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DESIGN AND IMPLEMENTATION OF A TEST BENCH FOR EVALUATING THE DYNAMICS OF PNEUMATIC WASTEGATE ACTUATORS

ABSTRACT: This paper presents the design and implementation of a dedicated, custom-built test bench for evaluating the dynamics of pneumatic wastegate actuators, focusing on the precision manufacturing and structural integration of a novel measurement setup. Earlier engine-level models have used measured boost-pressure responses to characterize actuator dynamics, while gas-stand studies have focused on wastegate flow. The effect of pneumatic-line length on the delay from the valve command to the onset of rod and flap movement remains insufficiently documented. To overcome these limitations, a specialized test bench was designed using Autodesk Inventor and fabricated via fused deposition modeling from polylactic acid (PLA). The mechanical design incorporates a rigid flat baseplate, modular brackets with elongated mounting slots for fine-adjustment, and a precise kinematic linkage that replicates actual turbocharger geometry. The experimental setup enables the simultaneous monitoring of the linear displacement of the piston rod and the angular rotation of the flap via slide and rotary potentiometers, thereby distinguishing the rod response from the flap response and measuring their onset-time difference. In this context, dead time is precisely defined as the inherent actuation delay—specifically, the time interval from the electrical command change at the solenoid valve coil until the physical onset of movement at the component. The measured interval can include valve switching, pressure buildup or venting in the line and chamber, and the initial mechanical response; their separate contributions were not identified. Experiments were conducted by varying the length of the pneumatic hose (inner diameter of 4 mm) across six values ranging from 5 cm to 30 cm at a constant supply pressure. The results demonstrate the viability of the developed test bench and measurement method for comparing characteristics under controlled conditions, free from the influence of aerodynamic forces and variable temperatures.

KEYWORDS: wastegate actuator; automotive mechatronics, 3D printing, test bench

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PROJEKTOVANJE I IZRADA PROBNOG STOLA ZA ISPITIVANJE DINAMIKE PNEUMATSKIH WASTEGATE AKTUATORA

REZIME: U ovom radu je prikazano projektovanje i izrada namenskog probnog stola za ispitivanje dinamike pneumatskih *wastegate* aktuatora, sa posebnim akcentom na konstrukciju i preciznu izradu mernog sistema. U ranijim modelima na nivou motora odziv aktuatora je procenjivan na osnovu odziva pritiska natpunjenja, dok su se ispitivanja na gasnom probnom stolu bavila protokom kroz wastegate ventil. Uticaj dužine pneumatskog voda na kašnjenje od komande elektroventilu do početka pomeranja klipnjače i klapne još nije dovoljno dokumentovan. Radi prevazilaženja ovih ograničenja, u programu Autodesk Inventor konstruisan je namenski probni sto čiji su noseći elementi izrađeni 3D štampom od polilaktida (PLA). Mehanička konstrukcija obuhvata krutu osnovnu ploču, modularne nosače sa produženim otvorima (prorezima) za fino pozicioniranje i preciznu kinematičku vezu koja verno kopira geometriju kućišta turbopunjača. Postavka omogućava istovremeno praćenje pravolinijskog pomeraja klipnjače i zaokreta klapne preko kliznog i kružnog potenciometra, čime se izdvajaju odzivi klipnjače i klapne i određuje razlika vremena početka njihovog kretanja. U ovom kontekstu, mrtvo vreme je definisano kao inherentno kašnjenje sistema — vremenski interval od električne komande na kalemu elektroventila do početka fizičkog pomeranja posmatranog dela. Izmereni interval može da obuhvati prebacivanje elektroventila, porast ili pad pritiska u vodu i komori, kao i početnu reakciju mehanizma; njihovi pojedinačni doprinosi nisu određeni. Eksperimenti su sprovedeni promenom dužine pneumatskog creva (unutrašnjeg prečnika 4 mm) u šest vrednosti od 5 cm do 30 cm, pri konstantnom pritisku napajanja. Rezultati potvrđuju upotrebljivost razvijenog probnog stola i merne metode za poređenje karakteristika pod kontrolisanim uslovima, bez uticaja aerodinamičkih sila i promenljivih temperatura.

