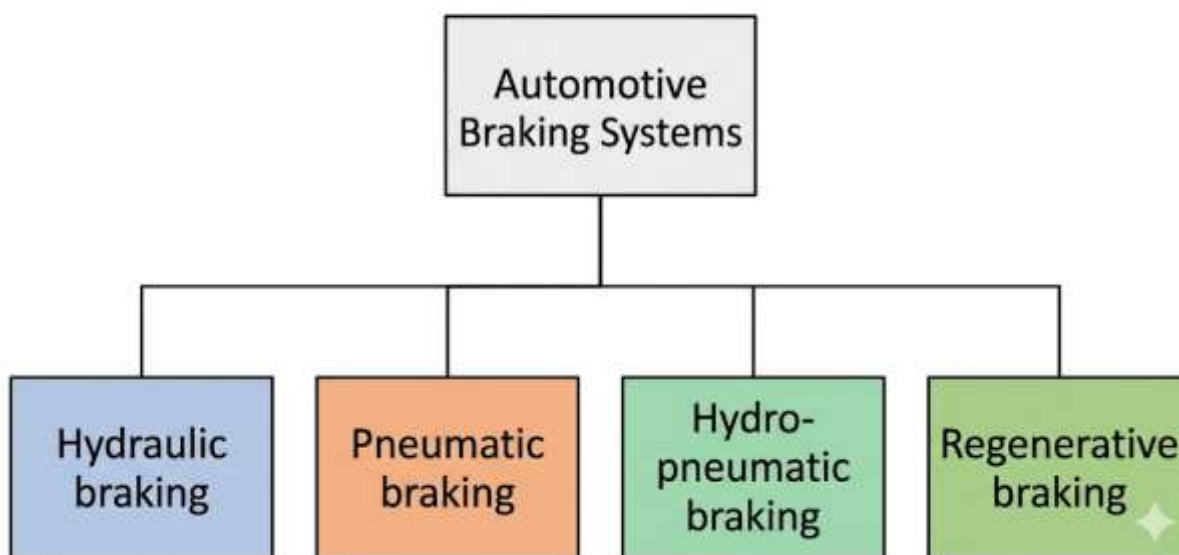


Figure 1: Classification of automotive braking system based on actuation

1.1.1 Conventional Hydraulic Braking System

Standard hydraulic brakes are the preferred option for most everyday passenger cars. They are simple, compact, and very reliable. The whole system is based on a basic physics idea called Pascal's law. This law states that when you apply pressure to a trapped fluid, that pressure spreads evenly in every direction. In a car, this creates a direct chain reaction. When you press your foot on the brake pedal, that push goes straight to the

master cylinder. The master cylinder turns your leg effort into hydraulic fluid pressure. This pressurized fluid moves down the brake lines to the calipers at each wheel. There, it pushes the internal pistons outward, squeezing the brake pads tightly against the spinning rotors. The friction created is what finally slows the car down. While hydraulic systems provide a smooth and predictable stop during regular driving, they do have limitations. Their stopping power is directly linked to the system's maximum pressure limit and, more importantly, to how hard the driver can push the pedal. If you are driving fast and need to stop suddenly, you have to push the pedal with a lot of force. Relying solely on the driver's leg strength in an emergency isn't always ideal. It can slow down response times and make braking feel heavy and hard to control.

Schematic Layout of Conventional Hydraulic Braking System

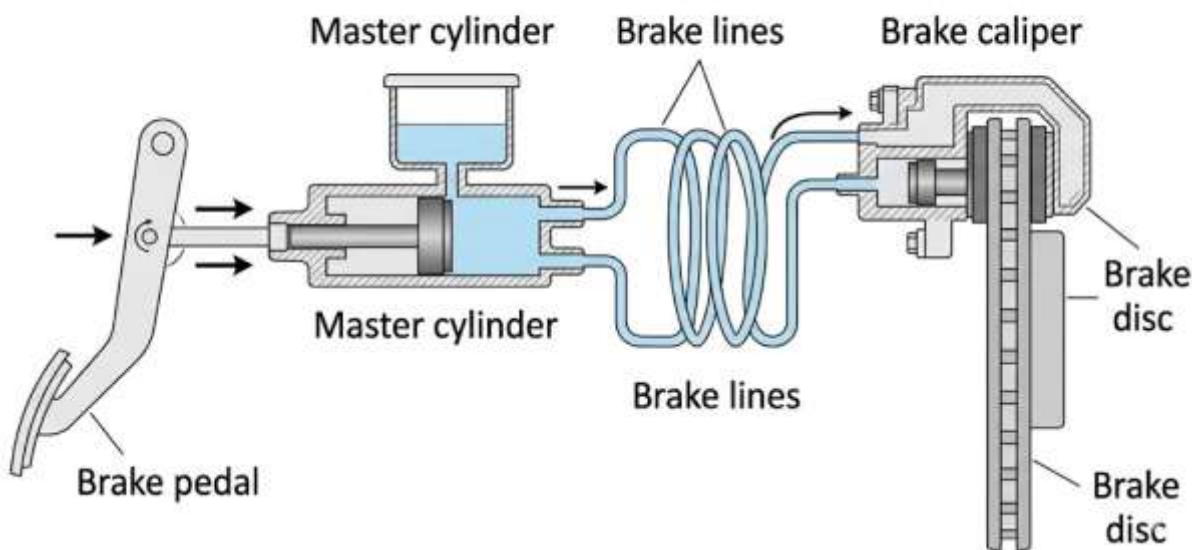


Figure 2: Schematic layout of conventional hydraulic braking system

1.1.2 Pneumatic Braking System

Unlike hydraulic setups that use fluid, pneumatic brakes rely entirely on compressed air to get the job done. You will almost exclusively find this type of system on heavy-duty vehicles like commercial trucks, buses, and trailers. Because these vehicles carry massive loads, they require a serious amount of stopping power that standard fluid-based systems simply cannot provide.

The mechanics behind it are fairly straightforward: an onboard air compressor constantly packs air into heavy-duty storage tanks. When the driver steps on the brake pedal, a series of control valves open up, sending that highly pressurized air directly into the brake chambers. From there, the air pressure physically forces the brake hardware against the wheels to stop the vehicle.

Air brakes bring some major benefits to the table. They generate incredible braking force, manage heat extremely well, and feature a brilliant built-in safety net: if the system ever springs a leak and loses air pressure, spring-loaded brakes automatically lock up to safely halt the vehicle.

However, all this heavy-duty performance comes with a catch. Pneumatic systems are incredibly bulky, packed with extra components, and require a strict maintenance schedule. Because of their sheer size and mechanical

complexity, they just aren't practical for standard passenger cars, where saving space and keeping things simple are top priorities.

