**MARMARA UNIVERSITY**

**FACULTY OF ENGINEERING**

# ELECTRONICALLY CONTROLLED AIR SUSPENSION (ECAS) SYSTEM DESIGN ON PUBLIC TRANSPORTATION BUSSES

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**GRADUATION PROJECT REPORT**

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**ELECTRONICALLY CONTROLLED**

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**ON PUBLIC TRANSPORTATION BUSSES**

**by**

**Burak Fatih YEŞİLSU**

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# ABSTRACT

## ELECTRONICALLY CONTROLLED AIR SUSPENSION (ECAS) SYSTEM DESIGN ON PUBLIC TRANSPORTATION BUSSES

A heavy-duty vehicle such as busses can benefit from the height control of the chassis that an air suspension provides. For example, to retain a pitch angle parallel to the road, regardless of what load it carries and the comfort of the passengers, easy accessibility for disabled passengers.

Electronically controlled air suspension (ECAS) systems have been widely used in commercial vehicles to improve the ride comfort and handling stability of vehicles, as it can adjust vehicle height according to the driving conditions and the driver's intent. In this paper, the vehicle height adjustment process of ECAS system is studied. A mathematical model of vehicle height adjustment is derived by combining vehicle dynamics theory and thermodynamics theory of variable mass system. In order to solve these problems, a PID controller is proposed to realize the accurate control of vehicle height. By simulation the effectiveness and performance of the proposed control algorithm are verified. [2]

# SYMBOLS

$\boldsymbol{q_m}$ : area-normalized mass flow rate

$\boldsymbol{C_r}$ : critical pressure ratio

$\boldsymbol{S_e}$ : effective area

$\boldsymbol{P_r}$ : reservoir pressure

$\boldsymbol{P_s}$ : spring pressure

$\boldsymbol{P_{atm}}$ : atmospheric pressure

$\boldsymbol{R}$ : perfect gas constant

$\boldsymbol{k}$ : polytropic index

$\boldsymbol{T}$ : temperature

$\boldsymbol{m_1}$ : sprung mass

$\boldsymbol{m_2}$ : unsprung mass

$\boldsymbol{h}$ : the height of air spring

$\boldsymbol{A_e}$ : the effective area of air spring

$\boldsymbol{g}$ : gravity constant

$\boldsymbol{z_1}$ : the displacement of sprung mass

$\boldsymbol{z_2}$ : the displacement of unsprung mass

$\boldsymbol{K_{tf}}$ : vertical stiffness of the tire

$\boldsymbol{q}$ : the vertical displacement of road

# ABBREVIATIONS

| | |
|---|---|
| **PID** | **:** Proportional Integral Derivative |
| **ECAS** | **:** Electronically Controlled Air Suspension |

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# 1. INTRODUCTION

The leaf spring suspension does not offer an optimum suspension performance. Due to the possibility of the levelling adjustment, the careful cargo treatment and the better ride comfort, the air suspension is, therefore, more and more succeeding [1].

*Figure 1 Leaf Spring suspension system*

Air suspension systems have been used in vehicles since the 1950s, especially in buses. ECAS is an electronically controlled air suspension system. In mechanically controlled air suspension systems, the device that measures the height of vehicle also controls the air spring. ECAS, on the other hand, control is taken over by an ECU. It actuates the air spring via solenoid valves using information received from sensors. Air springs have been primarily applied to commercial vehicles and luxury passenger cars because they are costly. They have many advantages, however, compared with conventional coil springs. Air springs provide better comfort and improvement in the handling performance because they can have relatively low stiffness and enable a vehicle to maintain optimum wheel alignment. In addition, air springs can protect the body of a vehicle on rough roads and make the task of loading baggage into the trunk of a vehicle more convenient because the heights of the air springs can be adjusted through supplying and exhausting the air via the pneumatic circuit connected to the air spring [4].

ECAS has been widely used in commercial vehicles, as opposed to steel spring suspension systems the advantages of ECAS are as follows: increase in ride comfort due to lower spring rate and low natural frequency; can adjust the height of the vehicle based on the driver's intent and driving conditions; control of lifting axles is possible; less impact on the road surface [2].

*Figure 2 Steel Spring suspension*

The function of height adjustment is one of the major features of ECAS. ECAS can adjust the height of vehicle's body according to the driver's intent and the vehicle's driving conditions, to achieve the best performance of commercial vehicle [2].

## 1.1. Background

Traditional suspension systems, relying on coil or leaf springs, had limitations in providing optimal ride comfort, especially under varying loads or dynamic driving conditions. The evolution toward ECAS began as automotive engineers sought to harness the benefits of air suspension and integrate electronic control mechanisms for more precise and dynamic adjustments. The shift was driven by a desire to enhance not only ride comfort but also overall vehicle performance, stability, and safety. The development of electronic sensors and control units allowed for real-time monitoring of various factors such as vehicle speed, load, and road conditions. This data became instrumental in the creation of sophisticated ECAS systems, which could dynamically adjust air pressure in the suspension components to optimize ride height, stiffness, and responsiveness.

The background of ECAS is closely linked to advancements in both air suspension and electronic control technologies, bringing together the best of both worlds to create a highly adaptable and customizable suspension system. Initially adopted in high-end luxury vehicles, ECAS systems have gradually expanded their presence to other automotive segments, including commercial trucks and buses, further emphasizing their effectiveness and versatility in addressing the challenges of diverse driving scenarios. The ongoing pursuit of improving ride quality and vehicle performance continues to drive innovations in ECAS technology, positioning it as a key element in the evolution of modern automotive suspension systems.

