ACTIVE STABILITY SYSTEM FOR HIGH-SPEED DRIVING

INC18

Eberechukwu Ajayi, Ethan Gabriel Paredes | Advisor: Assoc. Prof. Dr. Benjamas Panomruttanarug

ABSTRACT

Modern autonomous racing and emergency maneuvers require control architectures that can navigate the narrow boundary between maximum velocity and dynamic instability. Conventional path-tracking algorithms, such as Pure Pursuit and Stanley controllers, rely on kinematic assumptions that neglect vehicle mass, yaw inertia (I_{zz}), and tire-road friction limits. Consequently, these systems suffer catastrophic "spin-out" failures when lateral accelerations (a_y) approach the limits of the Kamm Friction Circle.

This study presents a proactive Active Stability System developed through a rigorous 100% Model-Based Design (MBD) paradigm. Utilizing a high-fidelity, non-linear 3-Degree-of-Freedom (3DOF) Single Track dynamic plant, the research evaluates an evolutionary progression of five control models. The study culminates in the design of an Explicit Model Predictive Controller (MPC) integrated with a "Smart Throttle" longitudinal governor. Unlike reactive safety systems that intervene via momentum-reducing braking, the proposed MPC architecture proactively optimizes steering (δ) and longitudinal force (F) to maintain stability while riding the physical tire slip angle (α) saturation limits.

INTRODUCTION

Most current safety systems, such as Electronic Stability Control (ESC), are reactive. They wait for instability to occur, then aggressively reduce engine power or apply brakes. While effective for safety, this interrupts performance and driver intent.

The Mission

Our Mission is to design a proactive stability system that preserves vehicle speed and performance while ensuring absolute directional control during high-speed maneuvers.

Project Objectives

- Dynamic Stability: Bound vehicle yaw rate (r) and slip angles (β) during high-speed cornering.
- Performance Tracking: Maintain sub-meter Cross-Track Error (CTE) at speeds up to 20 m/s.
- Predictive Avoidance: Integrate 360° spatial awareness using Artificial Potential Fields (APF) within the MPC horizon to dodge obstacles without compromising equilibrium.

THE HIGH-SPEED CHALLENGE

Standard controllers assume a "Point-Mass" model. At 20 m/s (72 km/h scale speed), the tires generate massive lateral forces. If the controller does not account for tire deformation and inertia, the vehicle enters terminal understeer. When the lateral acceleration a_y exceeds the available friction ($\mu \bullet g$), geometric steering becomes saturated.

$$\alpha_f = \text{atan}\left(\frac{\dot{y} + a \bullet r}{\dot{x}}\right)$$

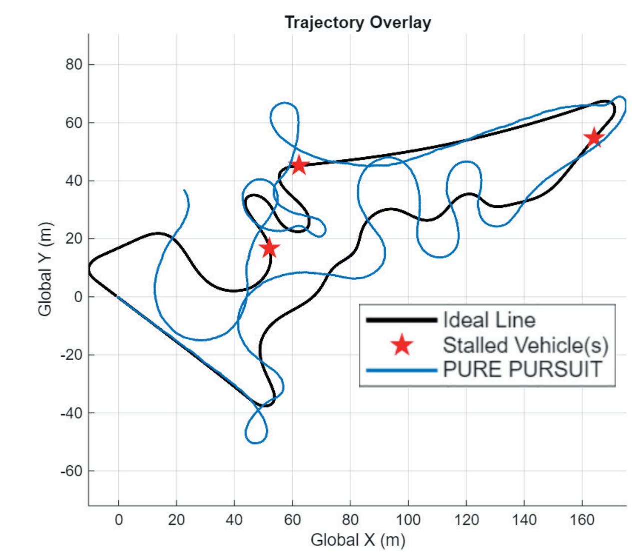


Figure 1: Model 1 (Pure Pursuit) – Terminal Trajectory Divergence at 20 m/s

METHODOLOGY (THE DIGITAL TWIN)

THE 3-DEGREE-OF-FREEDOM DYNAMIC PLANT

To move beyond point-mass physics, we implemented a **High-Fidelity 3DOF Single-Track (Bicycle) Model**. Unlike kinematic models, this dynamic plant accounts for the complex interplay between longitudinal velocity (V_x), lateral velocity (V_y), and yaw rate (r). This ensures the simulation captures body momentum and centrifugal forces that occur at 20 *m/s*.

