**Engineering Report: Active Suspension Design using LQR and Kalman Filter**

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**Project:** State Space Design of Active Vehicle Suspension

## 1. Summary

This report details the design, simulation, and validation of an active suspension control system. The primary objective was to develop a robust control architecture using a Linear Quadratic Regulator (LQR) and Kalman Filter to manage the inherent trade-off between **Ride Comfort** and **Road Holding**. While the system is capable of being tuned for luxury passenger isolation, this specific implementation focuses on a **High-Performance** configuration. Validated against a 20mm track irregularity, the system demonstrates a **~40% reduction in settling time** compared to a passive suspension, proving its efficacy for high-speed stability and grip recovery.

## 2. System Architecture & Control Strategy

**Physical System Model:** Quarter-car model in Figure 1, reference from is very often used for suspension analysis; because it is simple and can capture important characteristics of the full model. The equation for the model motions are found by adding vertical forces on the sprung and unsprung masses. Most of the quarter-car model suspension will represent the **m_s** as the sprung mass, while tire and axles are illustrated by the unsprung mass **m_us**. The spring, shock absorber and a variable force-generating element placed between the sprung and unsprung masses constitutes suspension. From the quarter car model, the design can be expanded into full car model.

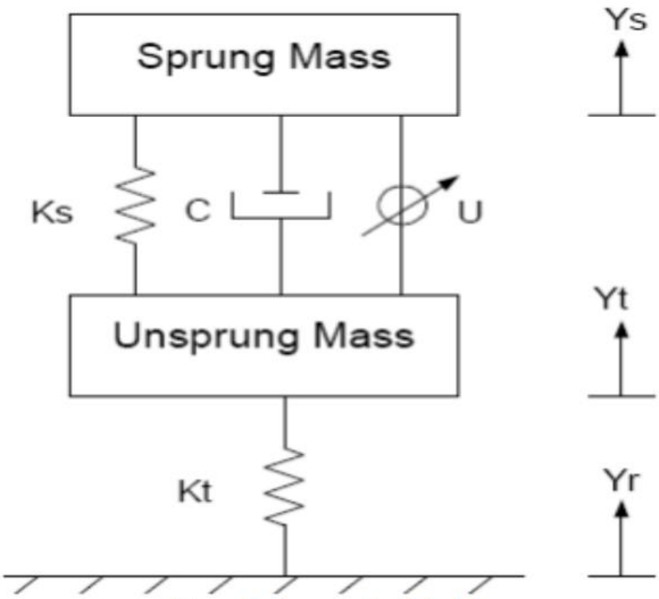


*Figure 1: Quarter Car Model from [1]*

**System Parameters:** To ensure real-world relevance, the simulation was based on a standard C-segment passenger vehicle referenced from [1].

*Table 1: System Parameters*

| Parameter | Symbol | Value | Unit | Description |
|---|---|---|---|---|
| Sprung Mass | $m\_s$ | 290 | kg | 1/4 Vehicle Body Mass (C-Segment) |
| Unsprung Mass | $m\_us$ | 59 | kg | Wheel & Upright Assembly |
| Suspension Stiffness | $Cs$ | 16,812 | N/m | Passive Spring Rate |
| Tire Stiffness | $Ct$ | 190,000 | N/m | Radial Tire Vertical Stiffness |
| Suspension Damping | $d$ | 1,000 | Ns/m | Passive Damping Coefficient |

The design utilizes a 2-Degree-of-Freedom (2-DOF) quarter-car model from Figure 1. The control loop consists of three main stages designed to handle real-world dynamics:

- **The Controller (LQR):** The core controller determines the ideal force required to stabilize the vehicle by minimizing a quadratic cost function from [1].
    - The Cost Function ($J$): The behavior of the suspension is governed by the following equation, which mathematically defines the "penalty" for bad performance:

$$J = \int_0^\infty (x^T Q x + u^T R u) dt$$

    Where:

        - $x^\top Q\, x$ **(Performance Cost):** represents the penalty for vibration and deviation from the target position. By increasing values in the $Q$ matrix, we tell the controller that stability is more important.
        - $u^\top R\, u$ **(Energy Cost):** represents the penalty for using actuator power.

- *Optimization Approach:* By adjusting the balance between $\boldsymbol{Q}$ and $\boldsymbol{R}$, the system can be biased towards softness (comfort) or stiffness (handling).
- *Current Tune:* For this report, the $\boldsymbol{Q}$ matrix was tuned to heavily penalize **Sprung Velocity** and **Suspension Deflection**. This forces the chassis to recover equilibrium instantly after a bump.