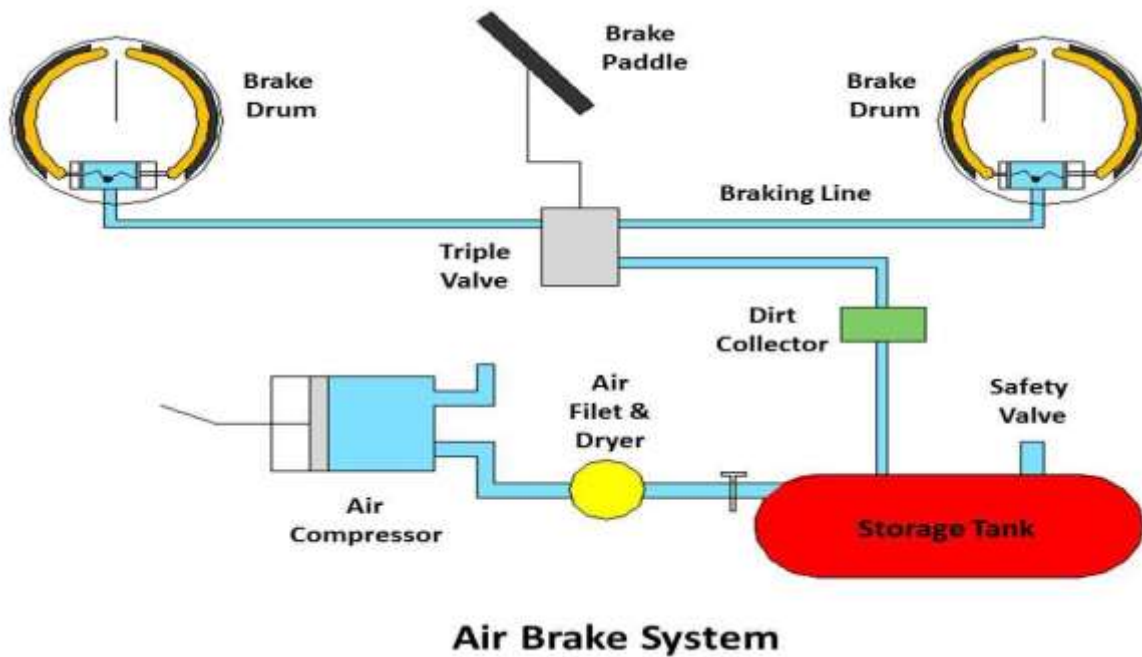


Figure 3: Schematic layout of pneumatic braking system

1.2 Hydro-Pneumatic Braking System

Hydro-pneumatic braking systems offer a clever middle ground, blending the strongest features of both air-based and fluid-based brakes. The secret to this setup is a device known as a hydro-pneumatic intensifier, which essentially uses a burst of compressed air to supercharge the system's overall hydraulic pressure.

The internal mechanics rely on a simple but highly effective trick of physics using two different-sized pistons. Inside the intensifier, there is a large piston driven by air pressure and a much smaller piston that pushes the hydraulic fluid. When compressed air forces the large piston forward, it generates a massive amount of physical push. All of that energy is then concentrated directly into the smaller hydraulic piston. Because all that force is being squeezed into a smaller area, it acts like a multiplier, causing a huge spike in fluid pressure.

When this highly pressurized fluid finally reaches the wheel calipers, it forces the brake pads to clamp down on the rotors with significantly more bite. For the driver, this means experiencing heavy-duty stopping power without having to mash the brake pedal to the floor. Beyond the obvious performance boost, one of the biggest advantages of this setup is its footprint. The intensifier is surprisingly compact and can easily piggyback onto a vehicle's existing hydraulic framework, making it a highly practical and efficient safety upgrade for standard passenger cars.

Conceptual Diagram of Hydro-Pneumatic Braking System

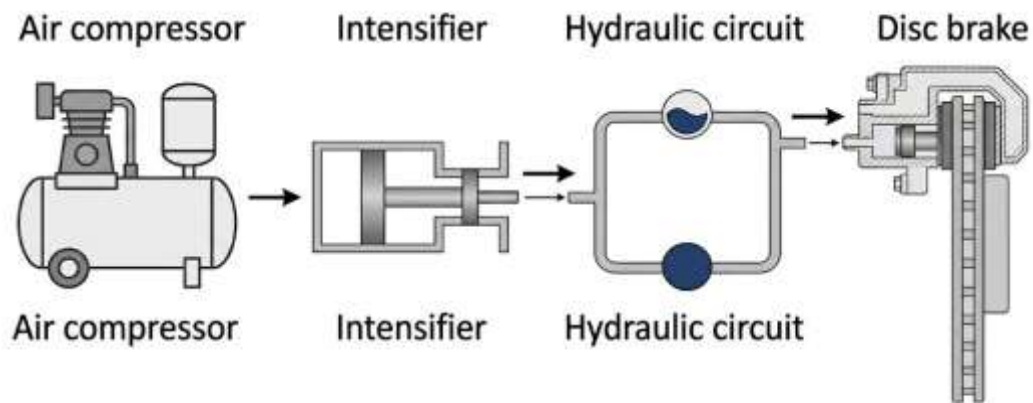


Figure 4: Schematic layout of hydro pneumatic braking system

1.3 Need for Hydro-Pneumatic Braking System

As automotive technology evolves and everyday vehicles become capable of higher speeds, engineering brakes that can safely keep up is a tougher—yet more vital—challenge than ever. While standard hydraulic brakes are undeniably dependable, they have a noticeable weak point during high-speed emergencies: they rely completely on the physical strength of the driver. If the driver cannot push the pedal hard enough in a panic situation, the car takes longer to stop, which seriously compromises safety.

On the flip side, full air-brake systems pack massive stopping power, but they are far too bulky, complex, and expensive to squeeze into a standard passenger car. This creates an obvious engineering gap for a middle-ground solution—something that delivers heavy-duty power but still fits into a compact space.

Hydro-pneumatic braking fits this exact niche perfectly. By acting as an add-on power booster, this hybrid setup multiplies the system's pressure without forcing the driver to stomp harder on the pedal. Ultimately, it provides a much sharper braking response and drastically shortens stopping distances, giving drivers a critical safety margin when they need it most.

2. PROBLEM STATEMENT

Standard hydraulic brakes have one major bottleneck: they rely completely on the physical strength of the driver's leg. When a vehicle is traveling at high speeds, bringing it to a safe halt requires a massive amount of stopping force. The problem is that a purely hydraulic setup cannot simply generate extra pressure on its own without demanding a much heavier push on the brake pedal.

This becomes a critical safety issue during emergency scenarios. In a sudden panic, drivers often fail to press the pedal hard enough to max out the system's braking pressure. Because of this, the car travels further before finally coming to a stop, severely compromising its overall braking efficiency.

While heavy-duty air brakes (pneumatic systems) could easily provide that missing power, they are far too massive and mechanically complex to cram into a standard passenger car. What everyday vehicles really need is a compact "helper" mechanism—something that substantially boosts stopping power without forcing engineers to scrap the reliable hydraulic setups already in use.

That is exactly the problem this study sets out to solve. By designing a specialized hydro-pneumatic brake intensifier, this research demonstrates how a burst of compressed air can be used to massively multiply hydraulic fluid pressure. Ultimately, the goal is to drastically shorten stopping distances and deliver superior braking performance, all while keeping the vehicle's underlying braking system simple and practical.

3. OBJECTIVES OF THE STUDY

The main objectives of this research are as follows:

1. To design a compact hydro-pneumatic brake intensifier suitable for light passenger vehicles such as sedans.
2. To develop a detailed CAD model of the intensifier assembly including the cylinder body, piston, piston rod, end caps, and hydraulic chamber.
3. To perform analytical calculations to determine the output force generated by the pneumatic piston and the hydraulic pressure amplification achieved by the intensifier.
4. To analyze the structural integrity of the intensifier components using finite element simulation in ANSYS.
5. To evaluate braking performance by calculating brake torque and stopping distance at different vehicle speeds.
6. To compare the braking performance of the proposed hydro-pneumatic system with conventional hydraulic braking systems.
7. To demonstrate the feasibility of implementing hydro-pneumatic assisted braking as a supplementary braking system for passenger vehicles.

4. LITERATURE REVIEW

A vast amount of engineering research has been dedicated to upgrading vehicle braking systems, but historically, the bulk of this work has focused heavily on commercial or heavy-duty applications. For instance, Salvi et al. (2014) successfully tested a hydro-pneumatic ABS setup specifically designed for heavy off-road military vehicles, proving that blending air and fluid mechanics can drastically improve stability in extreme environments. Taking a similar heavy-duty approach, Choi et al. (2016) explored air-over-hydraulic systems to sharpen the braking reflexes of commercial trucks. At the same time, researchers like Li et al. (2020) and Ji (2010) have taken deep dives into the diagnostic side of pneumatic brakes, using advanced digital simulations and mathematical models to predict valve failures and improve the system's overall reliability.

As the automotive industry shifts toward smarter, electrified platforms, another major wave of research has focused on highly complex electronic and hybrid braking architectures. Jang et al. (2018) and Kim et al. (2015) explored electro-hydro-mechanical systems, aiming to smooth out the driver's pedal feel while guaranteeing rapid, stable stops for passenger cars. Other studies have specifically targeted the unique challenges of electric and hybrid vehicles; for example, Peeie et al. (2016) integrated hydraulic-mechanical setups with regenerative braking to prevent skidding, while Zhang et al. (2021) and Lin et al. (2019) developed advanced software control strategies to balance fierce ABS performance with energy efficiency.