The Equations of Motion

These are the state-space depiction of the lateral and yaw dynamics:

$$m(\dot{v}_y + \dot{v}_x r) = F_{yf}\cos(\delta) + F_{yr}$$

$$I_{zz}\dot{r} = aF_{yf}\cos(\delta) - bF_{yr}$$

Instead of raw code, we mapped the simulation to a 1:10 scaled racing chassis:

Mass (m)	Yaw Inertia (I_{zz})	CG Distances (*a, b, h*)
8.0 kg	0.1634 $kg{\cdot}m^2$	0.21 *m* (Front), 0.13 *m* (Rear), 0.11 *m* (Height)

MPC ARCHITECTURE & TIRE DYNAMICS

The project utilizes an Explicit Model Predictive Control (MPC) architecture. This "Unified Controller" manages both steering (δ) and throttle (F_x) simultaneously to maintain stability while navigating complex tracks.

Unified MPC System Architecture

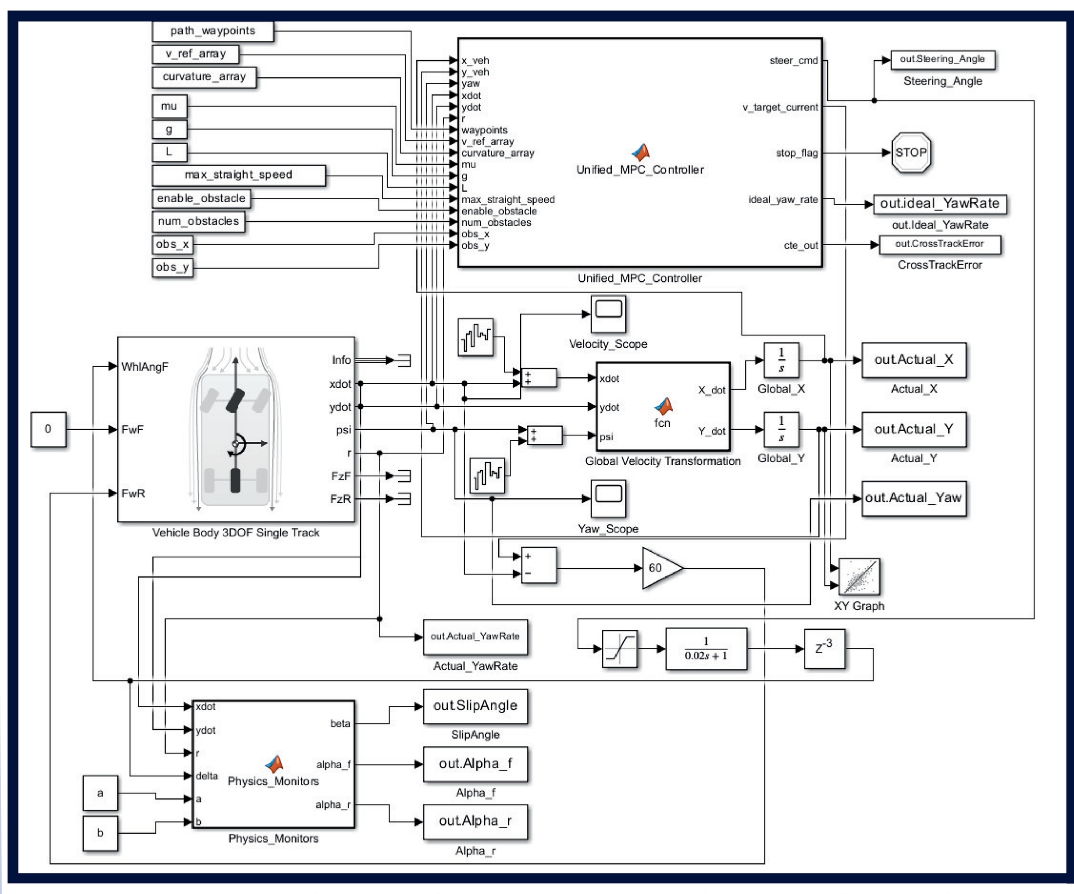


Figure 2: A high-level Simulink System Architecture for the Unified MPC Model

Tire Physics

$$F_{yf} = C_{af} \cdot af\ ,$$

$$F_{yr} = C_{ar} \cdot ar$$

Where C_a is the cornering stiffness (100 N/rad)

The Environment

To ensure professional-grade validation, the Circuit of the Americas (Austin) was scaled 1:10 and spline-interpolated into high-resolution waypoints (*ds* = 0.05m).

