



Estimating Slip Angles Using GPS with a Model-Based Estimator

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Outline

- Objectives
- Equations of Motion
- Model-Based Estimator
- Simulation Results
- Experimental Results
- Future Work and Questions



Objectives

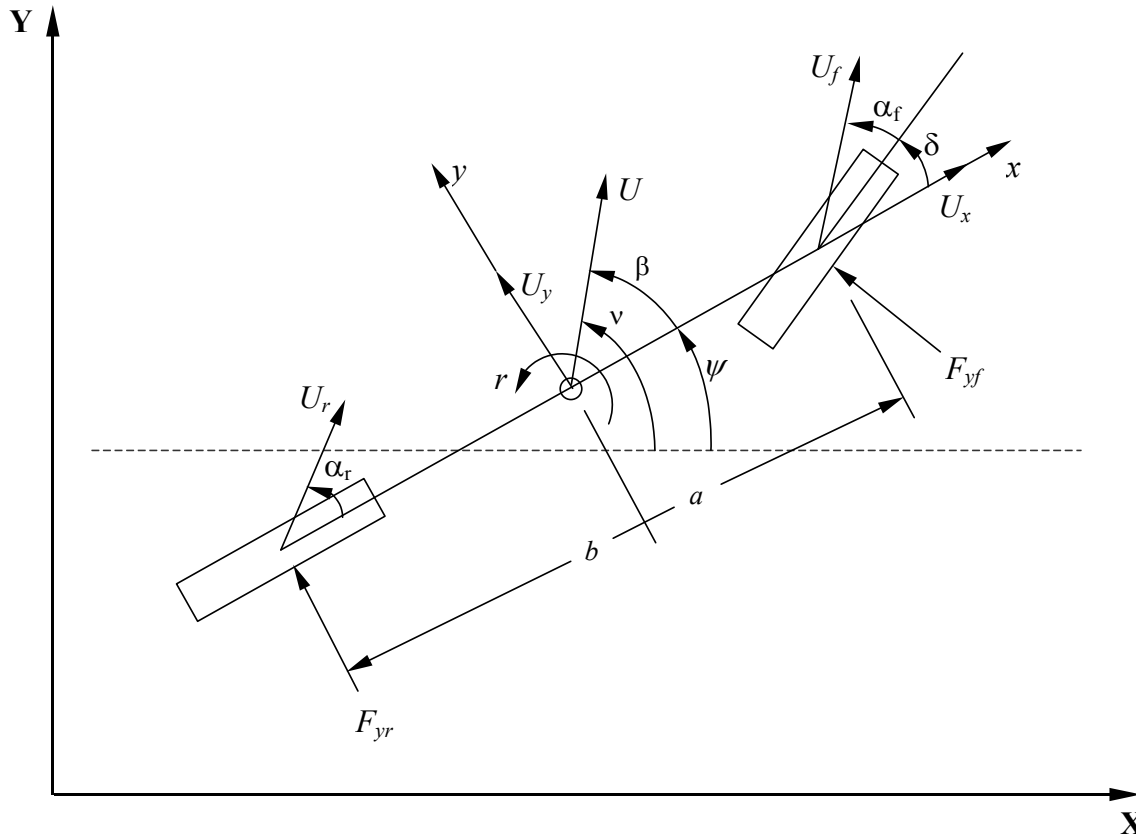
- Accurate estimation of sideslip and yaw rate
- Design an estimator that is robust to yaw rate gyro errors

Method:

- Combine GPS with a Model-Based Estimator



FBD Bicycle model



r = Yaw rate

β = Sideslip

ψ = Heading

ν = Course Angle

δ = Steer Angle



Equations of Motion in State Variable Form

$$\dot{x} = A_{act}x + B_{act}u$$

$$y = C_{act}x$$

$$A_{act} = \begin{bmatrix} -\frac{C_0}{mV} & -\frac{C_1}{mV^2} - 1 & 0 \\ -\frac{C_1}{I_z} & -\frac{C_2}{VI_z} & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad x = \begin{bmatrix} \beta \\ r \\ \psi \end{bmatrix}$$

$$B_{act} = \begin{bmatrix} \frac{C_{of}}{mV} \\ aC_{of} \\ I_z \\ 0 \end{bmatrix} \quad C_{act} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$