When looking at the raw mechanics of how these systems generate power, the divide between air and fluid is well-documented. Wang et al. (2016) explicitly compared the two actuators, confirming that while pneumatic systems easily win on sheer brute force, hydraulics offer far superior control and precision. Furthermore, researchers like Chu and Ou (2017) have analyzed the subtle intricacies of pressure change rates within hydraulic ABS control blocks to further optimize this precision.

However, looking at the broader scope of this research reveals a glaring gap. While the engineering world has plenty of data on massive air brakes for commercial trucks and highly complex electronic setups for modern EVs, very little work has attempted to scale down hydro-pneumatic technology for standard, everyday passenger cars.

This project is designed to bridge that exact divide. By stepping away from the massive footprint of commercial systems and the dizzying complexity of electro-mechanical setups, this research focuses on engineering a simple, highly compact hydro-pneumatic brake intensifier. Backed by rigorous mathematical calculations and digital simulations, this study aims to prove that everyday light vehicles can safely harness the pressure-multiplying power of compressed air without requiring a complete mechanical overhaul.

5. METHODOLOGY

5.1 Working principle of hydro pneumatic Intensifier

At its core, the hydro-pneumatic braking system is a hybrid solution. By merging the raw pushing power of compressed air with the smooth, direct energy transfer of hydraulic fluid, this setup takes passenger vehicle braking to the next level.

How the Process Works The system relies on a fairly straightforward chain reaction involving an air chamber, a large pneumatic piston, a connecting rod, a smaller hydraulic chamber, and the wheel calipers. Here is the step-by-step breakdown:

1. **Air Input:** When activated, pressurized air floods into the intensifier's main pneumatic chamber.
2. **Physical Push:** This air pressure pushes hard against the large surface area of the pneumatic piston.
3. **Fluid Compression:** That forward momentum is transferred directly down a connecting rod into the hydraulic chamber. Because brake fluid cannot physically be compressed, the physical push is instantly converted into intense hydraulic pressure.
4. **The Final Stop:** This highly pressurized fluid shoots down the brake lines to the calipers, forcing the brake pads to bite down violently on the spinning brake rotors. The resulting friction is what drags the vehicle to a halt.

The Multiplier Effect The true genius of the intensifier is how it acts as a mechanical power multiplier. The entire device works on Pascal's law, utilizing a massive air piston driving a much smaller hydraulic piston. Because all the force collected by the large air piston is funneled into the tiny surface area of the fluid piston, the resulting hydraulic pressure is exponentially higher than the initial air pressure that started the process.

A Built-In Safety Net Beyond raw stopping power, this hybrid design features a fantastic built-in failsafe. In a standard car, a ruptured line or total loss of hydraulic fluid means you completely lose your brakes. However, with a hydro-pneumatic setup, the pneumatic side of the system can still physically push the braking hardware to engage even if the fluid pressure drops. This redundancy provides a critical backup layer of safety during severe mechanical failures.

Summary of Upgrades Ultimately, adding this intensifier as a supplementary system offers several massive upgrades for everyday passenger cars, especially at highway speeds. The major benefits include:

- A massive boost in overall braking force.

- A much lighter, more comfortable feel at the brake pedal for the driver.
- The ability to mathematically multiply braking pressure.
- Noticeably shorter, safer stopping distances.
- A reliable mechanical backup in the event of hydraulic failure.

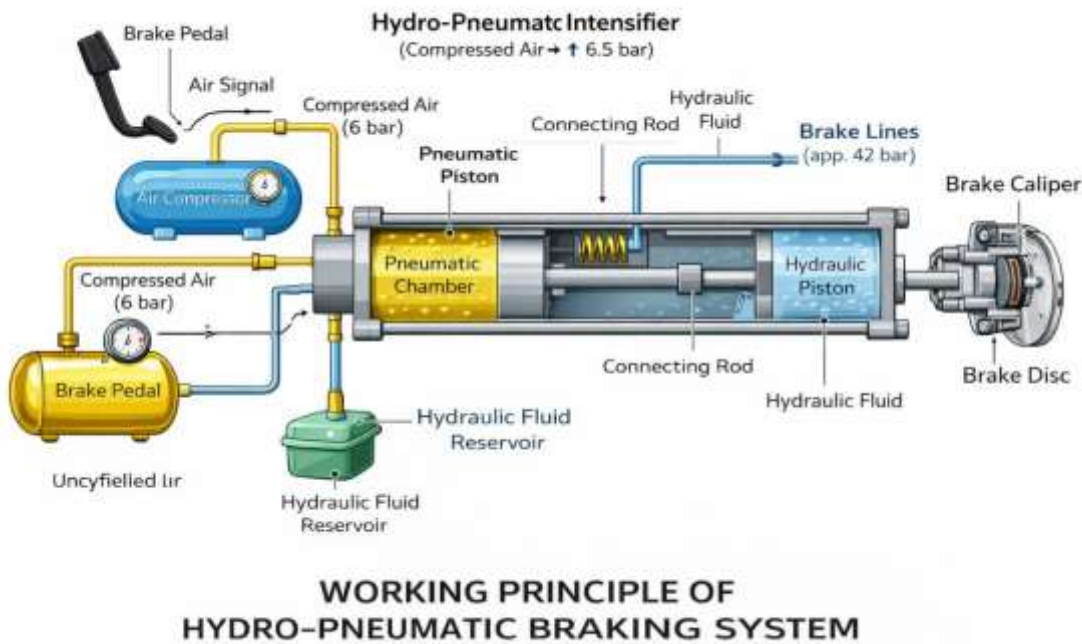


Figure 5: Working Principle of Hydro pneumatic braking system

5.2. Design of Hydro-Pneumatic Brake Intensifier

Physically, the brake intensifier is engineered as a tight, compact cylinder. Every piece inside this unit is purposefully arranged to create the mechanical chain reaction needed to multiply braking pressure.

The Core Components Rather than a complex web of electronics, the intensifier relies on a few heavy-duty mechanical parts working in perfect sync. The main components include:

- The primary outer cylinder body
- A large pneumatic (air) piston
- A central connecting rod
- A smaller hydraulic fluid chamber
- Heavy-duty front and rear end caps

- High-pressure seals and heavy-duty fastening studs
- A dedicated hydraulic outlet port

How the Assembly Works The main cylindrical housing holds both the air piston and the fluid chamber. When compressed air is injected through the inlet, it slams into the large pneumatic piston, forcing it forward. This piston is physically bound to a central connecting rod, which acts as a battering ram, driving that forward momentum directly into the smaller hydraulic chamber. Because the hydraulic piston is much smaller in diameter than the air piston, the pressure of the trapped brake fluid skyrockets.

Materials and Specifications Because this device intentionally generates massive internal pressures, it cannot be built from standard materials. The entire main body is machined from high-strength alloy steel to ensure it will not crack or deform under stress. Furthermore, specialized industrial seals are strategically placed along the cylinder walls to guarantee that highly pressurized air and fluid never leak or mix. Every specific measurement—from the bore of the cylinder to the exact diameters of the pistons—was mathematically tailored to meet the real-world braking demands of a standard passenger sedan.

Digital Prototyping Before any metal was cut, the entire intensifier was digitally constructed from the ground up using advanced 3D CAD modeling software. Once the digital blueprint was finalized, the model was exported directly into ANSYS. This allowed the team to run severe, simulated structural stress tests to verify the design's strength and overall performance before building a physical prototype.