- **Unified MPC Controller**: The "Brain" predicting future states over a 0.65s horizon.
- **Physics Monitors**: The module deriving real-time Slip Angles (α) and Vehicle Slip (β).
- **Actuator Dynamics**: Inclusion of 30ms transport delays and noisy sensor injection.

METHODOLOGY (CONTROL EVOUTION)

STAGE 1: Kinematic Baselines (Pure Pursuit & Stanley

Status: TERMINAL FAILURE
Logic: These models operate on purely geometric lookahead distance L_d or cross-track error e_{ct}. They assume zero tire-slip $\alpha = 0$.

The Failure: Without mass or inertia modeling, the car cannot compensate for centrifugal force. Unmodeled understeer leads to catastrophic track divergence.

STAGE 2: Cascaded PID (Reactive Stability / "ActiveYaw")

Status: STABLE BUT SUB-OPTIMAL
Logic: Implements an Inner Loop PID to track a reference yaw rate $(r_{ref} = \kappa \cdot v_x)$. It is "Reactive"—it only corrects errors after they occur.

The Result: Successfully completes the track but exhibits high "Actuator Chatter" and requires significant speed reduction to maintain stability.

STAGE 3: Cascaded LQR (State-Space Optimization)

Status: GOOD-PERFORMANCE STABILITY
Logic: Utilizes a Linear Quadratic Regulator to minimize the cost function $J = \int_0^\infty (x^T Q x + u^T R u) dt$ It optimizes steering effort vs. tracking accuracy using the full 3DOF state feedback.

The Breakthrough: Achieving the 0.786m RMSE Masterpiece at 13m/s and surviving the 20m/s stress test with smooth steering signals.

STAGE 4: THE FINAL BOSS - MPC + APF

Status: PREDICTIVE EXCELLENCE
Logic: Model Predictive Control with a 0.65s receding horizon. Unlike LQR, it proactively adjusts throttle and steering before the corner while respecting actuator limits.

The Edge: Integrated with Artificial Potential Fields (APF) to enable real-time, high-speed obstacle avoidance.

THE PREDICTIVE HORIZON

Unlike classical controllers, our MPC does not just react to current error; it predicts the vehicle's future state over a 0.65-second Receding Horizon.

Key Concept: Latency Compensation: The controller accounts for 30ms of sensor/actuator latency by predicting where the car will be when the steering command actually takes effect.

RECEEDING HORIZON LOGIC

1. **MEASURE**: Current State
2. **SOLVE**: Receding Horizon Optimal Control Problem (H_p = 0.65s).
3. **ACT**: Execute

Discard $\{u^*_{T+1}, ..., u^*_{T+13}\}$

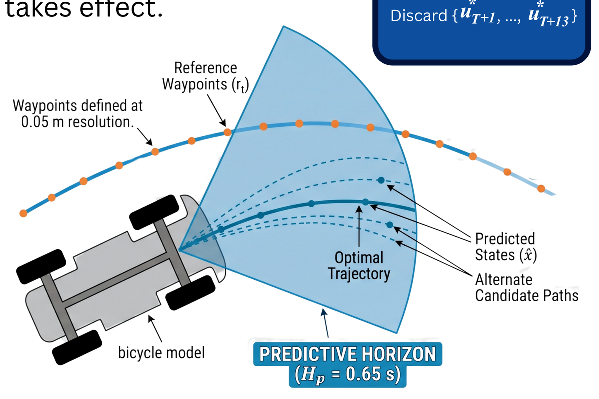


Fig 3: Receding Horizon Logic. The system optimizes the next 13 steps (at 0.05m resolution) to ensure smooth turn-in.

UNIFIED STEERING & THROTTLE

The controller simultaneously optimizes lateral steering (δ) and longitudinal force (F_x). It respects the Kamm Friction Circle, ensuring that total force never exceeds available traction ($\mu \bullet g$).

$$\text{Minimize } J = \sum_{i=1}^{H_p} \|x_i - x_{ref,i}\|_Q^2 + \|u_i\|_R^2$$

$$\text{Subject to: } |\delta| \leq 30^\circ, \quad |\alpha| \leq 5^\circ$$

The "Smart Throttle" Governor: The system proactively reduces speed before corner entry if the predicted lateral acceleration a_y exceeds the friction limit.

