

Woodward: On-Highway Transportation Efficiency Gains | Electronic Turbocharger Wastegate Actuator

Brooke Carlson

Department of Mechanical Engineering and Honors Program at Colorado State University

Advisor: Dr. Mitchell Stansloski

Committee Member: Kari Cowden

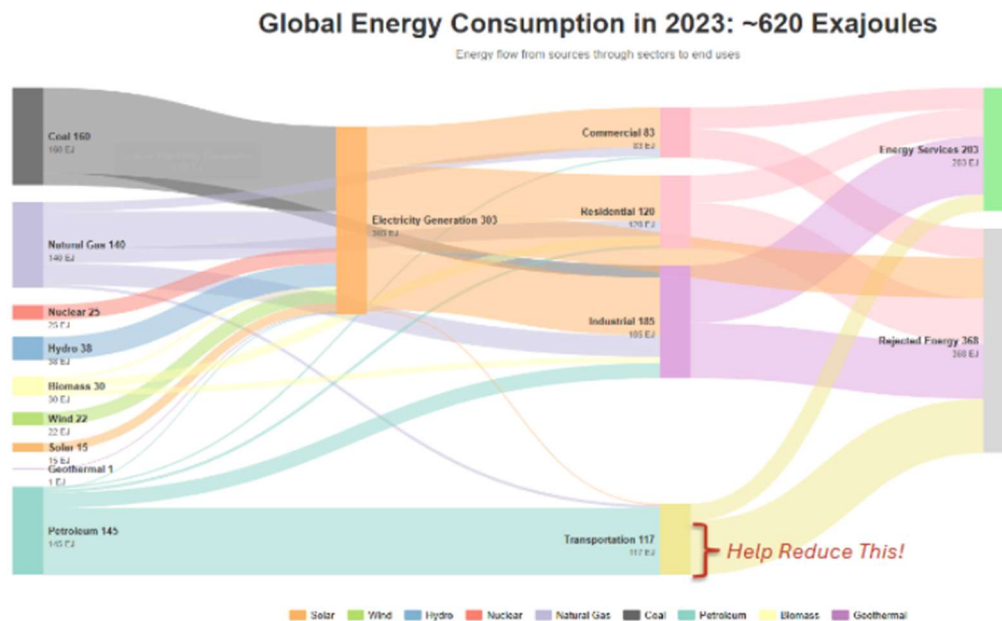
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## Overview

On-highway transportation is one of the largest consumers of global petroleum, yet internal combustion engines convert only about 24% of fuel energy, as seen in Figure 1, into useful mechanical work, with the remainder lost primarily as heat and pumping losses [1]. Improving engine efficiency within this sector therefore represents a significant opportunity for reducing fuel consumption and emissions at scale.



*Figure 1: Global Energy Consumption in 2023*

Turbocharging is a widely used method to improve engine efficiency by recovering waste exhaust energy to increase intake air density, enabling smaller engines to produce equivalent power output [2]. However, while turbochargers improve efficiency, their performance is strongly dependent on the wastegate system, which regulates exhaust flow to the turbine and directly controls boost pressure. If the engine has improved boost control, it has improved combustion

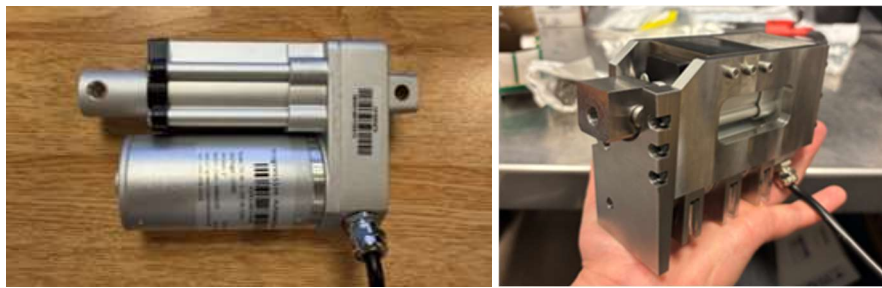
leading to improved efficiency. Most production on-highway engines use pneumatically actuated wastegates that rely on spring-diaphragm mechanisms driven by manifold pressure. Although robust and cost-effective, these systems are inherently passive and limited in controllability. They cannot adapt dynamically to varying engine loads and transient operating conditions, which restricts optimization of boost pressure across the full engine operating range.

Prior research has shown that wastegate control strategy is a key factor in determining turbocharged engine performance, including transient response, fuel efficiency, and torque delivery. Improved control of turbine flow can reduce boost lag and improve overall engine efficiency by better managing exhaust energy [4]. More recent work in electronically controlled systems demonstrates that integrating wastegate control into closed-loop electronic management enables more precise boost regulation and improved coordination with throttle and fueling systems. Despite these advantages, pneumatic wastegate systems remain widely used in on-highway applications due to their simplicity and durability. This creates a gap between modern control capability and production implementation.