## 1.2. The History of ECAS

The concept of air suspension dates back to the mid-20th century. In the 1950s and 1960s, companies like General Motors began experimenting with air springs to replace conventional coil and leaf springs. These early systems were manually controlled and aimed primarily at improving ride comfort by adjusting the air pressure in the springs.

The integration of electronic controls into air suspension systems began in the 1980s and 1990s. Advances in electronic sensors, actuators, and control units enabled real-time adjustments to suspension settings based on vehicle speed, load, and road conditions. The first ECAS systems were introduced in high-end luxury cars and heavy-duty commercial vehicles, where enhanced ride quality and handling were most desirable.

By the early 2000s, ECAS technology had become more sophisticated and widespread. Key developments during this period included:

Improved Sensors and Actuators: These components provided precise data on vehicle dynamics and allowed for accurate control of air spring pressure.

Integrated Electronic Control Units (ECUs): ECUs processed sensor data and adjusted the suspension in real-time to optimize performance.

Adaptive and Semi-Active Systems: These systems adjusted suspension settings dynamically based on driving conditions and driver preferences.

## 1.3. Components of ECAS System

ECAS system needs some components to work clearly. These components are described in following sections.

### 1.3.1. Air Springs

An air spring is a vehicle suspension component using compressed air in a flexible bag to provide a smoother ride. It adapts to varying loads, automatically levels the vehicle, and can be adjusted for customization. Common in various vehicles, air springs enhance comfort and stability.

*Figure 3 Air Spring examples*

#### 1.3.2. Air Compressor

An air compressor is employed to regulate the air pressure within the system. It works in tandem with the ECU to adjust the suspension settings based on real-time data.

#### 1.3.3. Electronic Control Unit (ECU)

The ECU acts as the brain of the system, collecting data from sensors and making rapid adjustments to the air pressure in the springs. This enables precise control over the vehicle's ride height, stiffness, and overall suspension behavior.

#### 1.3.4. Height Sensors

Sensors continuously measure the height of the vehicle, providing input to the ECU. This information allows the system to automatically adjust the ride height to maintain optimal levels, ensuring stability and comfort.

#### 1.3.5. Solenoid Valves

Solenoid valves control fluid or gas flow using an electromagnetic coil to actuate a plunger. They're known for rapid response, precise control, and versatility in applications like water treatment and gas control. These valves are reliable, efficient, and can be automated with electronic control systems.

*Figure 4 An example solenoid valve used in ECAS*

## 1.4. Advantages of ECAS in Public Buses

The advantages of Electronically Controlled Air Suspension (ECAS) in public buses are notable for their contribution to both passenger comfort and overall vehicle performance.

- Customizable Ride Height: ECAS allows public buses to adjust their ride height based on the number of passengers, cargo load, or road conditions. Customizable ride height contributes to improved accessibility, making boarding and disembarking easier for passengers.


*Figure 5 A commander unit for leveling inside the vehicle*

- Automatic Leveling: ECAS systems automatically level the bus, ensuring a consistent and stable ride even when carrying varying passenger loads. This feature enhances safety, stability, and handling, particularly during stops and acceleration.

*Figure 6 Automatic leveling is important for public busses*

- Enhanced Ride Comfort: The precise control over air pressure in ECAS results in a smoother and more comfortable ride for passengers. Reduced vibrations and shocks contribute to an overall pleasant travel experience.
- Improved Handling and Stability: ECAS optimizes the bus's suspension settings in real-time, enhancing its handling and stability on different road surfaces and during maneuvers. Improved stability is crucial for ensuring passenger safety and comfort.
- Adaptability to Road Conditions: ECAS systems can adapt to changing road conditions, providing a more controlled and responsive suspension system. This adaptability is particularly beneficial in urban environments with varying road surfaces.

*Figure 7 Disturbance road example*

- Dynamic Load Distribution: The ability of ECAS to dynamically distribute the load ensures that the bus maintains optimal performance and stability regardless of passenger distribution or cargo variations.
- Reduced Wear and Tear: The adaptive nature of ECAS minimizes stress on the vehicle components, potentially reducing wear and tear on the suspension system. This can lead to lower maintenance costs and increased longevity of the bus.

Overall, the advantages of ECAS in public buses align with the goals of enhancing passenger comfort, safety, and operational efficiency, making it a valuable technology for modern urban transit systems.

### 1.5. Applications ECAS in Modern Vehicles

Electronically controlled air suspension systems are used in different types of vehicles. These are, luxury and High-Performance cars, commercial vehicles such as busses, trucks, agricultural machines. In this paper the ECAS system is examined for public transportation busses.

Public transportation busses are closer to the ground. Passengers should take on and off the bus easily. When the passengers take on or off to the bus, the level of the bus should lower than the riding level. These level decrease helps especially disabled people.


*Figure 8 An inclined bus during take-on process*

## 2. MATERIAL AND METHOD

### 2.1. Sonic Flow

In most industrial applications (such as pneumatic actuators), the working gas flows through valves and orifices at a high speed, and therefore the gas is compressible. Compressible gas flow is a complex phenomenon, and, therefore, we do not develop the flow equations here.

Instead, we present the results for gas flow through a sharp-edged orifice, which we can use to model compressible flow in a pneumatic system. *Figure 9* shows compressible gas flow through a sharp-edged orifice with area A0 at the throat (minimum area) [6].