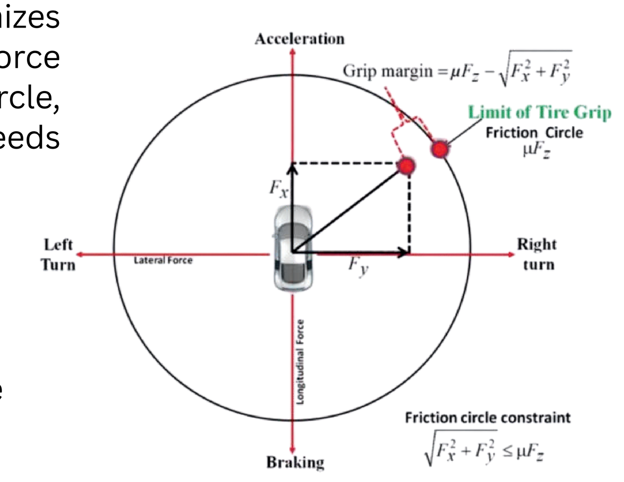


Fig 4: The Physical Limit. The MPC ensures the combined vector of lateral and longitudinal force remains within the tire's grip envelope.

ARTIFICIAL POTENTIAL FIELDS (APF)

To achieve 360° situational awareness, we integrated an Artificial Potential Field. Stalled vehicles generate a "Repulsive Force" that warps the MPC's cost function, forcing a proactive lane change. The APF provides a non-linear steering bias that forces the car to "leak" around obstacles while the MPC maintains high-speed stability.

$$U_{rep}(d) = \frac{1}{2}\eta\left(\frac{1}{d} - \frac{1}{d_0}\right)^2$$

Where d is the distance to the obstacle and d_0 is the 8.0 m influence radius.

RESULTS & COMPARATIVE ANALYTICS

PERFORMANCE BENCHMARKING AT 20 m/s

CONTROL MODEL	RMSE	TRACKING QUALITY
Pure Pursuit	6.615 m	Unstable / Off-Track
Stanley	3.789 m	Critical Divergence
ActiveYaw (PID)	3.352 m	Poor Adherence
Cascaded LQR	0.525 m	High Precision
UNIFIED MPC	0.488 m	Optimal (Masterpiece)

The MPC architecture achieved an 87% improvement in accuracy over the best-performing kinematic baseline (Stanley) by proactively managing vehicle momentum and tire slip.

TRAJECTORY ADHERENCE: MPC VS. BASELINE

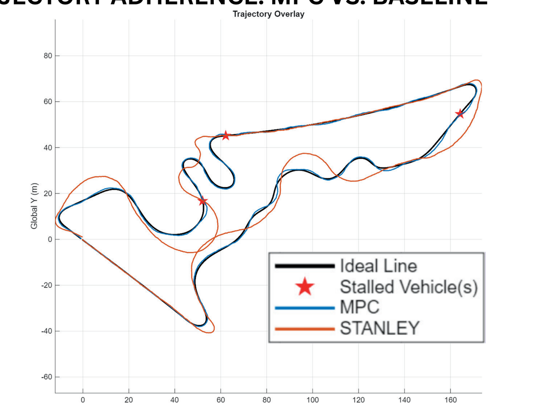
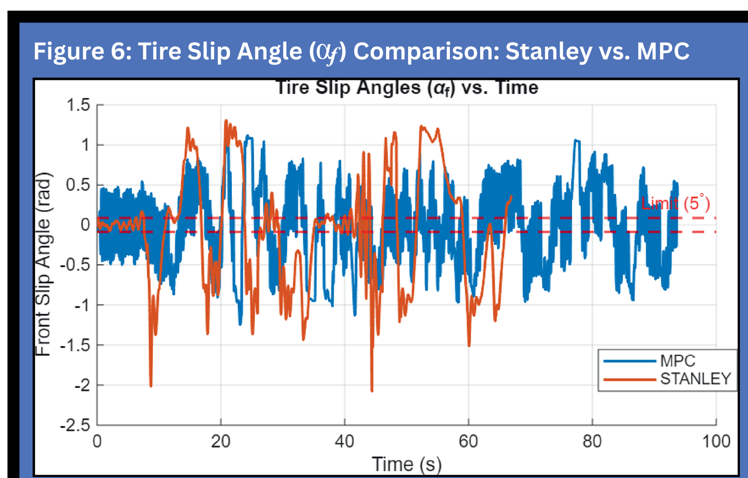


Figure 5: Trajectory Comparison at 20 m/s. The Stanley controller exhibits catastrophic understeer at high-curvature sections, while the MPC maintains sub-meter adherence.

