Estimation and Control of Lateral Tire Forces Using Steering Torque

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Motivation

- **Worldwide, 1.2 million people** are killed in vehicle crashes each year\(^1\)
  - Projected to increase by 65% by 2022 unless there is new commitment to prevention

- **In the US, motor vehicle accidents are leading cause of death for people ages 5-33**\(^2\)
  - For fatalities involving teens, 30% are due to loss of control\(^3\)

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3 USA Today, Study of deadly crashes involving 16-19 year old drivers (2003)
Vehicle Safety Systems

- Safety systems prevent unintended behavior, help drivers maintain control

- Current production systems include:
  - Anti-lock Braking Systems (1978)
    - Prevents wheel lock during braking
  - Traction Control (1985)
    - Prevents wheel spin during accelerating
    - Enhances lateral vehicle stability
Vehicle Motion is Governed by Tire Forces

- To stay in a turn, vehicles require lateral force
- If demanded lateral force exceeds tire-road friction, tires lose traction
  - Tires begin to skid sideways
  - They exceed their “limits of handling” (forces have saturated)
Electronic Stability Control (ESC)

- Compares driver intended yaw rate with measurements
- Corrects with selective braking after sufficient deviation is detected
Limitations of ESC

• ESC is a life-saving technology: prevents estimated 27% of loss of control accidents\(^1\)

• However, ESC must be conservative & has limitations
  – ESC is **reactive**: It must detect problem before intervening
  – No reliable measurement of **sideslip angle**
    • Relative measure of how much vehicle is skidding to the side
  – No knowledge of **lateral force limits**
    • Maximum tire grip available for a turn
    • Change with road conditions (e.g. dry, icy)

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Knowledge of sideslip angle and lateral limits can further improve effectiveness of current safety systems

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1 ESC Coalition Fact Sheet, DEKRA Automotive Research 2003.
Future Safety Systems

• Use multiple actuators (steering, brake, drive, camber) to prevent unintended behavior
• Example: Stanford’s P1 steer-by-wire research vehicle
  – Keep vehicle in a safe handling envelope, which must be identified
  – Require early knowledge of limits
Future Safety Systems

• Use multiple actuators (steering, brake, drive, camber) to prevent unintended behavior
• Example: Stanford’s P1 steer-by-wire research vehicle
  – Keep vehicle in a safe handling envelope, which must be identified
  – Require early knowledge of limits

Future vehicle safety systems would also benefit from knowledge of tire lateral handling limits before they are reached
A Predictive Approach to Vehicle Safety

Our goal is to design a safety system which has:

• “Limit Prediction” - Predict the vehicle’s limits of handling
• “Envelope Control” - Keep vehicle motion within safe operating envelope
Our Inspiration: Racecar Drivers

Racecar drivers routinely operate near the limits of handling

- **Steering system can serve in dual roles:**
  1. Actuator
  2. Sensor

<table>
<thead>
<tr>
<th>Racecar drivers</th>
<th>Current systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid in inner ear</td>
<td>Lateral acceleration</td>
</tr>
<tr>
<td>Steering wheel feel</td>
<td>Yaw rate</td>
</tr>
<tr>
<td></td>
<td><strong>Steering torque</strong></td>
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We can utilize **steering torque** to provide early warning of lateral limits and stabilize vehicle motion.
Summary of Contributions

1. I constructed online estimation techniques for characterizing lateral tire properties using steering torque and assuming access to GPS.

2. I developed an online, nonlinear observer to characterize lateral tire properties using steering torque and readily available sensors (no GPS).

3. I proved this nonlinear observer is mathematically guaranteed to converge in the presence of estimation error, and validated observer in experiment.

4. I designed and implemented an envelope controller to keep the vehicle within its lateral limits using front steering actuation.
Roadmap Today

1. Understanding steering torque
2. Estimation approach
   - Use steering system as virtual sensor
   - Stability proof sketch
   - Validation in experiment
3. Envelope control
   - Use steering system as actuator
   - Keep vehicle within safe envelope in experiment
Vehicle Motion is Governed by Tire Forces

- Lateral force results from deformation in the tire contact patch
- Angle of deformation is slip angle $\alpha$
- Force distribution is limited by friction limit $\mu F_z$:
  - Tire-road friction coefficient $\mu$
  - Normal force distribution $F_z$
Understanding Steering Torque