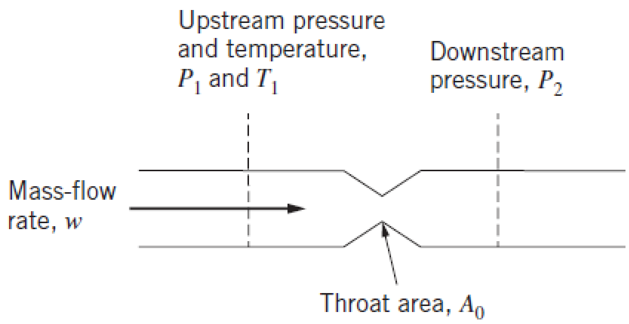


*Figure 9 Gas flow through a sharp-edged orifice [6]*

Expressions for the mass-flow rate of the gas can be derived by assuming that the expansion of an ideal gas through the orifice is isentropic (i.e., frictionless and adiabatic). In addition, we need to consider two cases: “unchoked” flow and “choked” flow. The flow is said to be “choked” when it achieves sonic conditions (the speed of sound, or Mach=1) at the throat. The ratio of the downstream-to-upstream pressures, $P2 / P1$, determines whether or not the flow is choked. Clearly, if the upstream and downstream pressures are nearly equal ($P2 / P1 \approx 1$), then no gas flows through the orifice. Gas begins to flow through the orifice at an increasing speed as the pressure ratio $P2 / P1$ decreases from unity. When the pressure ratio $P2 / P1$ is greater than the critical ratio $Cr$ the gas flow is subsonic and “unchoked” [6].

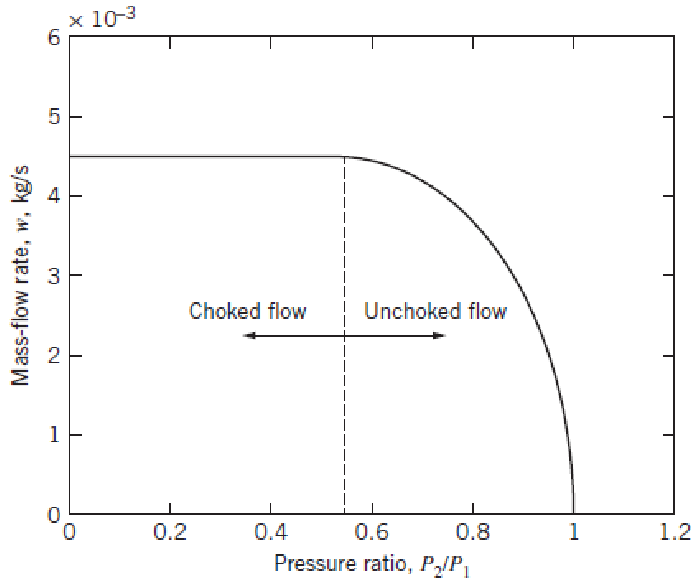


*Figure 10 Mass-flow rate for air through a sharp-edged orifice [6]*

If the downstream pressure P2 becomes low enough, the flow speed increases until it reaches the sonic (Mach 1) condition at the throat and the flow becomes choked. Decreasing downstream pressure P2 below this critical point will not alter the sonic conditions at the throat [6]. In this case, the choked and unchoked mass-flow rate equation is shown in equation (1) and equation (2) in section 2.2.1.

## 2.2. The Process of Height Adjustment for ECAS

The function of height adjustment for ECAS is achieved by charging and discharging of the air springs. The structure of charging and discharging circuit for ECAS system is shown in *Figure 11*. It includes four air springs installed at each corner of the vehicle, a solenoid valve which regulates air flows into the air springs, a compressor providing the compressed air, when the gas pressure in the reservoir is less than a certain value, the air compressor starts to work, a reservoir storing the compressed air, an air filter removing dirt in the circuit, and an air dryer absorbing moisture from the intake air to prevent moisture damage [2].

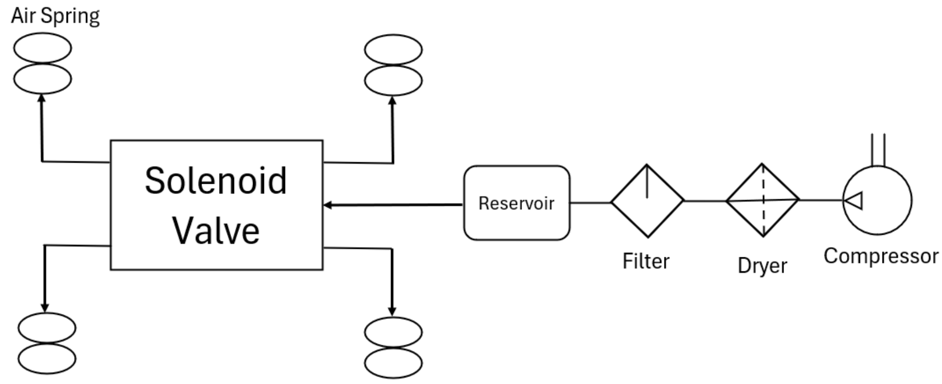


*Figure 11 Pneumatic scheme of the ECAS system*

The displacement of the sprung mass is changed by charging and discharging of compressed air, and the vehicle's height is adjusted to satisfy the vehicle driving performance. In the charging process, gas from the air reservoir is supplied into the air spring through the pipeline and the height of vehicle is increased. In the discharging process, gas from the air spring is exhausted into the atmosphere through the pipeline and the height of vehicle is decreased [1].