Kalman Filter Equations

Measurement Update

$$\mathbf{L}_k = \mathbf{P}_k \mathbf{C}_{d\text{ est}}^T (\mathbf{C}_{d\text{ est}} \mathbf{P}_k \mathbf{C}_{d\text{ est}}^T + \mathbf{R}_v)^{-1}$$

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k + \mathbf{L}_k (\mathbf{y}_{\text{meas}} - \mathbf{C}_{d\text{ est}} \hat{\mathbf{x}}_k)$$

$$\mathbf{P}_k = (\mathbf{I} - \mathbf{L}_k \mathbf{C}_{d\text{ est}}) \mathbf{P}_k$$

Time Update

$$\hat{\mathbf{x}}_{k+1} = \mathbf{A}_{d\text{ est}} \hat{\mathbf{x}}_k + \mathbf{B}_{d\text{ est}} \mathbf{u}_k$$

$$\mathbf{P}_{k+1} = \mathbf{A}_{d\text{ est}} \mathbf{P}_k \mathbf{A}_{d\text{ est}}^T + \mathbf{Q}_d$$



Kalman Filter Equations Cont.

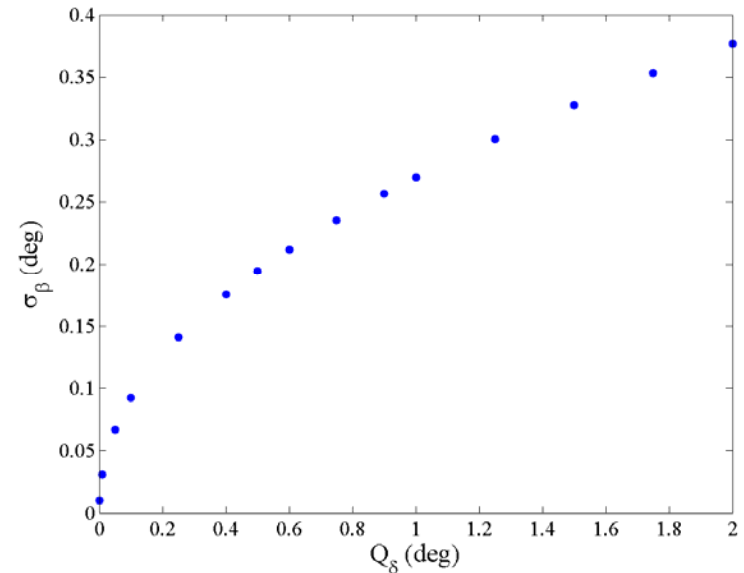
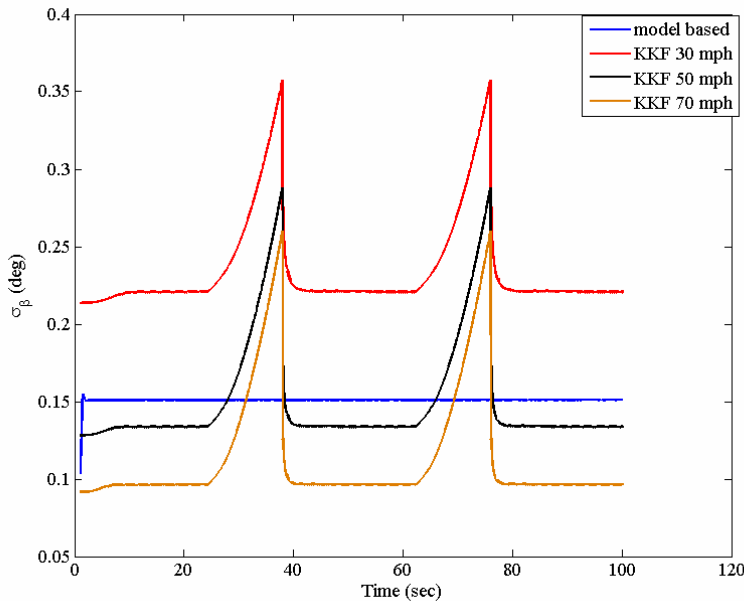
$$A_{\text{est}} = \begin{bmatrix} \frac{-C_0}{\text{mV}} & \frac{-C_1}{\text{mV}^2} - 1 & 0 & 0 \\ \frac{-C_1}{I_z} & \frac{-C_2}{VI_z} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad x = \begin{bmatrix} \beta \\ r \\ \psi \\ \text{Bias}_{\text{gyro}} \end{bmatrix}$$

$$B_{\text{est}} = \begin{bmatrix} \frac{C_{\text{af}}}{\text{mV}} \\ \frac{aC_{\text{af}}}{I_z} \\ 0 \\ 0 \end{bmatrix}$$

$$C_{\text{est}} = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$



Estimation Accuracy (from Covariance Matrix)