- Effective lateral force $F_y$ acts at a distance behind wheel center, called pneumatic trail $t_p$.
- Steering torque arises from $F_y$ acting at moment arm $t_p$:
  \[ \tau_a = -t_p F_y \]
- What drivers feel is steering torque*

* A simplified representation
Lateral Force Grows with Slip Angle

- As slip angle grows:
  - Lateral force $F_y$ increases (but is limited friction)
  - $F_y$ moves to center of contact patch
  - Pneumatic trail $t_p$ decreases
    - This is why steering wheel feels “light” near limits
Importance of Peak Lateral Force and Slip Angle

- $\mu F_z$ tells us where the limits of handling are
- $\alpha$ tells us how close we are to the limits

We would like an online estimation process for peak lateral force $\mu F_z$ and slip angle $\alpha$
Benefits of Pneumatic Trail for Estimation

- $F_y$ limits only apparent near saturation
- Pneumatic trail decreases as a function of $\mu F_z$
  - Enables **early** detection of limits (well before $F_y$ saturation)
  - Can be estimated from $\tau_\alpha$ measurements
Existing Methodologies

- Designed linear observers to estimate slip angle, but assumed accurate tire model and no estimation of lateral force limits.
  
  \[Kiencke\ 1997, \ Venhovens\ 1999, \ Stephant\ 2004,\ Yih\ 2004\]

- Relied on sensors unavailable on production cars (e.g. GPS, load cells) to directly measure slip angle and estimate friction, or require high levels of lateral dynamics for friction identification.
  
  \[Pasterkamp\ 1997, \ Bevly\ 2000, \ Ryu\ 2002, \ Hahn\ 2002, \ Grip\ 2006, \ Baffet\ 2007\]

- Used steering torque to enhance stability control, but no explicit estimation.
  
  \[Ono\ 2003, \ Yasui\ 2004, \ Endo\ 2006\]

My work

**Estimate** slip angle and **predict** lateral force limits using sensors available on production vehicles
Estimation Approach
Identifying Slip Angle and Peak Lateral Force

The concept: A combination of pneumatic trail (from steering torque measurements) with lateral force can be used to decode slip angle and peak force limits.
Observer Implementation

- Yaw rate
- Steer angle
- Speed
- Acceleration

Slip Angle Observer

- Slip angle estimates
- Lateral force estimates

Force & Friction Estimator

- Friction estimate

Extract Pneumatic Trail

Steering torque

Pneumatic Trail
Slip Angle Observer

To update slip angle estimates $\hat{\alpha}_f$, $\hat{\alpha}_r$, we use simple bicycle model of vehicle motion:

$$\hat{\alpha}_r = \hat{\alpha}_f + \delta - \left(\frac{a+b}{V_x}\right)r$$

$$\dot{\hat{\alpha}}_f = \left(\frac{1}{mV_x} + \frac{a^2}{I_zV_x}\right)\hat{F}_{yf}$$
$$+ \left(\frac{1}{mV_x} - \frac{ab}{I_zV_x}\right)\hat{F}_{yr} - r - \dot{\delta}$$
$$+ K(\hat{F}_{yf} + \hat{F}_{yr} - ma_y)$$

- Longitudinal dynamics neglected
- Known vehicle parameters $(m, a, b, I_z)$
- Measurements $(r, \delta, V_x, a_y)$
- Nonlinear lateral tire force estimates $(\hat{F}_{yf}, \hat{F}_{yr})$

How do we get $\hat{F}_{yf}$, $\hat{F}_{yr}$?
Observer Implementation

Steering torque

- Yaw rate
- Steer angle
- Speed
- Acceleration

Slip Angle Observer

- Slip angle estimates
- Lateral force estimates

Force & Friction Estimator

- Lateral Tire Force
- Pneumatic Trail

Friction estimate

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Lateral Force and Friction Estimator

- Why this coupled estimation scheme works
  - Lateral force is unaffected by friction limits for small slip angles
  - We have knowledge of friction limits before it affects lateral force (so we can track slip angle even when forces become nonlinear)
Observer Stability Proof (Sketch)