KLJUČNE REČI: wastegate aktuator; mehatronika motornih vozila, 3D štampa, probni sto

INTRODUCTION

Modern internal combustion engines almost universally employ turbocharging as a primary method for increasing specific power and reducing fuel consumption. Reducing engine displacement while maintaining or increasing output power—a process known as downsizing—is only feasible when air is supplied to the cylinders at pressures higher than atmospheric. This task is performed by the turbocharger, and the amount of energy extracted by the turbine from the exhaust gases must be continuously regulated to prevent boost pressure from exceeding allowable limits. This regulation is most commonly achieved via a *wastegate* valve, whose position is set by a pneumatic positive-pressure actuator. The response speed of this actuator directly determines how quickly and accurately the control system can regulate boost pressure.

Prior research has addressed different parts of the actuation chain: pneumatic valve circuits and solenoid dynamics (Galindo et al. 2009; Szente & Vad, 2001); a model of pneumatic wastegate pressure, position, and dynamics validated on an engine test bench (Thomasson et al. 2009); engine-cell estimation of wastegate position and flow including actuator and gas-load forces (Salehi et al. 2014); and gas-stand characterization of wastegate flow at prescribed openings (Serrano et al. 2017; Cordalonga et al. 2025). Transient turbocharger modelling also distinguishes fluid, mechanical, and thermal responses (Deng et al. 2021). These studies do not directly report the command-to-onset delays of both the rod and flap for controlled changes in pneumatic hose length. An in-service failure analysis linked rod deflection to localized diaphragm loading, further emphasizing the relevance of linkage geometry to tests closer to operating conditions (Li et al. 2025).

The primary contribution of this paper lies in the design and implementation of a dedicated test bench tailored specifically to isolate and evaluate the dynamic behaviour of the complete solenoid valve–line–actuator assembly. By constructing a specialized hardware environment, the setup enables precise measurement of the system's dead time—defined here as the inherent fluid-dynamic and mechanical delay spanning from the electrical command change at the valve coil to the physical onset of movement. Furthermore, the test bench incorporates a dual-sensor kinematic setup that successfully decouples the piston rod response from the flap response.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Published actuator models and engine-level tests describe the coupled boost and wastegate response, while gas-stand studies mainly quantify turbine and bypass flow (Thomasson et al. 2009; Salehi et al. 2014; Serrano et al. 2017; Cordalonga et al. 2025). The present study asks a narrower question: how does a controlled change in pneumatic hose length affect the interval from the valve coil command to the onset of rod and flap movement? The

objective is to design and demonstrate a dedicated test bench for simultaneous measurement of the solenoid valve–line–actuator–linkage assembly at fixed supply pressure, with an unloaded flap and at room temperature.

The measured dead time spans the interval from a change in voltage at the solenoid valve coil to the first detected movement of the rod or flap. It may include valve switching, filling or venting of the pneumatic line and chamber, and the mechanical response needed to initiate movement. During opening, pressure must build sufficiently to overcome the return spring preload. Because pressure was not recorded, the individual contributions to the measured delay cannot be separated in this study.

To capture this phenomenon without engine-induced interferences, the testing was conducted using the newly designed test bench by varying the pneumatic hose length from 5 cm to 30 cm across six steps at a constant supply pressure and room temperature, utilizing an unloaded flap to eliminate external aerodynamic forces.

Limitation

The limitations of the investigation are as follows. The flap remained unloaded during all measurements, meaning that the results describe the behaviour of the mechanism without the aerodynamic force of the exhaust gases. The testing was conducted at room temperature, whereas under operating conditions the diaphragm works at a significantly higher temperature, which alters its elasticity. Absolute pressure within the pressure chamber was not measured; instead, only displacement was measured, meaning that the individual contributions of the various causes of dead time cannot be isolated. These limitations do not diminish the usefulness of the results, as the objective of the study is comparison under identical conditions rather than absolute characterization of the actuator in its installed state.

TEST BENCH DESIGN AND MEASUREMENT SETUP

To carry out the measurements described it was necessary to design a dedicated test bench. The requirement set for the design was that the actuator must be tested independently of the engine, in a setup that enables simultaneous monitoring of the piston rod displacement and the flap rotation, with a simple change of the pneumatic line length while keeping all other parameters constant between measurement series.

Test Bench Concept

The base of the test bench consists of a flat plate to which all elements are attached. The plate ensures a constant relative position between the actuator, the lever, and the measurement sensors, thereby eliminating the most common cause of result scatter in improvised setups, which is the shifting of elements between measurements. The actuator is mounted on a bracket that supports it by its spring-half housing, in the exact position it occupies when installed on the turbine housing.