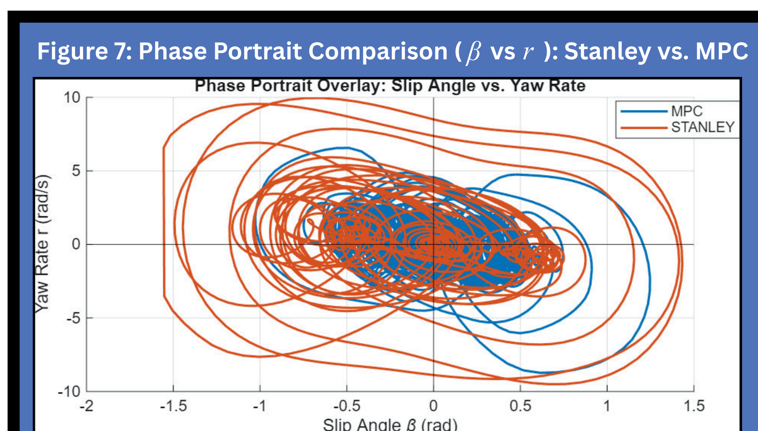
STABILITY BOUNDARY ANALYSIS

Figure 6: Tire Slip Angle (α_f) Comparison: Stanley vs. MPC



At 20 m/s, the extreme lateral demand pushes both models beyond the theoretical 5° (0.087 rad) linear limit. However, the MPC demonstrates superior limit-handling by maintaining a narrower and more stable range of slip angles. Conversely, the Stanley baseline exhibits violent, erratic oscillations, indicating a loss of directional authority at the friction limit.

Figure 7: Phase Portrait Comparison (β vs r): Stanley vs. MPC



The MPC trajectory remains tightly clustered near the origin, proving the system maintains dynamic equilibrium.

The Stanley baseline (Orange) reaches extreme vehicle slip angles (β) and yaw rates (r) on multiple occasions, that manifesting as wide loops approach the boundaries of unrecoverable instability. MPC demonstrates superior state-space containment, keeping the vehicle near its dynamic equilibrium even when operating in the non-linear tire region, unlike the erratic behavior of the Stanley baseline.

CONCLUSION

KEY FINDINGS

- Quantitative Success: The Unified MPC architecture achieved a 0.488m RMSE at 20 *m/s*, representing a 92.6% improvement in tracking precision over the Pure Pursuit baseline (6.615 *m*).
- Stability Validation:
  - Following the principles in Snider (2009) and Rajamani, we successfully identified the "Kinematic Limit." By transitioning to a dynamic 3DOF plant, the system effectively managed non-linear tire slip angles (α) that cause terminal failure in geometric planners.
- Proactive Safety:
  - Unlike reactive ESC systems, the proposed MPC-APF framework maintains dynamic equilibrium without momentum-reducing braking, riding the absolute limit of the Kamm Friction Circle.

THE MBD ADVANTAGE

The strategic move from toy-scale hardware to a 100% Model-Based Design (MBD) environment allowed the team to pursue high-order automotive control theory (MPC/APF). This methodology provides a deterministic, repeatable framework for validating safety-critical systems before hardware deployment, ensuring that failure occurs in the "Digital Twin" rather than on the track.

FUTURE WORK

- Simulink-to-C++ Deployment: Utilizing Simulink Coder for automated C-code generation to port the validated MPC logic back to the Jetson Nano/ROS 2 hardware platform.
- High-Fidelity 7DOF Dynamics: Upgrading the vehicle plant to a 7-Degree-of-Freedom multi-body model to account for vertical load transfer, suspension travel, and body roll during high-speed chicanes.
- Real-time Friction Estimation: Implementing an Extended Kalman Filter (EKF) to estimate the road friction coefficient (μ) in real-time, allowing the MPC to adapt to variable surface conditions (wet/dry).

SCHOLARLY REFERENCES

- Snider, J. M., "Automatic Steering Methods for Autonomous Automobile Path Tracking," CMU-RI-TR-09-08, 2009.
- Falcone, P., et al., "Predictive Active Steering Control for Autonomous Vehicle Systems," IEEE Transactions on Control Systems Technology, 2007.
- Rajamani, R., "Vehicle Dynamics and Control," Springer, 2011.
- Pacejka, H. B., "Tire and Vehicle Dynamics," Elsevier, 2005.
- Panomruttanarug, B., et al., "Practical Speed Control for an Autonomous Golf Cart," ITC-CSCC, 2022.