**Goal:** Would like to show slip angle estimate converges even in presence of estimation uncertainty

- Define estimation error as:
  \[ e_\alpha = \hat{\alpha}_f - \alpha_f \]
- Its derivative is:
  \[ \dot{e}_\alpha = \dot{\hat{\alpha}}_f - \dot{\alpha}_f \]
- Substituting slip angle update equation, observer’s error dynamics can be rewritten as
  \[ \dot{e}_\alpha = \left( \frac{a^2 + ab}{I_z V_x} + K \right) \left( F_{yf} - \hat{F}_{yf} \right) \]
  \[ K_{\alpha > 0} \]
- Let’s assume slip angle is positive. There are two possible situations:
  **Case 1:** Slip angle estimate is larger \( \hat{\alpha}_f > \alpha_f \)
  **Case 2:** Slip angle estimate is smaller \( \hat{\alpha}_f < \alpha_f \)
Case 1: $\hat{\alpha}_f > \alpha_f$

For stability, we want: $\hat{\alpha}_f < \hat{\alpha}_f \Rightarrow \hat{\alpha}_f - \alpha_f < 0 \Rightarrow \dot{\hat{\alpha}} < 0$

We have: $\dot{\hat{\alpha}} = K_{\alpha} \left( F_{yf} - \hat{F}_{yf} \right) < 0 \checkmark$
Case 2: \( \hat{\alpha}_f < \alpha_f \)

For stability, we want: 
\[
\hat{\alpha}_f > \alpha_f \Rightarrow \hat{\alpha}_f - \alpha_f > 0 \Rightarrow \dot{\alpha} > 0
\]

We have: 
\[
\dot{\alpha} = K_\alpha \left( F_{yf} - \hat{F}_{yf} \right) > 0 \quad \checkmark
\]
Observer Validation in Experiment
P1 By-Wire Research Vehicle

- Independent Steer-By-Wire
- GPS
- Independent AC Electric Drive
- Batteries
- Data Acquisition and Control
## Experimental Test Matrix

<table>
<thead>
<tr>
<th>Experimental Test</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Slalom</td>
<td>Will observer respond quickly enough?</td>
</tr>
<tr>
<td></td>
<td><em>Investigate the lag involved</em></td>
</tr>
<tr>
<td>2. Ramp steer</td>
<td>Will it work when tires saturate?</td>
</tr>
<tr>
<td></td>
<td><em>Determine whether estimate diverges</em></td>
</tr>
<tr>
<td>3. Gravel surface</td>
<td>How well does it work on different friction surfaces?</td>
</tr>
<tr>
<td></td>
<td><em>Look at sensitivity to unmodeled effects</em></td>
</tr>
</tbody>
</table>
1. Experimental Slalom on Dry Pavement

- P1 driven at 15 m/s constant speed, $\mu=1$

Enter nonlinear region
1. Experimental Slalom Results

- Friction estimate is around $\mu=1$
- Slip angle estimates compared with
  - GPS (truth)
  - Linear slip angle estimator
    - Within family of observers that only estimate slip angle (not friction)
- In nonlinear region, see better tracking with pneumatic trail estimation method
- Observer responds well during fast, transient maneuver
Driver Camera
Experimental Ramp on Dry Pavement
2. Experimental Ramp Data Set

- P1 driven at 10 m/s, ramp steer maneuver
2. Experimental Ramp Results

- Good tracking even when tire hits grate (t = 6.5 s)
- **Linear** region
  - Both estimates are accurate
- **Nonlinear** region
  - Pneumatic-trail based estimator is better
- Shows simple models used sufficient for accurate estimation
3. Experimental Gravel Maneuver

Loose gravel on pavement
3. Experimental Gravel Maneuver

- Automated steering system maintaining P1 on oval course, driver controlling speed
- Series of aggressive left turns on $\mu = 0.5$ to $0.7$

![Graphs showing steering angle, sideslip angle, yaw rate, speed, and vehicle trajectory](image)

*Undulating speed*
3. Estimates on Gravel Match Well with GPS

- Friction holds at nominal when driving straight
- Very close slip angle tracking with slight deviation
- Maneuver challenges model assumptions
  - Uneven surface
  - Variable friction
  - Changing speeds
- For perspective, no other methods exist which use this sensor suite and can do this
Advantages for Vehicle Safety

Nonlinear observer
• Early knowledge of friction limits from pneumatic trail derived from steering torque
  – Friction identified at only 50% utilization of peak force
• Proof of observer stability developed
• Offer the ability to anticipate, rather than react to, loss of control situations
  – Potential to reduce vehicle-related fatalities

Next: Validate estimation technique with a stability control strategy
• Design basic envelope control system
• Does observer provide controller with early, accurate knowledge of limits?
Envelope Control Design
Envelope Protection Systems in Aircraft

• Envelope protection
  – Use of actuators to prevent aircraft from entering state or control regions outside of safe flight regime
  – Limitations often imposed on aircraft's state
    • e.g. Angle of attack, airspeed, bank angle, altitude

• Modern military and commercial aircraft have onboard envelope protection systems
  – e.g. Airbus A320, A330, A340 series and Boeing 777
This idea of envelope protection, or envelope control, could be extended to passenger vehicles.