The actuator piston rod acts on the lever via an eyelet, and the lever is fitted into a rotational pivot that represents the flap shaft. Linear rod displacement is thus converted into rotation around a fixed axis using the corresponding linkage geometry. The difference between the detected motion-onset times of rod and flap is reported as a timing indicator of their transmission. It cannot by itself quantify mechanical clearance, because the two sensors observe different motions and use threshold-based onset detection.

The flap on the test bench is unloaded, which was stated as a limitation in section 1. This choice avoids the influence of varying aerodynamic load; however, uncontrolled differences between measurement sessions may still affect the results. The general layout of the assembly is shown in Figure 1, the view from the opposite direction in Figure 2, and a detail in Figure 3.



Figure 1 Three-dimensional model of the test bench assembly



Figure 2 Test bench assembly, view from the opposite direction

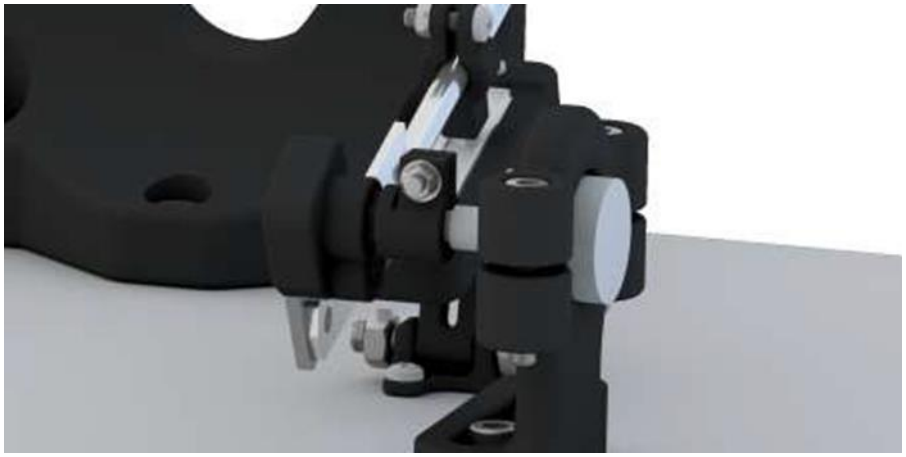


Figure 3 Detail of the joint connection of the piston rod and lever with the slide potentiometer bracket

The final appearance of the test bench is shown in Figure 4.



Figure 4 final appearance of the test bench

Three-Dimensional Modeling

All load-bearing elements of the test bench were ***modelled*** in the Autodesk Inventor software package, using a procedure that starts with a 2D sketch and extrusion of the basic shape, followed by adding holes, reinforcements, and fillets. The models were created as separate parts and then assembled into an assembly where constraints defined their relative positions and degrees of freedom. Such a procedure enabled verification of whether the piston rod remains free of collisions with the bracket throughout its entire stroke and whether the lever has sufficient clearance for rotation.

During modeling, special attention was paid to two aspects. First, all bolt holes were designed as elongated slots instead of circular holes, which enabled fine adjustment of the bracket position during assembly. Second, wall thicknesses were chosen so that the parts are sufficiently rigid for the arising loads, yet suitable for fabrication via material deposition without requiring a large amount of auxiliary (support) material.

From the adopted models, workshop documentation was derived, consisting of one drawing for each part, with necessary cross-sections, dimensions, material designations, and general tolerances according to the ISO 2768-m standard.

Parts Produced by 3D Printing

The load-bearing parts were produced via fused deposition modeling using polylactic acid (PLA). This material was chosen due to its satisfactory rigidity, low tendency to warp during cooling, and ease of fabrication. Since testing has a short duration and is conducted at room temperature, the limited thermal resistance of polylactic acid does not present an obstacle.

The largest part, the actuator bracket, absorbs the reaction force developed by the actuator and is therefore designed with reinforced ribs and a large contact surface resting on the plate. The smallest parts, the potentiometer coupling and the rod clamp, serve to connect the measurement sensors to the moving parts and were manufactured at an enlarged scale on the drawings for clarity.

Installation of Measurement Potentiometers

The slide potentiometer is positioned so that its slider directly tracks the displacement of the actuator piston rod. The connection is realized via a coupling clamped onto the rod, thereby eliminating slippage. The potentiometer body is attached to a bracket connected to the plate via a base, and slots on the base allow adjustment so that the slider occupies the middle portion of its stroke at rest. The working stroke of the slide potentiometer is 10 mm, covering the entire stroke of the piston rod.