## 2.3. Mathematical Model of Vehicle Height Adjustment

According to the described processes of height adjustment, a mathematical model of vehicle height adjustment is derived by combining vehicle dynamics and thermodynamics theory of variable mass system. In order to facilitate the research, the model is established on the basis of the following reasonable simplifications [3]:

1. The air is perfect gas, and its kinetic energy is negligible in all air springs.
2. The pressure of the air reservoir is assumed constant, and there is no gas leakage happens in the system.
3. The solenoid valve in the circuit is simplified as a throttle hole.
4. The pressure and temperature of the gas in the air springs are supposed to be homogeneous.
5. The volume change rate and effective area of a reversible sleeve air spring are assumed to be constant.

### 2.3.1. The Model of Solenoid Valve

As the solenoid valve in the gas circuit is simplified as a throttle hole, when the solenoid valve is open, area-normalized mass flow rate of the valve is:

$$q_m = S_e P_u \Phi \tag{1}$$

$$\Phi = \begin{cases} \sqrt{\dfrac{k}{RT}\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}} & \dfrac{P_d}{P_u} \le C_r \\ \sqrt{\dfrac{2k}{k-1} * \dfrac{1}{RT}\left[\left(\dfrac{P_d}{P_u}\right)^{\frac{2}{k}} - \left(\dfrac{P_d}{P_u}\right)^{\frac{k+1}{k}}\right]} & \dfrac{P_d}{P_u} > C_r \end{cases} \tag{2}$$

Where,

$q_m$ is area-normalized mass flow rate,

$C_r$ is the critical pressure ratio,

$S_e$ is effective area of the valve,

$P_u$ is the upstream pressure,

$P_d$ is downstream pressure,

$R$ is perfect gas constant,

$k$ is polytropic index,

$T$ is temperature.

When increasing the vehicle, the upstream pressure is the pressure of the gas in reservoir, $P_u = P_r$. The downstream pressure is the pressure of the gas in air spring, $P_d = P_s$.

When decreasing the vehicle by exhausting the air spring, the upstream pressure is the pressure of the gas in air spring, $P_u = P_s$. the downstream pressure is the pressure of atmosphere, $P_d = P_{atm}$.

### 2.3.2. The Model of Air Spring

Through the analysis of the thermodynamic process of the gas in the air spring, the variable mass thermodynamics system model of air spring is built, to obtain the relationship of air spring pressure and the area-normalized mass flow rate of the pipeline. In the practical application, due to the delay characteristics of the air spring and the resistance of the damper, the system needs time to become stable after the closed of the solenoid valve. So, the height adjustment process can be divided into charging and discharging process of variable volume and the stable stage of the closed system after the solenoid valve is closed. The charging and discharging process of the air spring is independent of each other and relatively quickly, so the charging and discharging process of the air spring can be regarded as adiabatic process. According to the first law of thermodynamics, the nonlinear dynamic model of the simplified air spring is obtained as follow [1]:

$$\frac{dP_s}{dt} = \frac{kRT}{V} q_m - \frac{kP_s}{V}\frac{dV}{dt} \tag{3}$$

Where, $V$ is the volume of the air spring, $\frac{dV}{dt}$ is the rate of volumetric change, which can be described as,

$$\frac{dV}{dt} = \frac{dV}{dx}\frac{dx}{dt} = \frac{dV}{dx}\dot{h} \tag{4}$$

### 2.3.3. The Dynamics Model of Air Suspension System

Refer to the air suspension system of a certain commercial vehicle and combined with the specific condition of the test bench, a 1/4 vehicle model of air suspension system is built. The tire is simplified as an equivalent spring. The model includes two degrees of freedom, namely the displacement of sprung mass and unsprung mass, as shown in *Figure 12*.

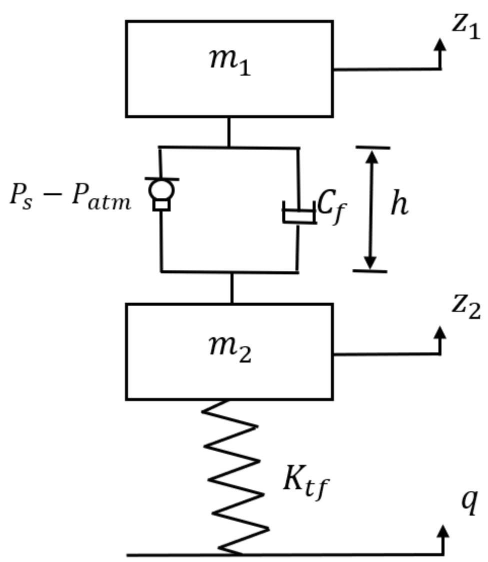


*Figure 12 1/4 vehicle model of air suspension system*

According to Newton's Second Law of Motion, the kinetic equation of the system can be expressed as,

$$m_1\ddot{z}_1 = (P_s - P_{atm})A_e + C_f\dot{h} - m_1 g \tag{5}$$

$$m_2\ddot{z}_2 = K_{tf}(q - z_2) - (P_s - P_{atm})A_e - C_f\dot{h} \tag{6}$$

$$\dot{h} = \dot{z}_2 - \dot{z}_1 \tag{7}$$

Where,

$m_1$ is sprung mass,

$m_2$ is unsprung mass,

$C_f$ is the damping coefficient of the damper,

$h$ is the height of air spring,

$A_e$ is the effective area of air spring,

$P_{atm}$ is atmospheric pressure,

$g$ is gravity constant,

$z_1$ is the displacement of sprung mass,

$z_2$ is the displacement of unsprung mass,

$K_{tf}$ is vertical stiffness of the tire,

$q$ is the vertical displacement of road.