The problem addressed in this project is that conventional pneumatic wastegate actuators lack the precision, responsiveness, and adaptability required to fully optimize turbocharged engine performance across real-world operating conditions. This limitation restricts the ability of engine control systems to maximize efficiency and transient performance simultaneously. To address this issue, this project develops an electronic wastegate actuator system that replaces passive pneumatic control with electronically controlled actuation integrated into the engine control system. This enables real-time, precise control of wastegate position, improving boost regulation, transient response, and overall system flexibility across varying engine conditions.

## Final Design

The final design selected for this project is an electronically actuated wastegate system using a motor-driven linear actuator integrated with a custom mounting bracket and closed-loop ECU control strategy. This system replaces the original pneumatic wastegate actuator while maintaining full compatibility with the existing turbocharger architecture and mounting interface. The design was implemented as a retrofit solution to avoid modifications to the base engine while enabling active control of boost via electronically commanded wastegate positioning.



*Figure 2: Actuator and Mounting Bracket Assembly*

## *Critical Design Specifications*

To ensure system-level performance, the design was evaluated against six critical specifications: engine fit, force output, temperature, vibration, position sensing, and response time.

### **Engine Fit**

The actuator and mounting bracket were constrained to the existing compressor-mounted pneumatic actuator envelope. A compact multi-plate stainless steel bracket was designed to ensure full integration within the available engine space while maintaining necessary clearances for linkage motion and thermal isolation.

### **Force Capability:**

The actuator was required to generate sufficient linear force to overcome wastegate exhaust backpressure forces. A motor with gear drive was selected specifically to amplify motor torque into high linear output force while maintaining fine positional resolution.

#### **Temperature Resistance:**

The system was designed to operate within a -40°C to 120°C range. Material selection (17-4 PH stainless steel, H1150 condition) and thermal isolation strategies were used to ensure structural integrity and prevent degradation of mechanical properties under sustained high-temperature exposure near the turbocharger.

#### **Vibration Resistance:**

Given the high-vibration environment of on-highway engines, the bracket and fastener system were designed with care using all-metal lock nuts and threadlocker. The structure was also validated for dynamic loading conditions representative of engine operation.

#### **Position Sensing:**

A Hall-effect sensor integrated into the actuator provides real-time positional feedback. The sensor output is interpreted as incremental displacement, enabling closed-loop control of wastegate position through the ECU. This ensures repeatable positioning accuracy across the full stroke range (0–0.25 in).

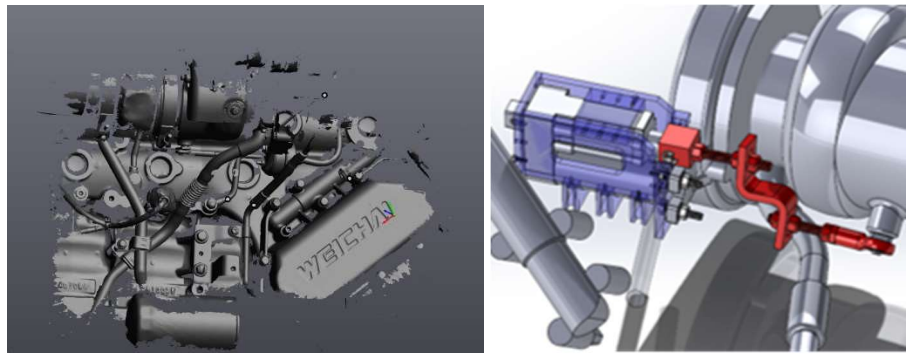
#### **Response Time:**

System response was designed to meet transient engine demand requirements by minimizing actuator lag. The combination of DC motor actuation and PID tuning enables fast positional correction and improved boost tracking compared to passive pneumatic systems.

## ***Verification and Validation***

Each critical specification was verified through a combination of analytical modeling, CAD validation, and subsystem testing throughout the design process.

Engine fit was validated by first designing around a 3D scan CAD model seen in Figure 3. Then, using a physical 3D-printed prototype of the mounting bracket, confirmed spatial compatibility within the turbocharger envelope and proper alignment with OEM mounting points.



*Figure 3: Engine Scan and CAD Model Design*

Force capability was verified through hand calculations treating the bracket as a cantilevered structure under combined static actuator load and dynamic vibration loading. Safety factors were calculated for all critical load paths, including fasteners, bracket plates, and linkage interfaces, confirming sufficient structural margin.

Temperature performance was validated through material property analysis of 17-4 PH stainless steel (H1150 condition), cross-referenced with ASTM material standards and manufacturer data. Thermal margins were confirmed relative to maximum expected engine bay temperatures, ensuring stable mechanical performance under operating conditions.

Vibration performance was evaluated using industry-standard fastening strategies. While full engine vibration testing was outside the project scope, the combination of prevailing torque

lock nuts and threadlocker was validated as an accepted method in similar on-highway engine applications, providing high confidence in joint retention under cyclic loading.