Sideslip accuracy for
Kinematic and
Model-Based Kalman
Filter

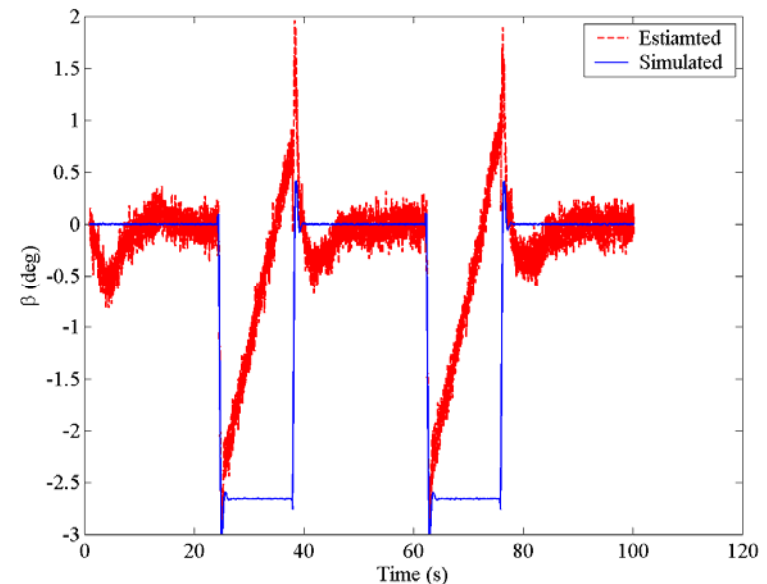
Effects of different
process noise applied
to a Model-Based
Kalman Filter



Kinematic Kalman Filter

Simulation results

- Simulate a vehicle driving around 2 180 degree turns
- Measurement and process noise added to system
- A 2% gyro scale factor error added to gyro measurement