In this mathematical model, sprung mass represents the weight of the bus and unsprung mass represents the weight of the suspension system.

### 2.3.4. Road Conditions

While driving, a vehicle is subjected to road disturbances. This disturbance is because of road conditions, such as road quality and bumpers on the road.

A first order filter that takes white noise as its input is represented in the road surface [5].

$$q = w - \frac{1}{\nu V_x}\dot{q} \tag{8}$$

Where,

$q$ is the vertical displacement of road.

$w$ is the white noise signal,

$\nu$ is the cut-off frequency,

$V_x$ is the vehicle’s horizontal speed.

For rough road conditions, the values are used below in *Table 1*.

*Table 1 Road Condition Parameters*

| **Road Condition Parameters** | |
|---|---|
| $\boldsymbol{\nu}$ [rad/m] | 0.8 |
| $\boldsymbol{V_x}$ [m/s] | 7.5 |

In *Figure 13* the disturbance of the road is shown according to parameters in *Table 1*.

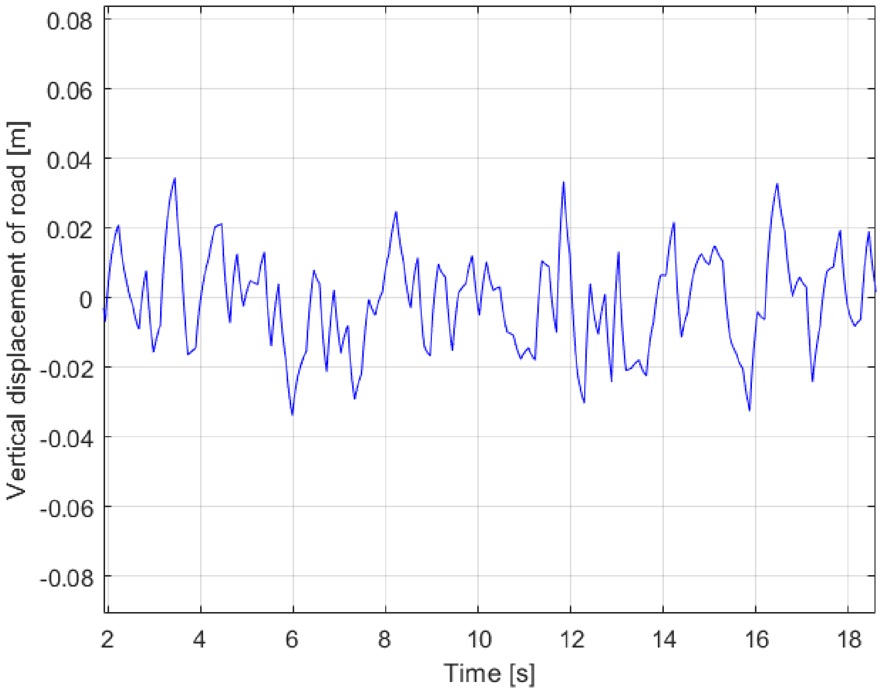


*Figure 13 Disturbance of typical road*

The bumpy road condition is generated by in terms of a sin function, which defines equation and is dependent on the parameter t which is the time. The function specifies a maximum bump of 0.15-meter height.

$$q = 0.15 * \sin(9 * \pi * t) \tag{9}$$

In the disturbance model there is only one bump. The bumper function works only between time 8-8.1111 seconds. It represents a real bump which height is 15 cm and width is 83 cm. The simulated bump road disturbance model is shown in *Figure 14* and the physical dimension of the bump is shown in *Figure 15*.