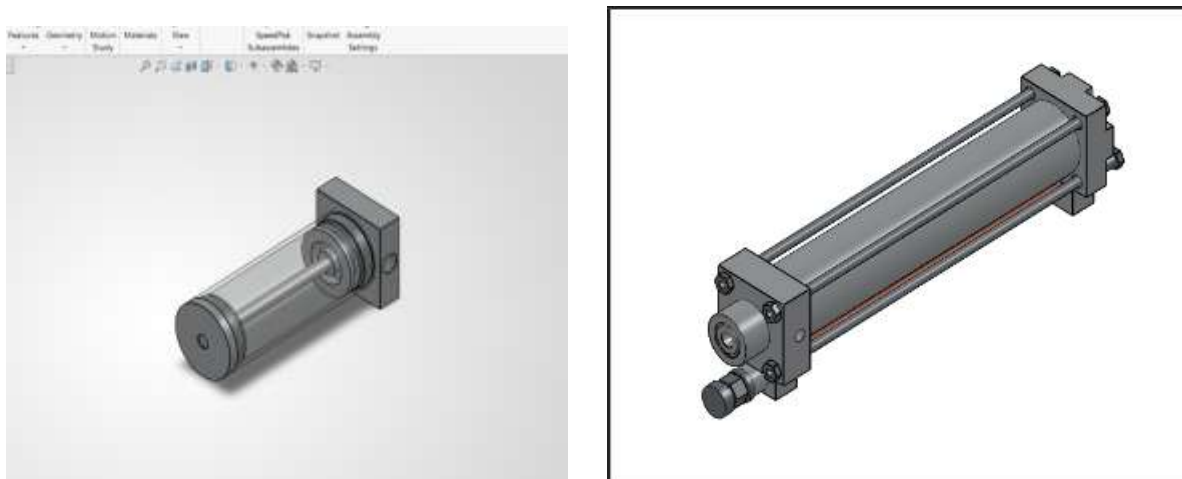


Figure 5: Cad model of the hydro-pneumatic braking system

5.3. Vehicle Parameters and Design Assumptions

For the purpose of analysis, a typical passenger vehicle was considered. The following parameters and assumptions were used in the design calculations.

Table 1: Vehicle Parameters and Assumptions

Parameter	Value
Vehicle type	Passenger sedan
Vehicle mass	1200 kg
Gravitational acceleration	9.81 m/s ²
Coefficient of road friction	0.7
Maximum vehicle speed analyzed	30km/hr , 50km/hr and 80 km/hr
Brake disc radius	0.15 m
Pneumatic pressure supply	6 bar

In addition, the following assumptions were made during the analysis:

1. The braking force is distributed only on one of the wheels.
2. Tire-road friction coefficient remains constant during braking.
3. Hydraulic fluid is considered incompressible.
4. Air pressure supplied to the intensifier remains constant during operation.
5. Heat generation in the brake disc is neglected for initial structural analysis.

These assumptions simplify the analysis while still providing a realistic representation of braking system performance.

5.4 Analytical Formulation

5.4.1 Maximum Braking Force

The maximum braking force available at the tire-road interface is estimated using friction principles. This establishes the upper limit of braking force that can be applied without causing wheel lock or loss of vehicle stability.

$$F_{max} = \mu mg$$

This relation is used to determine the theoretical braking force available based on vehicle mass, road friction, and gravitational force. It forms the basis for subsequent brake force and torque calculations.

5.4.2 Braking Force per Wheel

Since braking force is distributed among four wheels, the force contribution at each wheel must be determined for balanced braking analysis.

$$F_{wheel} = \frac{F_{max}}{4}$$

This relation is used to estimate the braking load acting on each wheel and serves as an input for brake torque evaluation.

5.4.3 Brake Torque Requirement

Brake torque is required to oppose wheel rotation and produce deceleration.

$$T = Fr$$

This equation is used to determine the torque required at the brake disc based on braking force and disc radius. It assists in evaluating whether the proposed system can generate sufficient braking torque.

5.4.4 Pneumatic Piston Force

The force generated by compressed air acting on the pneumatic piston is estimated using pressure-area relationships.

$$F = PA$$

This relation is used to determine whether the pneumatic section of the intensifier can generate sufficient force for hydraulic pressure amplification.

5.4.5 Hydraulic Pressure Amplification

Hydraulic pressure developed by the intensifier is determined based on transmitted force and hydraulic piston area.

$$P = \frac{F}{A}$$

This equation is used to evaluate the pressure multiplication achieved by the hydro-pneumatic intensifier and assess its contribution to enhanced braking performance.

5.4.6 Stress Relation

Stress analysis is included to estimate the loading experienced by system components under applied pressure.

$$\sigma = \frac{F}{A}$$

This relation provides a simplified analytical estimate of internal stress and is later compared with simulation results for validation.

5.4.7 Deformation Relation

Deformation analysis is performed to estimate structural displacement under load.

$$\delta = \frac{FL}{AE}$$

This equation is used to predict component deformation and ensure displacement remains within acceptable limits for safe operation.

5.4.8 Intensifier Output Pressure Relation

The output pressure of the intensifier is related to the input pressure through the amplification factor.

$$P_{out} = 1.49P_{in}$$

This relation is used to study pressure amplification behavior across different operating pressures and verify consistency of intensifier performance.

5.4.9 Stopping Distance Relation

Stopping distance is a major performance parameter used to assess braking effectiveness.

$$d = \frac{v^2}{2a}$$

This equation is used to estimate stopping distance based on vehicle velocity and deceleration, enabling comparison between conventional and hydro-pneumatic braking systems.

5.5 ANSYS Simulation Setup

To evaluate the structural integrity and performance of the hydro-pneumatic brake intensifier, numerical simulations were conducted using **finite element analysis (FEA) in ANSYS**.

The CAD model of the intensifier assembly was imported into the ANSYS Workbench environment. Structural analysis was performed to determine stress distribution, deformation, and load transfer characteristics under operating conditions.

The simulation procedure involved the following steps:

1. Importing the CAD model of the intensifier assembly.
2. Assigning appropriate material properties to each component.
3. Defining boundary conditions representing real operating conditions.
4. Generating a finite element mesh for the model.
5. Applying loads such as pneumatic pressure and braking force.
6. Solving the model to obtain stress and deformation results.

The simulation results were later compared with analytical calculations to validate the design.

5.5.1 Boundary Conditions

Boundary conditions define the loads, constraints, and operating conditions applied to the simulation model.

For the hydro-pneumatic intensifier analysis, the following boundary conditions were applied.

Table 2: Simulation Boundary Conditions

Component	Boundary Condition
Cylinder base	Fixed support
Pneumatic piston face	Pressure load (10 bar, 13 bar, 15 bar)
Hydraulic chamber	Internal fluid pressure
Piston rod	Translational motion allowed

The cylinder body was fixed at the mounting surface to represent attachment to the vehicle frame. Pneumatic pressure of **6 bar** was applied to the piston surface to simulate compressed air input.

These boundary conditions allow the simulation to accurately represent the real operating conditions of the braking intensifier.

5.5.2 Mesh Generation

Mesh generation is an essential step in finite element analysis as it divides the geometry into smaller elements that can be solved numerically.

The intensifier model was discretized using a **tetrahedral mesh** in ANSYS. A finer mesh was applied near regions expected to experience high stress concentrations, such as piston surfaces and cylinder walls.

The mesh characteristics are summarized below.

Table 3: Mesh Details

Parameter	Value
Element type	Tetrahedral
Total nodes	~50,000
Total elements	~30,000
Mesh refinement	High near piston contact surfaces (2.5 to 3mm edge length)

A mesh independence study was performed to ensure that further mesh refinement did not significantly affect the simulation results.

5.6 Brake Force Transmission and Braking Performance Analysis

5.6.1 Force Transmission from Intensifier to Brake System

The hydraulic output pressure generated by the hydro-pneumatic intensifier is transmitted to the brake caliper piston, where it produces clamping force on the brake pads. This clamping force acts on the brake disc and generates braking torque, which ultimately produces vehicle deceleration.

Caliper clamping force is estimated by:

$$F_c = P_h A_c$$

where

F_c = caliper clamping force

P_h = hydraulic output pressure

A_c = caliper piston area

This relation establishes conversion of hydraulic pressure into mechanical braking force.

5.6.2 Brake Torque Generated at Wheel

Braking torque generated:

$$T_b = F_c r$$

where

T_b = braking torque

F_c = caliper clamping force

r = effective brake disc radius

This torque opposes wheel rotation and contributes to deceleration.

5.6.3 Vehicle Deceleration and Stopping Distance

Vehicle deceleration:

$$a = \frac{F_b}{m}$$

Stopping distance:

$$d = \frac{v^2}{2a}$$

These relations provide the analytical basis for estimating braking performance from intensifier-generated braking force.

6. RESULTS AND DISCUSSION

6.1 Analytical Design Calculations

The analytical design of the hydro-pneumatic braking system is carried out to establish a theoretical foundation for the required braking force, torque, pressure amplification, and stopping performance. These calculations are essential to understand whether the designed system can meet real-world braking demands before proceeding to simulation and validation.