- **Current examples:** ABS, TCS, ESC
  - However, they are *reactive* envelope control systems
  - Knowledge of limits only available after exceeding them

- **Our strategy**
  - During normal driving, drivers can freely maneuver the vehicle
  - If there is danger of crossing the limits (*predicted beforehand*), the controller would engage to assist driver in staying within safe operating bounds.
Envelope Control Applied to P1

- Use **front steering actuation** as mechanism for sensing and control
- Nonlinear observer provides
  - Front/rear **tire slip angle** estimates
  - Front/rear **peak tire force** estimates
P1 Envelope Control Approach

Lateral tire forces

Understeer
- Front tire saturation
- Desirable driver steering response
  - Limit steer input
  - Control front slip angle directly
P1 Envelope Control Approach

Lateral tire forces

Oversteer
- Fast increase in yaw rate
- Desirable driver steering response
  - Countersteer
  - Reduce spike in yaw rate
  - Reduce rear slip angle indirectly through vehicle dynamics
Simple Envelope Control Strategy for P1

Monitor
Continual estimation of front/rear axle **slip angle** and **peak force limits**

Safe Operating Envelope
Directly send driver command through

Countersteer/Limit Steer Angle
Add corrective steer addition on top of driver command to keep tire forces within limits

Limit Throttle Torque
Prevent driver from increasing speed

Front or rear close to saturation?
Safely away from limits?
Safely away from limits?
Envelope Control in Experiment
# Experimental Test Matrix

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Purpose</th>
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</table>
| 1. Dropped throttle oversteer    | Controller OFF  
  • Perform a destabilizing oversteer maneuver (during a turn, driver suddenly lets off throttle, sends car into spinout) |
| 2. Sequence of **three** dropped throttles | Controller ON  
  • Demonstrate controller uses steering to stabilize vehicle motion |
Dropped throttle: no controller
Dropped Throttle Oversteer (No Control)

Vehicle Trajectory Top View

- Steer Angle \( \delta \) (deg)
- Sideslip Angle \( \beta \) (deg)
- Yaw Rate \( r \) (deg/s)
- Lateral Acceleration \( a_y \) (m/s\(^2\))
- Speed \( V_x \) (m/s)

Dropped Throttle Event vs. Time (s)
Series of Dropped Throttles: Envelope Controller With Throttle Limit

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Series of Dropped Throttles: Envelope Controller With Throttle Limit
Series of Three Dropped Throttles

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Estimation results

Friction Estimate

Front Slip Angle Results

Rear Slip Angle Results

Time (s)

Actual
Linear
Estimate

First event
Second event
Third event

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First Dropped Throttle: Controller Correction

- **Steering Angle**
  - Actual
  - Controller addition
  - Driver

- **Sideslip Angle**
  - Controller Countersteer

- **Yaw Rate**

- **Lateral Acceleration**

- **Speed**

- **Time (s)**

- **Dropped Throttle Event**
First Dropped Throttle: Controller Correction

Vehicle Trajectory Top View

North Position (m)

East Position (m)

Controller Countersteer

t = 5s
t = 12s
Second Dropped Throttle: Driver Correction

- Controller addition is minimal
- Control system should be unobtrusive to drivers who are able to make their own self-corrections
Third Dropped Throttle: Controller Catch & Release Corrections

- Driver *accelerates* after first correction
  - Further reduction of rear tire traction
- Example of controller making two corrections in quick succession
Third Dropped Throttle: Controller Catch & Release Corrections

Vehicle Trajectory Top View

Vehicle does not spin out!
Conclusions

• Nonlinear observer successfully validated with a control strategy
• Simple envelope control design proved to be effective
  – Used front steering to both sense lateral operating limits and stabilize vehicle motion

Future Work

• Inclusion of longitudinal forces in observer
  – Enable estimation during braking/accelerating
• Design a more sophisticated envelope control strategy
  – To anticipate unsafe trajectories and smoothly correct them
• Use of multiple actuators in control strategy
  – Independent drive/brake forces, rear steering, active camber