Position sensing was validated through ECU bench testing using a simulated input environment. A calibrated dial indicator was used as a reference measurement tool, and actuator position feedback from the Hall-effect sensor was compared across multiple commanded stroke positions (0%, 25%, 50%, 75%, 100%). Error values were recorded to confirm acceptable positional accuracy.

Response time was evaluated through controlled actuation tests during bench validation, where commanded step inputs were applied and system settling behavior was observed through sensor feedback. PID control tuning was adjusted to minimize overshoot and improve transient response.

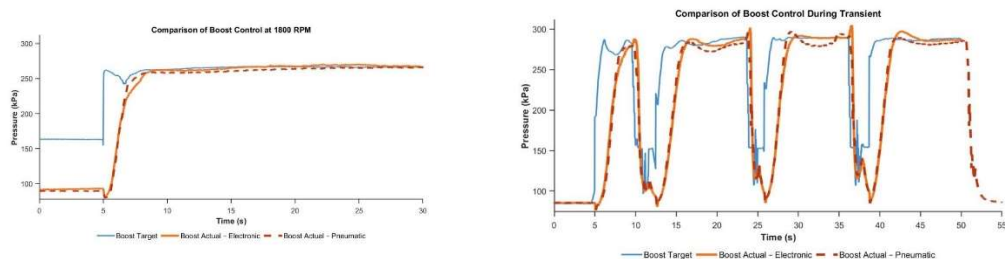
### ***Testing and Final System Performance***

The electronic wastegate actuator was installed on the turbocharger assembly seen in Figure 4 and evaluated through both steady-state and transient engine testing. Steady-state operation confirmed baseline controllability across fixed load conditions, while transient testing was used to assess real-world response under rapidly changing engine demand. All results were benchmarked against datum data collected from the original pneumatic wastegate actuator for direct comparison.



*Figure 4: Actuator On The Engine*

During transient operation, the electronic actuator demonstrated noticeably improved boost control compared to the pneumatic system seen in Figure 5. Boost pressure tracked the target more closely, with reduced lag and improved stability during rapid throttle transitions. This behavior aligns with established findings that electronically actuated wastegates improve transient boost regulation by enabling closed-loop control of exhaust energy flow [2], [4]. A thermal issue was observed during extended operation, where partial softening of the actuator housing occurred under sustained high-temperature exposure, highlighting the need for improved thermal isolation in future iterations.



*Figure 5: Boost Control Data – Steady and Transient*

During early testing, a binding issue in the adjustable Z-bar linkage required a design change to a bent Z-bar direct-drive configuration. This modification eliminated misalignment and significantly improved mechanical consistency and response behavior. With the updated linkage, actuator response time improved, allowing boost to reach target levels more quickly and

remain stable for longer periods. Overall, the final system achieved stronger boost control authority than the pneumatic baseline, resulting in improved combustion stability and reinforcing the potential for efficiency gains in turbocharged on-highway applications [1].

## Reflection

Through this Honors Thesis, I see this project becoming one of the defining “hands-on engineering” chapters of my college experience. I’ve learned a lot about how I work under real constraints—not just technical ones, but time, manufacturing limits, testing failures, and the reality that designs almost never work perfectly the first time. I’ve also learned more about teamwork and how everyone collaborates differently. Working through disagreements on design direction or even just when we were stressed in our own ways, showed me that good engineering is usually less about being right and more about being adaptable and willing to iterate quickly. I’m going to carry that mindset into whatever I do next.

The central focus of my project was designing an electronic wastegate actuator system to improve turbocharger control on on-highway engines and proving a concept that it could outperform a pneumatic design. We worked on replacing a traditional pneumatic wastegate with an electronically controlled linear actuator. The goal was to improve boost control precision and transient response by integrating closed-loop control through the SECM112 ECU using position feedback from a Hall-effect sensor. The project involved mechanical design (brackets, linkage, mounting), control integration (PID loop and ECU interfacing), and experimental validation through steady-state and transient engine testing compared to a baseline pneumatic system. In short, we were trying to turn a pressure-driven system into an actively controlled subsystem that could respond in real time to engine demand.

The broader context of this work is that transportation efficiency has a huge impact far beyond just engines or vehicles. On-highway engines are used in freight and logistics systems that move most of the goods people rely on every day. Even small efficiency improvements at the engine level scale into massive fuel savings, cost reductions, and emissions impacts across fleets. I think this matters to more than just engineers because it connects directly to fuel prices, environmental impact, and energy consumption at a global level. Fleet operators care about cost and reliability, policymakers care about emissions, and everyday people are affected by both through supply chains and air quality. Even though this is just a project on a turbocharger, I see it as part of a much larger push toward making existing transportation systems more efficient without requiring a complete overhaul of infrastructure.

## References

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