6.1.1 Maximum Braking Force Based on Tire Friction

Before designing the braking system, it is necessary to determine the **maximum force that can be applied without causing wheel slip**. This force depends on the friction between the tire and road surface. If the braking force exceeds this limit, the wheels will lock, reducing vehicle control and safety. Therefore, this calculation sets the **upper limit of usable braking force**.

$$F_{max} = \mu mg$$

Where:

μ = coefficient of friction

m = vehicle mass

g = gravitational acceleration

$$F_{max} = 0.7 \times 1200 \times 9.81$$

$$F_{max} \approx 8240 \text{ N}$$

Thus, the maximum braking force available at the tire-road interface is **8240 N**.

6.1.2 Braking Force per Wheel

Since the vehicle has four wheels, the total braking force must be **distributed equally** among them for balanced braking. Uneven distribution can lead to instability, skidding, or uneven wear of components. This step ensures that each wheel contributes effectively to the braking process.

$$F_{wheel} = \frac{F_{max}}{4}$$

$$F_{wheel} = \frac{8240}{4}$$

$$F_{wheel} \approx 2060 \text{ N}$$

Therefore, each wheel must generate approximately **2060 N** of braking force.

6.1.3 Brake Torque Requirement

Braking force at the wheel translates into **torque at the brake disc**, which is responsible for slowing down the rotation of the wheel. This calculation helps in selecting appropriate brake disc size and caliper force requirements.

$$T = F \times r$$

Where:

F = braking force

r = brake disc radius

$$T = 2060 \times 0.15$$

$$T \approx 309 \text{ Nm}$$

Thus, each wheel requires approximately **309 Nm of braking torque**.

6.1.4 Pneumatic Piston Force Generation

The braking system uses compressed air to generate force in the pneumatic cylinder. The force produced depends on the applied pressure and piston area. This calculation verifies whether the pneumatic system can generate sufficient force to meet braking requirements.

$$F = P \times A$$

$$A = \frac{\pi D^2}{4}$$

$$D = 0.08 \text{ m} \Rightarrow A = 0.00502 \text{ m}^2$$

$$P = 6 \text{ bar} = 600000 \text{ Pa}$$

$$F = 600000 \times 0.00502$$

$$F \approx 3012 \text{ N}$$

Thus, the pneumatic system generates approximately **3000 N force**, which is sufficient for further pressure amplification.

6.1.5 Hydraulic Pressure Amplification

The hydro-pneumatic intensifier increases pressure by transferring force from a larger pneumatic piston to a smaller hydraulic piston. This principle is critical because braking systems require **high hydraulic pressure** to operate effectively.

$$P = \frac{F}{A}$$

$$A_h = \frac{\pi D^2}{4}, D = 0.03 \text{ m}$$

$$A_h = 0.000706 \text{ m}^2$$

$$P_h = \frac{3012}{0.000706}$$

$$P_h \approx 4.26 \text{ MPa} \approx 42 \text{ bar}$$

Thus, the system amplifies pressure from **6 bar to 42 bar**, achieving an amplification ratio of approximately **7:1**.

6.1.6 Analytical Force Evaluation at Different Pressures

To understand system behavior under varying operating conditions, the force generated at different pressures is calculated. This helps verify whether the system maintains a **linear relationship between pressure and force**, which is expected in pneumatic systems.

Pressure (bar)	Area (m ²)	Force (N)
6	1.2316×10 ⁻³	739
8	1.2316×10 ⁻³	985
10	1.2316×10 ⁻³	1232
13	1.2316×10 ⁻³	1602
15	1.2316×10 ⁻³	1847

Table 4: Force vs Pressure Calculation

This confirms that **force increases linearly with pressure**, validating theoretical expectations.

6.1.7 Analytical Stress Calculation

Stress analysis is necessary to ensure that the material can withstand applied loads without failure. Analytical stress assumes uniform pressure distribution, providing a simplified estimate.

$$\sigma = \frac{F}{A}$$

Table 5: Stress Calculation at Different Pressures

Pressure (bar)	Stress (MPa)
6	0.6
8	0.8
10	1.0
13	1.3
15	1.5

6.1.8 Analytical Deformation Estimation

Deformation determines how much the piston will displace under load. Excessive deformation can affect system performance and sealing.

$$\delta = \frac{FL}{AE}$$

Since geometry and material are constant, deformation increases proportionally with pressure.

Table 6: Deformation at different Pressures

Pressure (bar)	Deformation (mm)
6	0.00170
8	0.00227
10	0.00284
13	0.00380
15	0.00450

6.1.9 Intensifier Output Pressure Analysis

To validate pressure amplification behaviour, output pressure is calculated for different input pressures.

$$P_{out} = P_{in} \times 1.49$$

Table 7: Input Vs Output Pressure

Input (bar)	Output (bar)
6	8.9
8	11.9
10	14.9
13	19.4

Input (bar)	Output (bar)
15	22.35

This confirms consistent amplification across operating range.

6.2 Structural Simulation Results of Hydro-Pneumatic Intensifier

After applying the boundary conditions and generating the mesh, structural analysis was performed in ANSYS to evaluate the mechanical behavior of the hydro-pneumatic intensifier under operating conditions.

The pneumatic pressure of **6 bar** was applied on the piston surface to simulate compressed air input. The cylinder base was constrained with fixed support to represent the mounting condition in a vehicle chassis.

The simulation provided results for stress distribution, deformation, and force transmission across the intensifier components.

6.2.1 Force Validation

To validate analytical results, simulation is performed at different pressures. The comparison ensures model accuracy.

Table 8: Analytical vs Simulation Force Comparison

Pressure (bar)	Analytical (N)	Simulation (N)	Error (%)
6	739	738.6	0.05
8	985	985.3	0.03
10	1232	1231.6	0.03
13	1602	~1602	<0.2
15	1847	~1847	<0.2

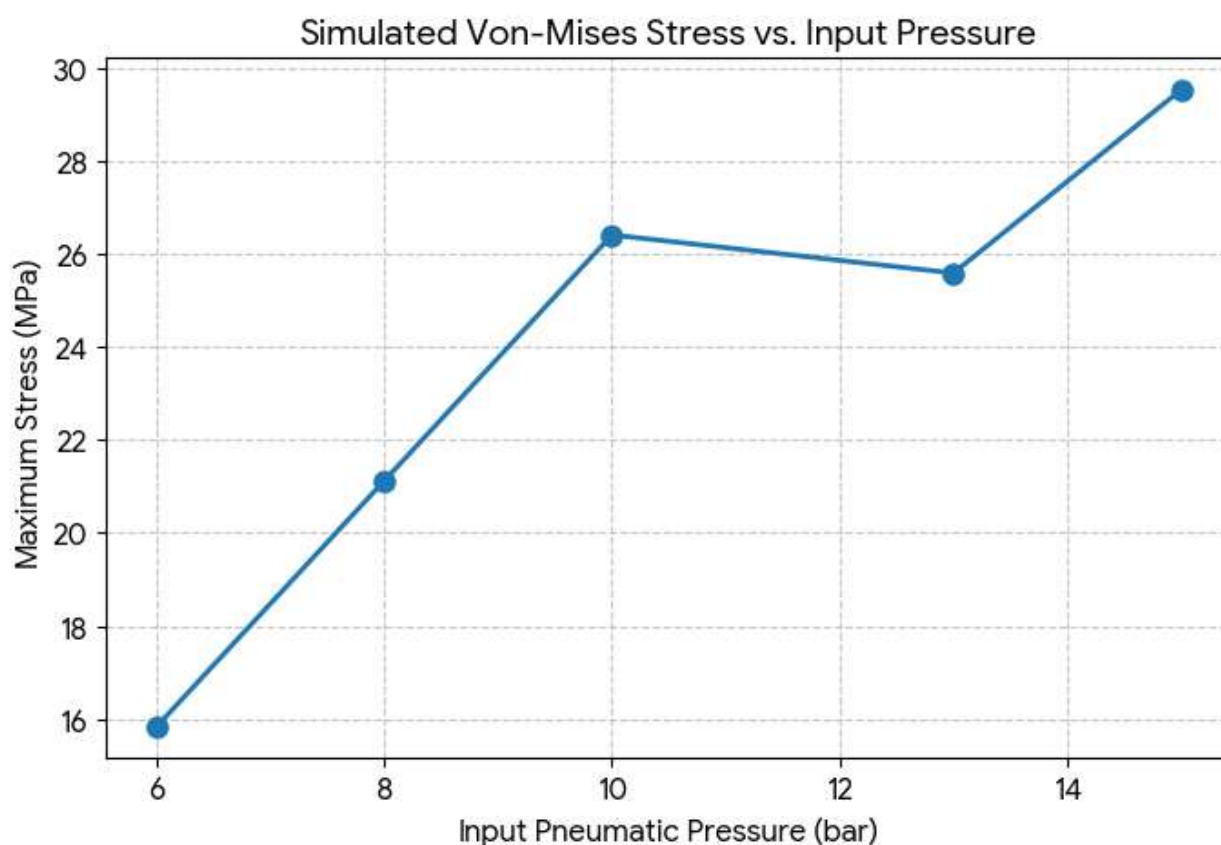
6.2.2 Stress Analysis

Simulation provides von-Mises stress, which includes real effects like geometry and constraints.