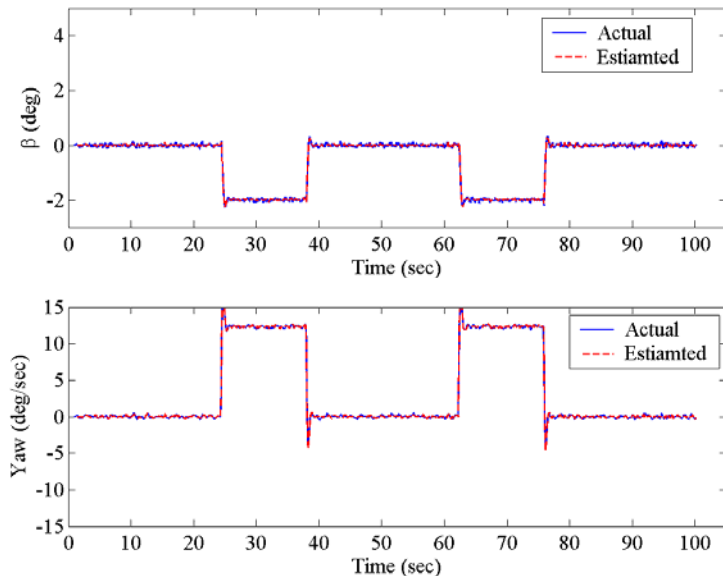


Sideslip of vehicle using a kinematic Kalman filter



Model-Based Estimator

Simulation results

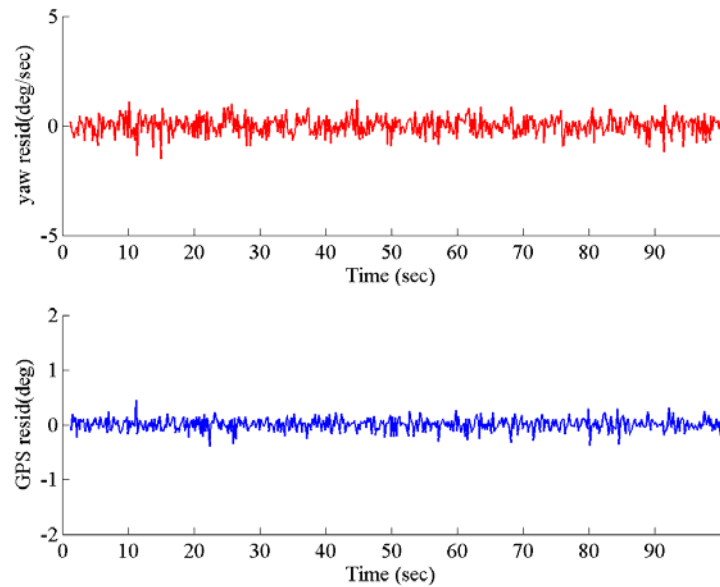
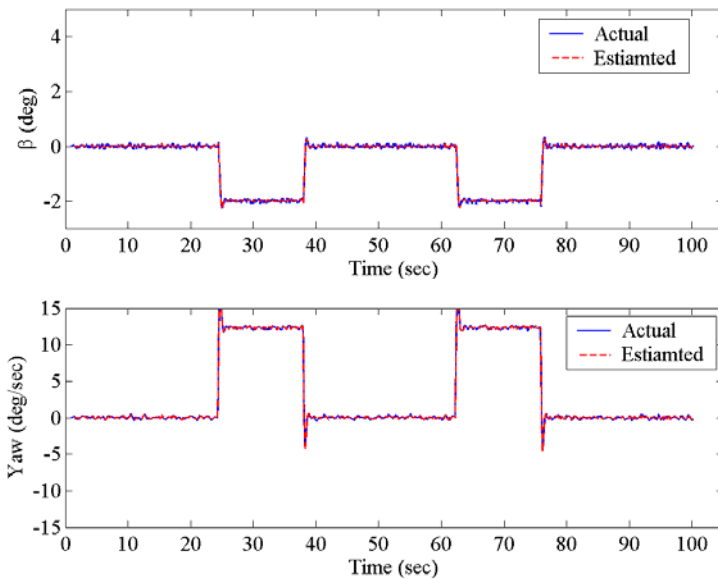


Sideslip and Yaw rate results of vehicle with correct model

- Kalman filter was given correct model
- Allowed only two measurements (gyro and course).
- A 2 % gyro scale was added to gyro measurement



Model-Based Estimator Simulation results (cont)



Sideslip and Yaw rate
results of vehicle with
correct model

Residuals for yaw rate
and GPS with correct
model



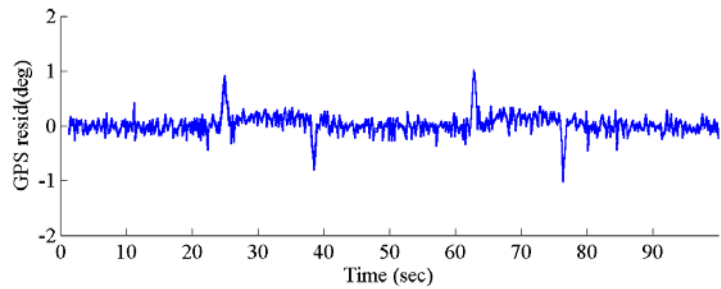
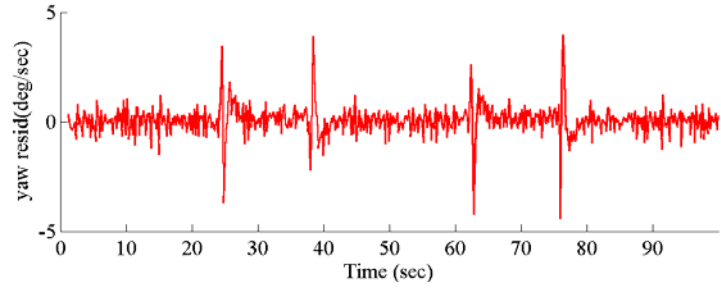
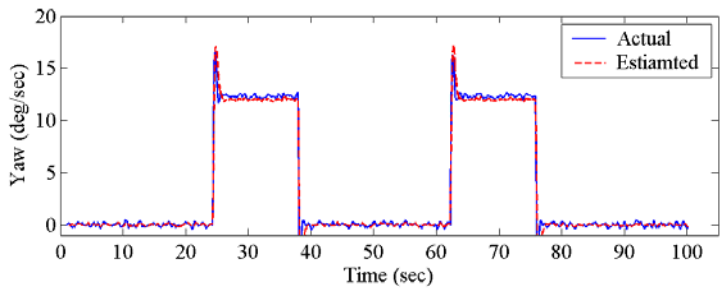
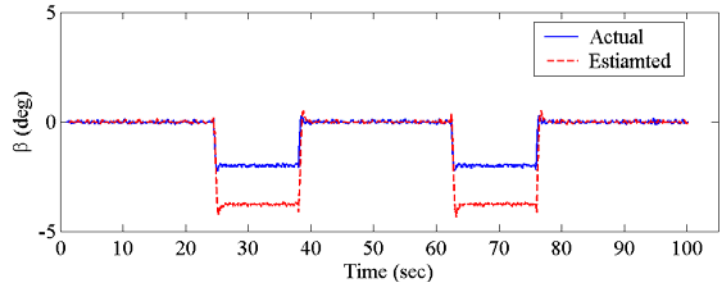
Problems with the Model-Based Estimator