The rotary potentiometer is positioned on the lever rotation axis so that its shaft tracks the rotation of the flap. Since the angular stroke of the flap is only about 15° to 20°, while the potentiometer has a significantly larger available angle, initial measurements showed that it is important to carefully adjust the initial position of the shaft. If the initial position is chosen close to the end of the available range, the output voltage reaches the limit of the analog-to-digital

converter's measuring range and clips, making the moment of motion onset indefinite. After adjusting the initial position, the scatter of measured times on this channel was significantly reduced. Both potentiometers are wired as voltage dividers between a 3.3 V supply and ground, with the wiper connected to an analog input of the microcontroller. Since, the moment of change is measured rather than the absolute value of displacement, calibration in units of length and angle was not necessary.

Pneumatic Installation

Air is supplied to the actuator via a 3/2-way valve (three ports, two positions), model 3V210-06, shown in Figure 5. The valve is spring-return, meaning that in the de-energized state it connects the actuator port to the exhaust, allowing the actuator spring to return the piston rod to its initial position. The operating pressure range of the valve is from 1.5 bar to 8 bar. The supply pressure was maintained within the range of 1.9 bar to 2.0 bar throughout all measurements and was not changed between series. Hose length was the only parameter intentionally varied; small supply-pressure fluctuations could still contribute to the observed scatter. A polyurethane hose with an inner diameter of 4 mm was placed between the valve and the actuator. Six lengths were tested: 5, 10, 15, 20, 25, and 30 cm. The hoses were cut to size and connected using quick-release fittings, so that changing the length took a short time and did not require moving any other element of the setup. Each hose change marked the beginning of a new measurement series.



Figure 5 Valve 3V210-06 with coil and ports

DISCUSSION AND ANALYSIS OF RESULTS

The supplied measurement log contains 501 recorded cycles for six hose lengths (5, 10, 15, 20, 25, and 30 cm). The 482 cycles marked “OK” were used for the plots; 19 cycles flagged as outliers were excluded. The first cycle of each session and one invalid 5 cm session had already been omitted from the log. Dead time is measured from the coil-voltage change to a displacement threshold of 4% of the measured stroke in each cycle. Figure 6 presents the arithmetic mean and sample standard deviation of accepted cycles at each length.

From 5 to 30 cm, mean opening dead time increased from 33.61 to 37.82 ms for the rod and from 41.14 to 45.91 ms for the flap. The six means show an overall upward trend, but not a strictly monotonic or proportional relationship: the 20 cm opening means are lower than those at 15 cm. The opening-rod standard deviation within a length was 1.09–1.42 ms. These observations are consistent with a contribution from the greater pneumatic volume, but without a pressure trace its share of the measured delay cannot be quantified.

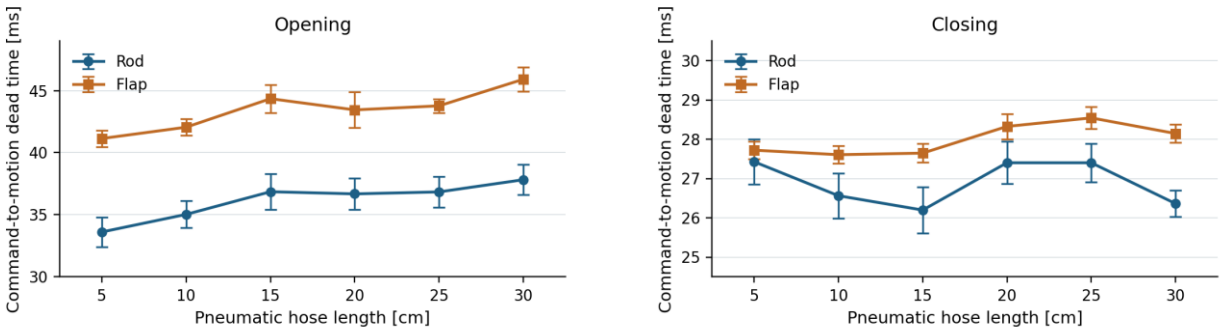


Figure 6 Mean dead time at opening and closing versus pneumatic hose length; error bars represent ±1 sample standard deviation. Accepted cycles per length: 42, 80, 89, 98, 103, and 70.

The closing phase shows a different pattern (Figure 6). The rod means range from 26.20 to 27.43 ms across the six lengths without a consistent monotonic change; the flap means range from 27.61 to 28.54 ms. The closing-rod

standard deviations (0.33–0.59 ms) are smaller than their opening counterparts. A spring-driven return after venting provides a plausible explanation for this asymmetry, although valve switching and pressure decay were not recorded separately.