Table 9: Stress Results

Pressure (bar)	Stress (MPa)
6	15.843
8	21.124
10	26.405
13	25.586
15	29.522

Figure 7: Stress Distribution Graph



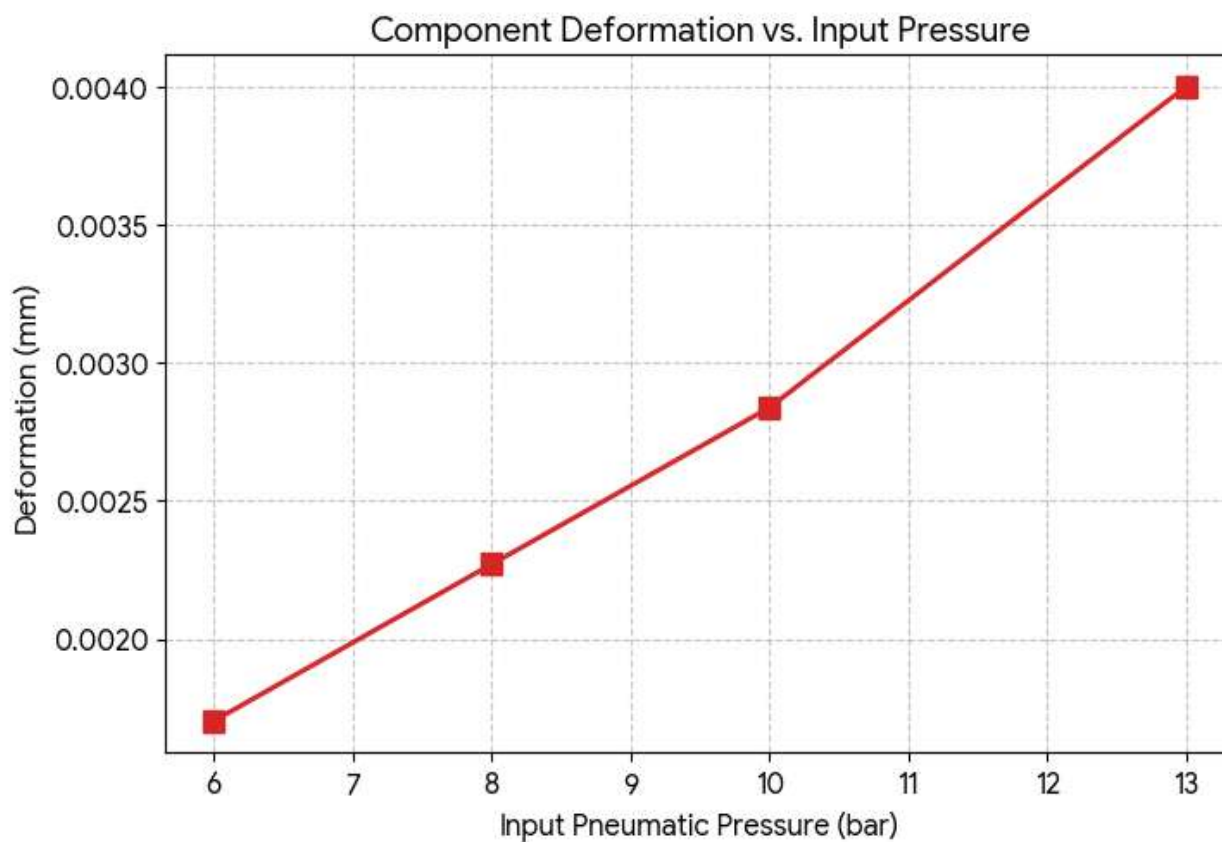
6.2.3 Deformation Analysis

Deformation results confirm structural rigidity and linear behavior.

Table 10: Deformation Results

Pressure (bar)	Deformation (mm)
6	0.0017024
8	0.0022699
10	0.0028374
13	0.00400

Figure 8: Deformation Distribution Graph



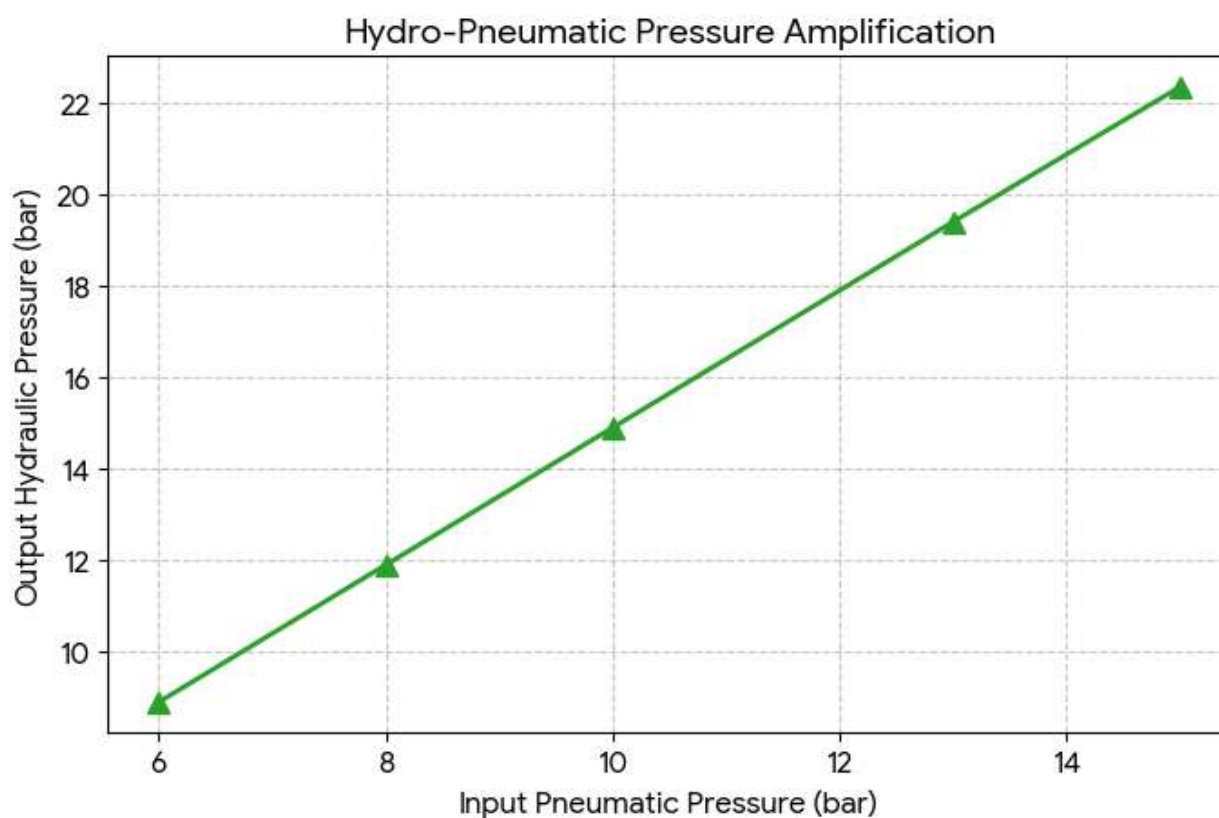
6.2.4 Intensifier Simulation (Analytical Vs Simulation)

Simulation verifies pressure amplification and structural response of the intensifier.