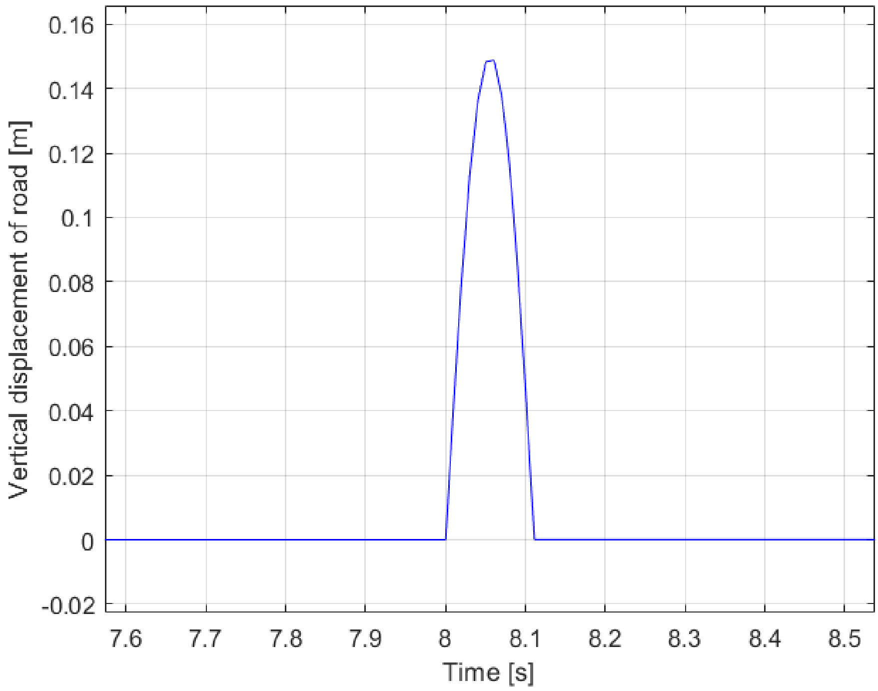


*Figure 14 The bump model*

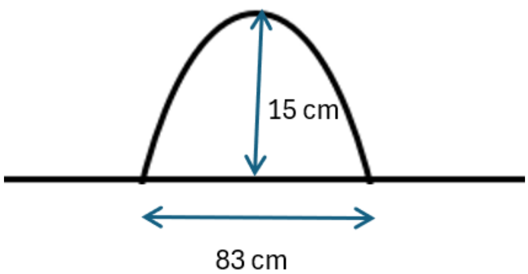


*Figure 15 Physical dimensions of the bump*

## 2.4. Simulation of the Dynamics Model for ECAS System

According to the mathematical model of air suspension system, combined with the designed PID controller, the simulation and control model of height adjustment for ECAS is built in the MATLAB/Simulink software. The simulation model consists of the model of solenoid valve, the variable mass thermodynamics system model of air spring, the quarter vehicle model of air suspension system, and the PID controller. Through simulation the performance of the designed controller is verified. The simulation parameters are shown in the *Table 2*.

*Table 2 Simulation parameters*

| | | |
|---|---|---|
| Sprung mass | $m_1$ | 1550 kg |
| Unsprung mass | $m_2$ | 200 kg |
| Damping coefficient | $C_f$ | 8300 N.s/m |
| Vertical stiffness of the tire | $K_{tf}$ | 750000 N/m |
| Effective area of air spring | $A_e$ | 0.042 $m^2$ |
| Volume Changing rate | $\frac{dV}{dx}$ | 0.045 $m^3/m$ |
| Pressure of air reservoir | $P_r$ | 0.8 MPa |
| Effective area of the valve | $S_e$ | 7.34 x $10^{-6}$ $m^2$ |
| Polytropic index | $k$ | 1.38 |
| Critical pressure ratio | $C_r$ | 0.528 |
| Working temperature | $T$ | 300 K |

According to the practical operation of the vehicle, three height adjustment mode of ECAS system are defined as follow: high mode (0.75m), normal mode which is driving mode (0.5m), low mode (0.25m). These modes measured from the ground level which is 0. In the ECAS system simulation, a PID controller used. The PID controller's gain values are in *Table 3*.

*Table 3 PID controller's gain values*

| | | |
|---|---|---|
| Proportional gain | $P$ | 3.5 |
| Integral gain | $I$ | 0.06 |
| Derivative gain | $D$ | 1.5 |
| Filter coefficient | $N$ | 100 |

# 3. RESULTS AND DISCUSSION

The ECAS system is tested in the Simulink simulation in three different conditions. These are a bump response, disturbance road response and height adjustment process. The busses velocity is 7.5 m/s (27 km/h) on the road.

## 3.1. The Bump Response of ECAS System

When the bus is moving on the road, it passes over a bump is described in section 2.2.4. When the bus passes over an 83 cm width and 15 cm height bump, the ECAS system works, and maximum vehicle height is 0.55 m. It is 0.05 m higher than the road condition 0.5 m. The response of the bus is shown in *Figure 16*. The ECAS system has 67% suppression of the bump. The bus reaches a steady-state condition wit the help of the PID controller in 3 seconds.

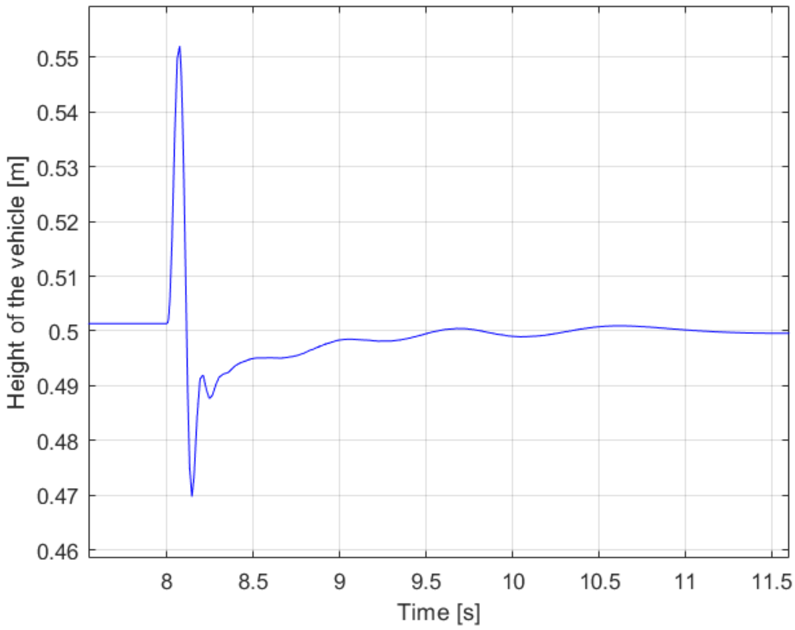


*Figure 16 Response to a bump*

## 3.2. Road Disturbance Response

The road disturbance is defined in section 2.2.4. That disturbance model has 0.03 m peak values and -0.03 m valley values. The ECAS system adjusted as 0.02 m disturbance is normal condition. If the road disturbance higher than 0.02 m or smaller than -0.02 m the air valves works and the bus's height changes. This mode is very usable for the valves and air consumption rate. With the help of this adjustment, air valves do not open and close continuously and their life is increases. Another profit of this mode is about air consumption rate. When the valve is not open and close continuously, air consumption rate is decreases. In the figure, the bus's height is proportional by road disturbance, when the disturbance is between -0.02 m and 0.02 m. However, if the disturbance is higher than 0.02 m or smaller than -0.02 m the valves works, and the system suppresses the disturbance. The response of the bus to the disturbance in *Figure 13* shown in *Figure 17*.