The simultaneous measurements also yield the flap-minus-rod onset difference shown in Figure 7. In opening, the mean difference was 6.77–8.09 ms, and the rod was detected first in all 482 accepted cycles. In closing, the mean difference was 0.30–1.78 ms; the rod was detected first in 455 cycles, the times were equal in 16, and the flap was detected first in 11. With 0.33 ms recording resolution and separate displacement thresholds, this timing difference must not be interpreted as a direct measurement of joint clearance alone.

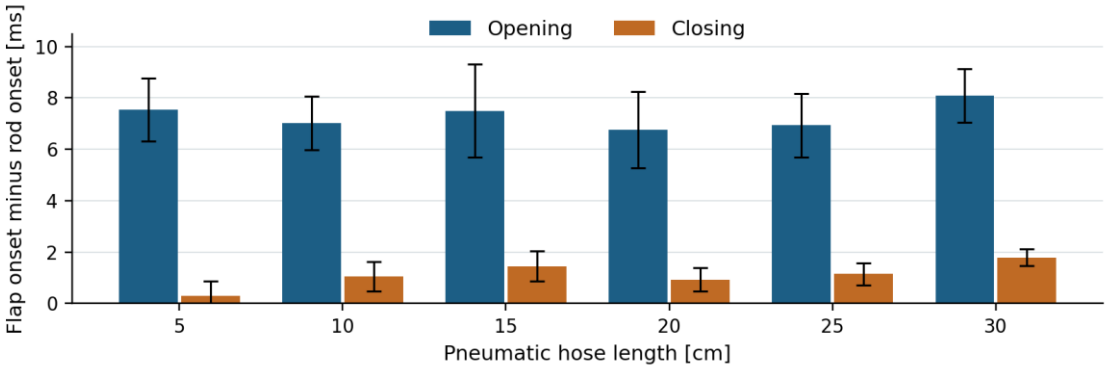


Figure 7 Mean difference between flap and rod motion-onset times for opening and closing; error bars represent ±1 sample standard deviation.

The figures therefore support a descriptive comparison within the tested, unloaded room-temperature setup. Error bars show scatter among accepted cycles rather than uncertainty in the mean across independent installations: most lengths were tested in one or two sessions. Additional pressure measurements, repeat sessions, controlled flap loading, and elevated-temperature tests are required before attributing the delays to individual physical causes or generalizing them to an installed turbocharger.

CONCLUSIONS

The successful realization of this research relied heavily on the dedicated design, 3D modeling, and physical fabrication of a specialized test bench. Modeled entirely within the Autodesk Inventor software package, the test bench was engineered to test the pneumatic wastegate actuator independently of an engine environment, featuring carefully designed components with elongated bolt holes for fine-tuning and optimized wall thicknesses for fused deposition modeling using polylactic acid (PLA). Complete workshop documentation with free-dimension tolerances according to ISO 2768-m ensured precise manufacturing, while the structural layout—utilizing a flat baseplate and a precise kinematic linkage—successfully eliminated component shifting and reproduced exact engine-like geometry, including joint clearances.

The dual-potentiometer arrangement resolved the onset of rod and flap movement separately. Among the accepted cycles, mean opening dead time increased by 4.21 ms for the rod and 4.77 ms for the flap between the 5 and 30 cm hoses, with departures from a monotonic trend at intermediate lengths. Closing rod dead time showed no comparable monotonic increase. The rod preceded the flap in all accepted opening cycles, whereas 27 closing cycles showed equal or reversed detected onset times. The measured onset-time difference is not a direct estimate of mechanical backlash. These results demonstrate the bench's value for controlled comparison, while the present measurements do not identify the separate pneumatic and mechanical contributions or establish in-service delays.

Future work should first add synchronized measurements of coil current and pressure at the valve outlet and actuator inlet or chamber. This would help separate electrical switching, line filling or venting, and the pressure threshold for motion, which the present displacement-only setup cannot resolve.

The rig should then be equipped with a calibrated, repeatable flap load and temperature control, using temperature-suitable parts where the current PLA brackets are unsuitable, to test how exhaust-gas loading and heating alter the observed delays. Finally, repeating the tests with other actuator and linkage specimens, hose diameters and supply pressures, and comparing selected conditions with an installed or gas-stand assembly would establish whether the room-temperature, unloaded trends transfer to service conditions. Pressure and position sensor calibration, together with an uncertainty analysis of motion-onset detection, should accompany these extensions.

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