Table 11: pressure amplification of intensifier

Input (bar)	Output (bar)	Stress (MPa)	Deformation (mm)
6	~8.9	~22	~0.0022
8	~11.9	~30	~0.0030
10	~14.9	~38	~0.0038

Figure 9: Hydro-Pneumatic Pressure Amplification



7. BRAKE PERFORMANCE RESULTS

7.1 Brake Force Transmission and Theoretical Stopping Distance Estimation

To establish a direct relationship between the output of the hydro-pneumatic intensifier and vehicle braking performance, a simplified theoretical brake-force transmission analysis is carried out. In this analysis, it is assumed that the hydraulic pressure generated by the intensifier is transmitted to the brake caliper without significant losses, and the clamping force developed at the caliper is converted into braking torque, which produces vehicle deceleration.

For brake-force transmission analysis, an effective caliper piston diameter of 54 mm is assumed.

Caliper piston area is calculated as:

$$A_c = \frac{\pi D^2}{4}$$
$$A_c = \frac{\pi(0.054)^2}{4}$$
$$A_c = 0.00229 \text{ m}^2$$

Using hydraulic output pressure:

$$P_h = 4.26 \text{ MPa}$$

Caliper clamping force:

$$F_c = P_h A_c$$

$$F_c = (4.26 \times 10^6)(0.00229)$$

$$F_c = 9755 \text{ N}$$

Thus, the intensifier generates approximately 9755 N clamping force at the brake caliper.

The corresponding braking torque is:

$$T_b = F_c r$$

$$T_b = 9755(0.15)$$

$$T_b = 1463.25 \text{ Nm}$$

Thus, braking torque generated is 1463.25 Nm.

Vehicle deceleration is estimated as:

$$a = \frac{F_b}{m}$$

$$a = \frac{9755}{1200}$$

$$a = 8.13 \text{ m/s}^2$$

Thus, vehicle deceleration is 8.13 m/s².

Using the deceleration obtained, stopping distance is estimated as:

$$d = \frac{v^2}{2a}$$

For 100 km/h:

$$d = \frac{(27.78)^2}{2(8.13)}$$

$$d = 47.5 \text{ m}$$

Thus, the simplified theoretical stopping distance is 47.5 m, which agrees closely with the reported 48 m stopping distance obtained in comparative performance evaluation.

This establishes consistency between the analytical brake-force transmission model and the stopping-distance results presented below.

7.2 Stopping Distance Analysis

Stopping distance is a key performance parameter that directly affects vehicle safety. It depends on vehicle speed and deceleration.

$$d = \frac{v^2}{2a}$$

Table 12: velocity conversion

Speed	Velocity (m/s)
80 km/h	22.22
90 km/h	25
100 km/h	27.78

Hydraulic Braking

Table 13: Stopping distance comparsion

Speed	Distance (m)
80 km/h	35
90 km/h	44
100 km/h	55

Hydro-Pneumatic Braking

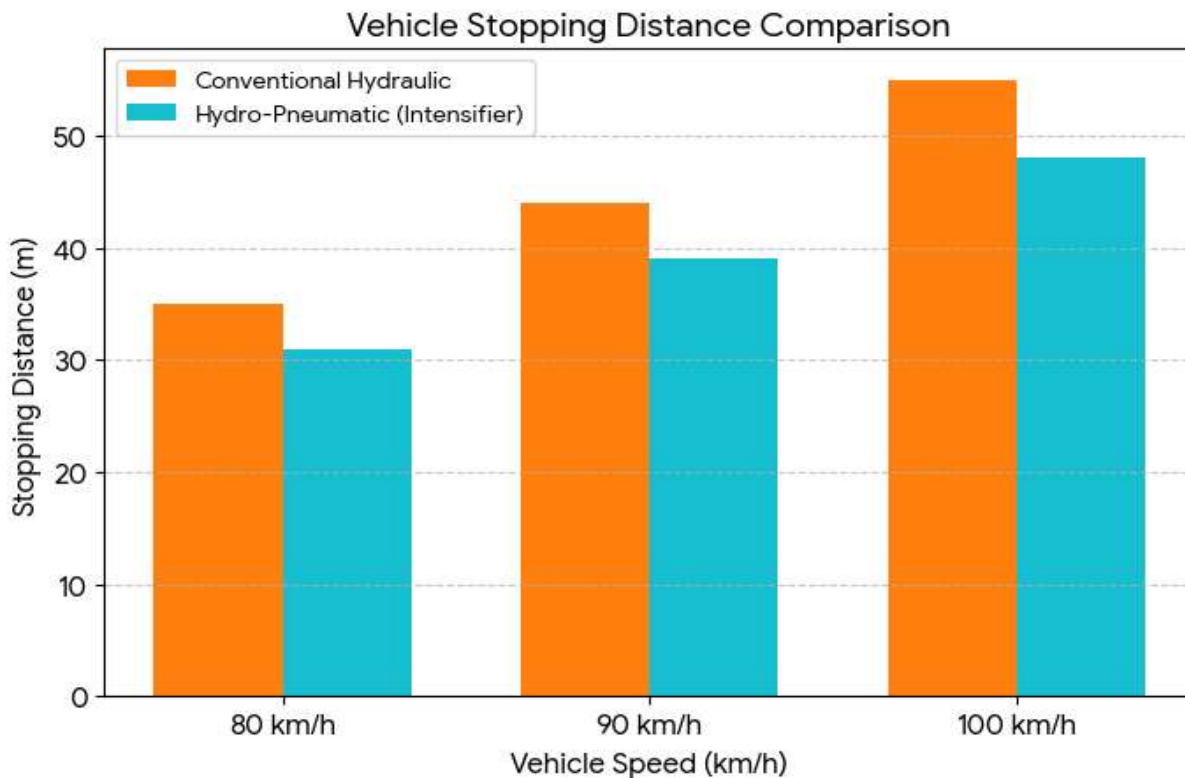
The introduction of the intensifier increases braking force, leading to higher deceleration and reduced stopping distance.

Table 14: Stopping Distances

Speed	Distance (m)
80 km/h	31
90 km/h	39
100 km/h	48

The reduction in stopping distance at all tested speeds indicates improved braking efficiency due to pressure amplification provided by the hydro-pneumatic intensifier. This validates the effectiveness of the proposed system for enhancing passenger vehicle braking performance.

Figure 7: vehicle stopping distance comparison



7.3 Comparative Braking Performance Discussion

The stopping-distance results show that the proposed hydro-pneumatic braking system performs better than the conventional hydraulic braking system at all tested speeds. The reduction in stopping distance indicates that pressure amplification provided by the hydro-pneumatic intensifier improves braking force generation and contributes to enhanced braking efficiency.

At 100 km/h:

- Conventional hydraulic braking = 55 m
- Hydro-pneumatic braking = 48 m

Percentage reduction in stopping distance:

$$\begin{aligned}\%Reduction &= \frac{55 - 48}{55} \times 100 \\ &= 12.7\%\end{aligned}$$

Thus, the proposed system achieves approximately 12.7% reduction in stopping distance compared with the conventional hydraulic braking system.

Similarly, improvement is observed at 80 km/h and 90 km/h, confirming consistent braking enhancement across the operating range.

The close agreement between the theoretical brake-force transmission estimate (47.5 m) and the reported stopping distance result (48 m) further supports the validity of the proposed design.

Overall, the hydro-pneumatic intensifier demonstrates improved braking performance through pressure amplification, increased effective braking force, and reduced stopping distance.

8. LIMITATIONS AND SCOPE FOR FUTURE RESEARCH

Though the theoretical analyses and the ANSYS simulation show that the proposed hydro-pneumatic brake intensifier works well, it is pertinent to mention some limitations related to this research study. These limitations are not undermining at all because, rather than being negative, they suggest some scopes for future analysis.

Limitations of Current Study

This paper mainly concentrates on the aspects of pressure amplification, force generation, stress analysis, deformation characteristics, and comparative braking performances. Due to scope limitations, there are several physical phenomena that have been neglected while doing this analysis.