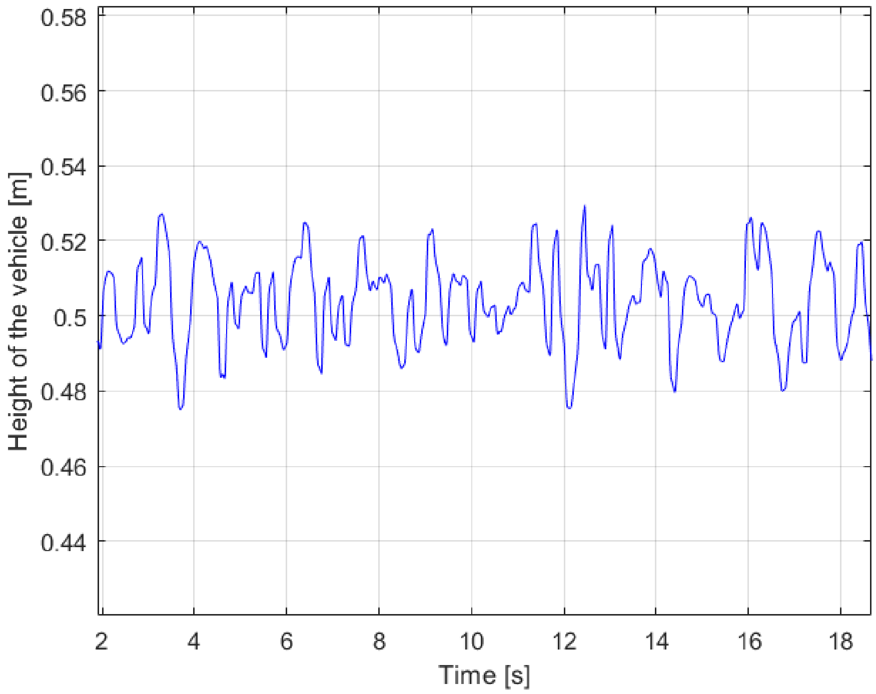


*Figure 17 Disturbance response*

### 3.3. Height Adjustment Process

The ECAS system enable to the driver adjusting the height of the bus rather than a passive suspension. When the driver adjusts the final height of the bus, air valves work according to the controller and the bus reaches the final and target height in a couple of seconds. The initial condition and normal height is 0.5 m.

In *Figure 18*, height increasing process is simulated. The green dashed line is the target height which is 0.75 m. The system increases the bus's height up to 0.8 m without a PID controller. With the help of the PID controller the steady state error is decreased and the bus reached the target height. When the driver set the value 0.75 m (high mode) the bus reaches the target height in 3 seconds.

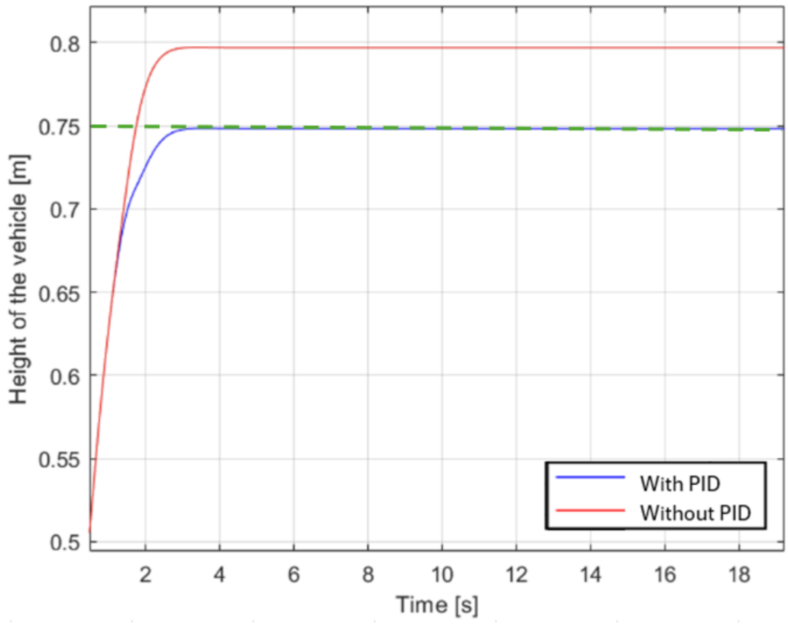


*Figure 18 Height increasing process*

In *Figure 19*, height decreasing process is simulated. The green dashed line is the target height which is 0.25 m. The system decreases the bus's height up to 0.3 m without a PID controller. With the help of the PID controller the steady state error is decreased, and the bus reached the target height. When the driver set the value 0.25 m (low mode) the bus reaches the target height in 6 seconds.