- **State Estimation (Kalman Filter):** Real sensors (like potentiometers and accelerometers) are noisy. This was simulated here with the help of Band-Limited white noise block from the Simulink library. If this noisy data is fed directly into the controller, it causes the actuator to "twitch" or jitter, leading to instability. A Kalman Filter was implemented to fuse these noisy measurements with the system mathematical model's prediction, providing a clean, estimated signal to the controller. This prevents actuator "jitter" and ensures smooth operation.

**Noise Rejection Performance:**

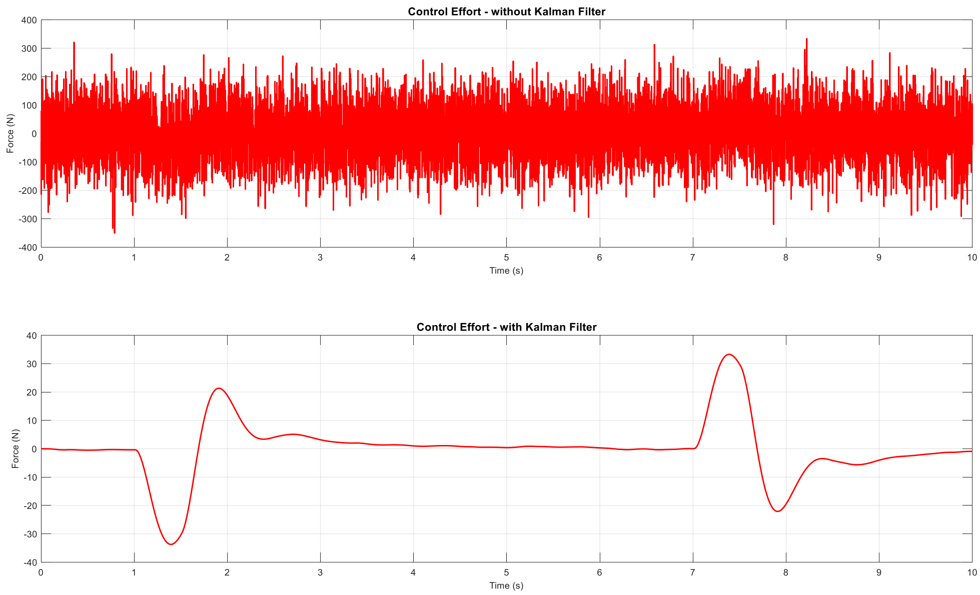


*Figure 2: Noise Rejection with the use of Kalman Filter*

**Observation:** As shown in the figure above, the raw sensor data fluctuates significantly due to noise. The Kalman estimate successfully filters this high-frequency noise while maintaining the correct phase and amplitude of the motion.
**Result:** This allows the LQR controller to apply smooth, consistent force, preventing mechanical wear.

- **Physical Constraints:** The design includes input saturation to limit control effort to $\pm 2000\ \mathrm{N}$, ensuring the simulation respects the physical limits of a standard hydraulic or electromagnetic actuator. The control force remains smooth (due to the Kalman filter's noise rejection) and peaks at **~35 N** for the 20mm input. This is exceptionally efficient, requiring less than 2% of a standard actuator's capacity

### 3. Performance Validation

The system was stress-tested using a Trapezoidal profile with an amplitude of **0.02m (20mm)**, representing a standard race track curb.