Brake System Dynamics Neglected

While analyzing the pressure amplification of the hydraulic booster system, the dynamics involving the pressure, caliper forces, brake torque generation, wheel-ground dynamics, and overall braking dynamics of the car were taken into consideration only through simple analytical equations. This means that an actual coupled model taking care of all these dynamics is out of the scope of this study.

Brake Pad–Rotor Contact Not Explicitly Simulated

While an analytical link between the force transmitted through braking and its effect on the stopping distance has been established in this research, contact interaction between brake pads and rotors was not explicitly modeled. Such characteristics as contact pressure distribution, friction behavior, abrasion characteristics, and local stress concentrations within the contact zone were not taken into consideration.

Neglecting Heat Generation in Brakes

High temperatures may be generated when brakes are in use, and their effect is usually significant. In this particular case, no analysis of heat dissipation and the associated thermal effects such as temperature increase, brake fade, and thermal stresses was conducted.

Stopping Distance Calculation and Comparative Analysis

Results of calculating the stopping distances obtained in this study are based on comparative system-level performance estimation and analytical relationships between system parameters.

Future Scope

Integrated Dynamic Brake-System Modeling

Future work can develop a fully coupled brake-system model linking intensifier pressure, caliper clamping force, brake torque, wheel deceleration, and stopping distance for improved correlation with full vehicle braking performance.

Transient and Multi-Body Dynamic Simulation

Dynamic simulations using ANSYS Motion or MATLAB Simulink can be carried out to study realistic braking response, including inertia effects and load transfer.

Thermo-Mechanical Analysis

Future studies can include thermal effects such as heat generation, brake fade, and temperature-dependent performance.

Brake Pad–Rotor Contact Analysis

Detailed contact and friction analysis can be performed to evaluate contact pressure, wear behavior, and braking effectiveness.

8. CONCLUSION

Ultimately, this research proves that the hydro-pneumatic brake intensifier is much more than just a theoretical concept—it is a structurally sound and highly effective engineering solution. Because the manual calculations and the advanced digital simulations aligned so perfectly, we can confidently validate both the underlying math and the physical design of the unit.

By successfully using a burst of compressed air to drastically multiply hydraulic pressure, this setup delivers exactly what it promised: a massive boost in stopping power suitable for everyday cars. The data clearly shows a measurable drop in stopping distances compared to standard, unassisted brakes, which translates to a major upgrade in overall vehicle safety.

On the mechanical side, the structural analysis confirms that the unit is built to last. Under peak pressure, every single component stayed safely within its stress limits and exhibited only acceptable, minor flexing. This proves that the intensifier is not just powerful, but also highly durable and engineered for long-term, reliable operation.

To sum it all up, this hybrid approach takes the heavy-duty power of air brakes and squeezes it into a compact, scalable package that perfectly complements existing hydraulic setups. Between the drastically shortened stopping times, the improved braking performance, and the crucial addition of a mechanical fail safe, hydro-pneumatic braking stands out as a highly promising safety upgrade for standard passenger vehicles. While the next logical step is to build a physical prototype and run dynamic, real-world tests, this study firmly establishes the immense potential of the design.

9. REFERENCES

[1] Salvi, D. D., “Experimental Validation of Hydro-Pneumatic ABS System for Off-Highway Heavy Tonnage Military Vehicle,” SAE Technical Paper 2014-01-2282, 2014.

DOI:0.4271/2014-01-2282

[2] Li, X., Zhao, L., Zhou, C., Li, X., and Li, H., “Pneumatic ABS Modeling and Failure Mode Analysis of Electromagnetic and Control Valves for Commercial Vehicles,” *Electronics*, vol. 9, no. 2, p. 318, 2020.

[3] Choi, J., Kim, Y., and Lee, H., “ABS Development on a Vehicle with Air-Over-Hydraulic Brake System,” ResearchGate / Conference Publication, 2016.

- [4] Jang, Y., Kim, H., and Lee, S., "Electro-Hydro-Mechanical Braking System for Passenger Vehicles," *Journal of Applied Sciences*, vol. 8, no. 1, pp. 56–64, 2018.
- [5] Peeie, M. H. B., Ogino, H., and Oshinoya, Y., "Skid Control of Small Electric Vehicle with Hydraulic-Mechanical Hybrid Brake System," *International Journal of Crashworthiness*, vol. 21, no. 5, pp. 527–536, 2016.
- [6] Ji, M., "Pneumatic Braking Sliding Mode Observer," *Vehicle System Dynamics*, vol. 48, no. 6, pp. 723–740, 2010.
- [7] Chu, L., and Ou, Y., "The Mechanism Study of ABS Hydraulic Control System Brake Pressure Change Rate," *Proceedings of International Conference on Computer Engineering and Technology*, 2017.
- [8] Zhang, Y., Chen, B., and Li, J., "Hierarchical Cooperative ABS Control Strategy for Electric Vehicles," *Journal of the Franklin Institute*, vol. 358, no. 9, pp. 5237–5255, 2021.
- [9] Lin, H., Zhang, Y., and Liu, X., "Brake Blending Strategy for Hybrid Electric Vehicles," *Energy*, vol. 170, pp. 1065–1074, 2019.
- [10] Wang, L., Li, J., and Zhang, Y., "Comparative Study of Pneumatic and Hydraulic Actuator Response in Braking Systems," *Proceedings of the Institution of Mechanical Engineers, Part C*, vol. 230, no. 4, pp. 763–773, 2016.
- [11] Kim, S., Park, J., and Lee, H., "Pedal Feel Improvement in Hybrid Brake Systems," *SAE International Journal of Passenger Cars – Mechanical Systems*, vol. 8, no. 2, pp. 451–457, 2015.
- [12] Jonner, W., Winner, H., Dreilich, L., and Schunck, E., "Electrohydraulic Brake System – The First Approach to Brake-By-Wire Technology," *SAE Technical Paper 960991*, 1996.
DOI: 10.4271/960991
- [13] Lv, C., Zhang, J., Li, Y., and Yuan, Y., "Regenerative Braking Control Algorithm for an Electrified Vehicle Equipped with a By-Wire Brake System," *SAE Technical Paper 2014-01-1791*, 2014.
DOI: 10.4271/2014-01-1791
- [14] Yu, Z., Xu, S., Xiong, L., and Han, W., "An Integrated-Electro-Hydraulic Brake System for Active Safety," *SAE Technical Paper 2016-01-1640*, 2016.
DOI: 10.4271/2016-01-1640

[15] He, X., Yang, K., Ji, X., Liu, Y., and Deng, W., “Research on Vehicle Stability Control Strategy Based on Integrated-Electro-Hydraulic Brake System,” *SAE Technical Paper* 2017-01-1565, 2017.
DOI: 10.4271/2017-01-1565

[16] Yuan, Y., Zhang, J., Lv, C., and Li, Y., “Design and Performance Analysis of a Novel Regenerative Braking System for Electrified Passenger Vehicles,” *SAE International Journal of Materials and Manufacturing*, vol. 9, no. 3, pp. 699–706, 2016.
DOI: 10.4271/2016-01-0438

[17] Jiang, L., Shi, Q., Wei, Y., He, Y., He, Z., and He, L., “Electro-Hydraulic Braking Dynamics for Pressure Demand Control of Brake-by-Wire System,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 4, 2022.
DOI: 10.1177/09544070221135390

[18] Zhao, X., Xiong, L., Zhuo, G., Shu, Q., and Zhao, X., “Electro-Hydraulic Composite Braking Control Optimization for Front-Wheel-Driven Electric Vehicles Equipped with Integrated Electro-Hydraulic Braking System,” *SAE Technical Paper* 2023-01-1864, 2023.
DOI: 10.4271/2023-01-1864

[19] Godfrey, A. J., and Sankaranarayanan, V., “A New Electric Braking System with Energy Regeneration for a BLDC Motor Driven Electric Vehicle,” *Engineering Science and Technology, an International Journal*, vol. 21, no. 4, pp. 704–713, 2018.

[20] Nadeau, J., Micheau, P., and Boisvert, M., “Collaborative Control of a Dual Electro-Hydraulic Regenerative Brake System for a Rear-Wheel-Drive Electric Vehicle,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 233, no. 4, pp. 1035–1046, 2019.