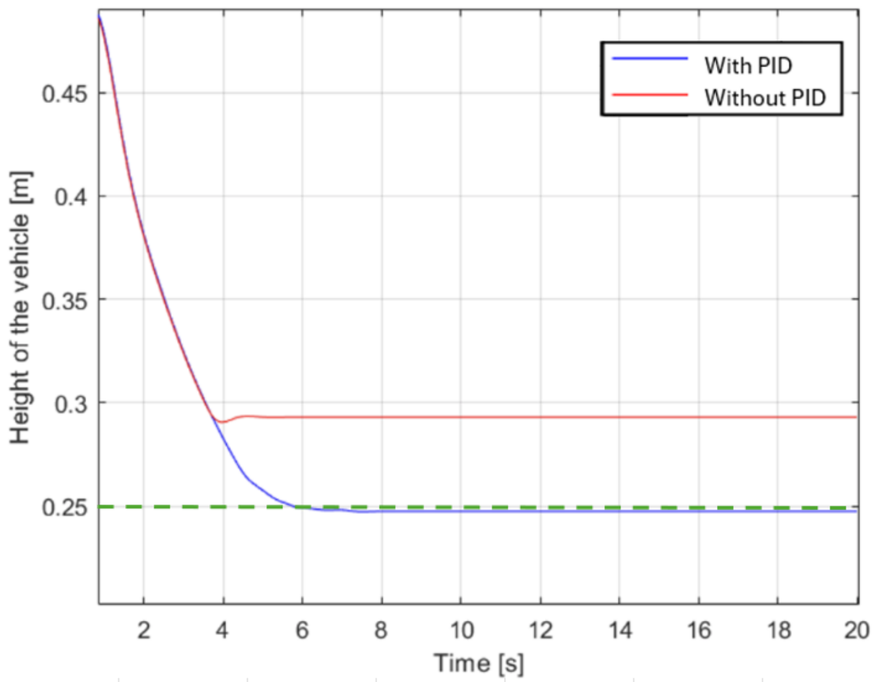


*Figure 19 Height decreasing process*

The time up to steady state condition is higher than increasing height process. Because, when increasing the bus upstream pressure is reservoir pressure. When decreasing the bus, upstream pressure is air spring inside pressure. Reservoir pressure value is accepted constant and 0.8 MPa and air spring pressure is average 0.58 MPa. Reservoir pressure is higher than air spring pressure, so increasing the bus is faster than decreasing process.

## 3.4. Cost Analysis

To perform a comprehensive cost analysis for implementing an Electronically Controlled Air Suspension (ECAS) system on public transportation buses, several key components and factors are considered. The costs are calculated by per bus.

### 3.4.1. Initial Costs

- Air suspension system components (air springs – 15 000 TL, shock absorbers – 9 000 TL, air compressor – 12 000 TL, control unit – 7 500 TL, sensors and valves – 4 500 TL)
- Electronic control unit (ECU) – 18 000 TL
- Wiring and connectors – 3000 TL
- Labor costs for installation – 30 000 TL

### 3.4.2. Operational Costs

- Regular maintenance of the ECAS system – 6 000 TL
- Training for maintenance staff and bus operators – 15 000 TL

### 3.4.3. Potential Savings

- Improved Fuel Efficiency saving per year – 4 500 TL
- Reduced Wear and Tear – 5 000 TL
- Extended solenoid valve lifetime – 6 000 TL
- Passenger Satisfaction – 5 000 TL
- Decreasing air consumption ratio – 3 000 TL

The initial cost for implementing an ECAS system on a bus is 99 000 TL. The operational cost is 21 000 TL, but the savings amount to 23 500 TL, resulting in a net savings of 2 500 TL for one bus. This cost-benefit analysis indicates that while the initial investment is significant, the ECAS system can provide long-term savings and benefits, including improved ride comfort, extended vehicle lifespan, and increased passenger satisfaction.

# 4. CONCLUSION

In conclusion, Electronically Controlled Air Suspension (ECAS) systems represent a significant advancement in the field of public transportation, offering enhanced ride quality, improved safety, and enabling height adjustment. The implementation of ECAS in public buses addresses the critical need for adaptive suspension solutions that can respond dynamically to varying load conditions and road surfaces, thereby optimizing passenger comfort and vehicle stability and passengers' accessibility by height adjustment. The height adjustment process is an important difference from the passive suspension systems. In section 3, profits of the ECAS under the distributed road and a bump on the road has discussed. The ECAS system with a PID controller can suppress the bump up to 67%. The PID controller helps decreasing the steady-state error. The controller also prevents to damage on the air valves by adjusting it. The system does not work if the distance between the desired height and the real height of the bus is between -0.02 m to 0.02 m. This adjustment helps also decreasing the air consumption rate from the air reservoir. Al in all, ECAS system is very useful, comfortable and conservative for components such as air valves.

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# APPENDICES

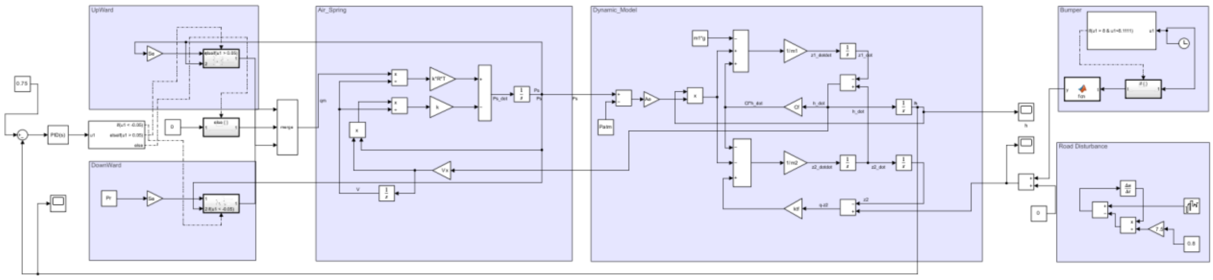

*Figure 20 Simulink model of the ECAS system*

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