### A. Chassis Stability (Vertical Acceleration)

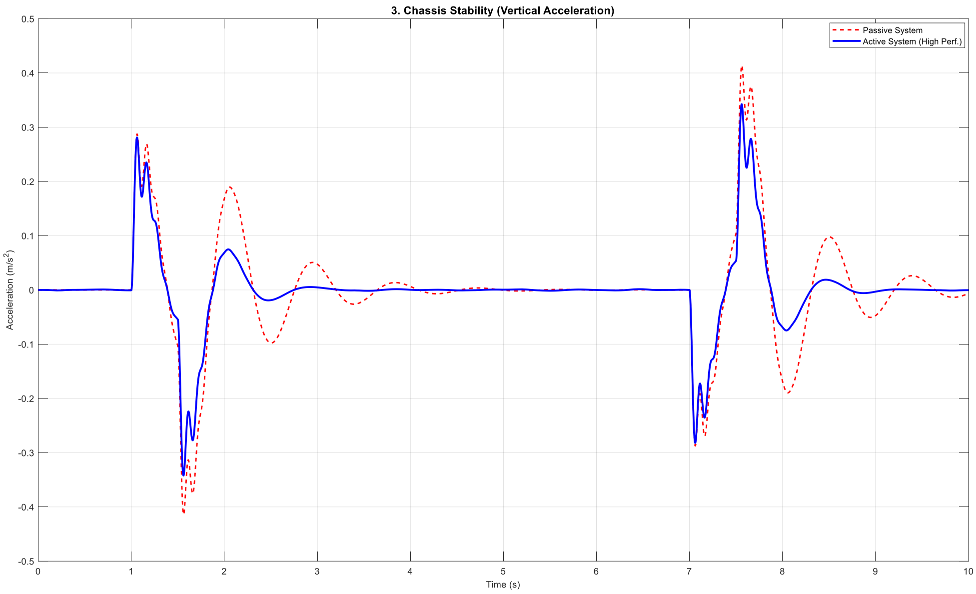


*Figure 3: Passive vs. Active Vertical Acceleration*

- **Observation:** The active system (Blue) eliminates the post-bump "ringing" observed in the passive system (Red).
- **Result:** While the passive system continues to oscillate for **~3.0** seconds, the Active Controller stabilizes the chassis in approximately **1.8 seconds**. Peak vertical acceleration was contained to **~0.34 m/s$^2$**.

### B. Road Holding (Tire Deflection)

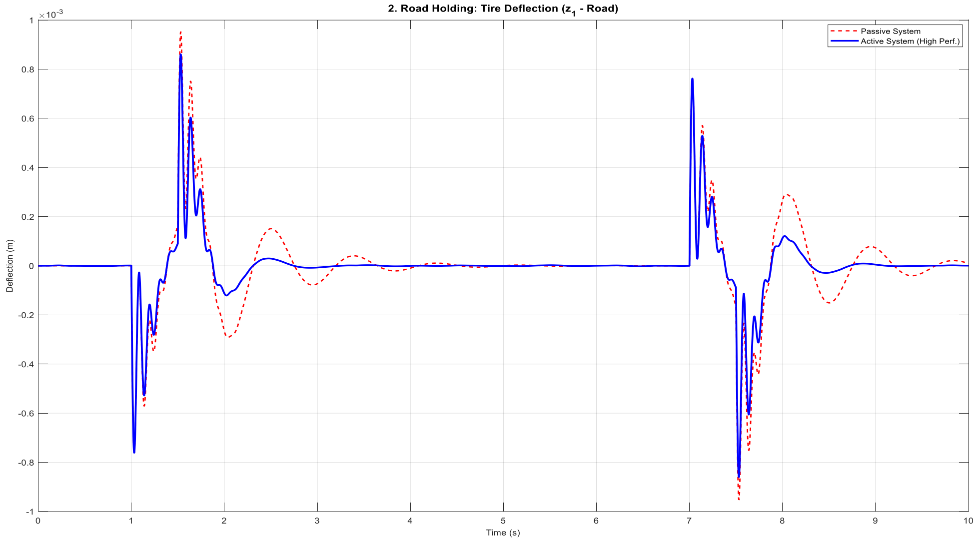


*Figure 4: Passive vs. Active Road Holding Ability*

- **Observation:** The active controller forces the tire deflection back to zero significantly faster than the passive setup.
- **Result:** This minimizes the duration of reduced contact patch pressure. In a racing context, this means the driver has full mechanical grip available much sooner after hitting a curb.

### 5. Conclusion

The proposed architecture successfully transforms the suspension dynamics from an under-damped passive system to a precision instrument. The results confirm that the **LQR-Kalman** combination provides:

1. **Stability:** Post-disturbance oscillations were eliminated almost instantly, reducing settling time by **~40%**.
2. **Grip:** Tire contact was restored significantly faster, maximizing mechanical traction.
3. **High Efficiency:** The control system exhibits exceptional energy efficiency. Because the passive spring handles the primary static load, the active actuator requires only a peak force of **~35 N** to damp out the residual oscillations. This low power demand (< 2% of standard actuator capacity) minimizes the impact on the vehicle's electrical system while still achieving the 40% reduction in settling time.
4. **Robustness:** Smooth actuation even in the presence of sensor noise.

While this report demonstrates a high-performance tune, the modular nature of the LQR cost function allows this exact same architecture to be re-optimized for luxury ride comfort simply by adjusting the $\boldsymbol{Q}$ and $\boldsymbol{R}$ weights, making it a highly versatile solution for modern automotive engineering.

# References


1. **Agharkakli, G. S. Sabet, and A. Barouz, "Simulation and Analysis of Passive and Active Suspension System Using Quarter Car Model for Different Road Profile,"** *International Journal of Engineering Trends and Technology (IJETT)*, vol. 3, no. 5, pp. 636–644, Oct. 2012.