- Parameters are often identified inaccurately
- Parameters can change over time
- Investigate sensitivity of the model based estimator to model error



Model-Based Estimator

Simulation Results with incorrect model



Sideslip and Yaw rate results of vehicle with incorrect model

Residuals for yaw rate and GPS with incorrect Model



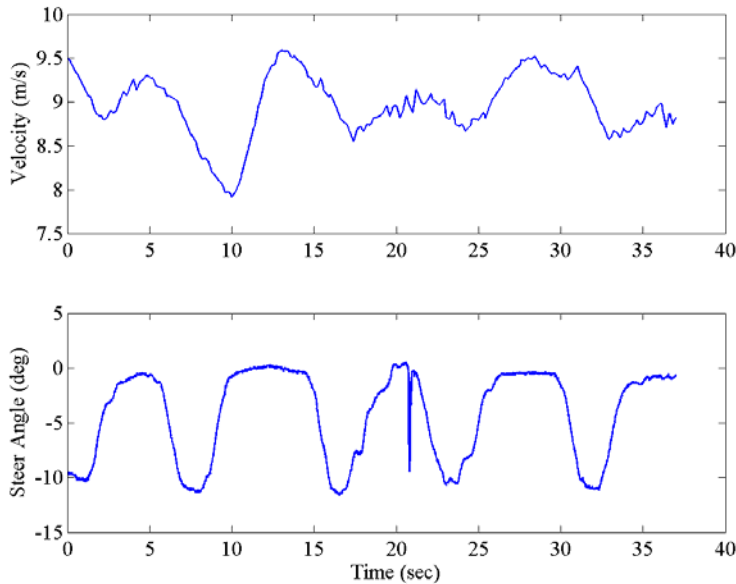
Experimental Setup



- 2000 Chevy Blazer
- 6 DOF IMU with 100 Hz update rate
- Steer Angle Sensor with 100 Hz update rate
- Starfire GPS receiver with 5 Hz update rate



Parking Lot Experiment

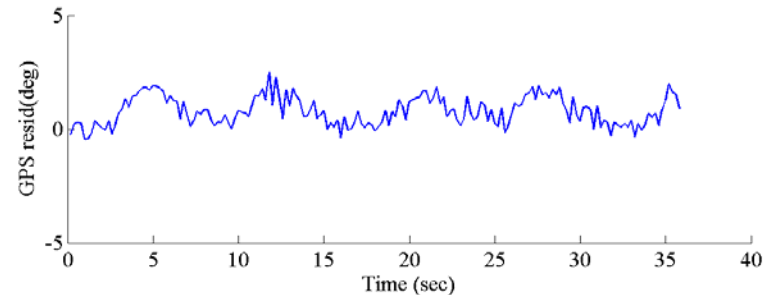
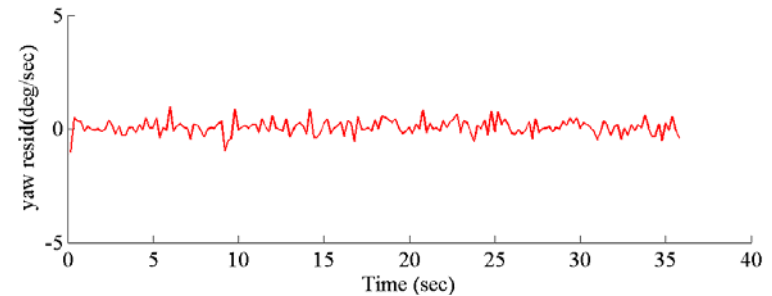
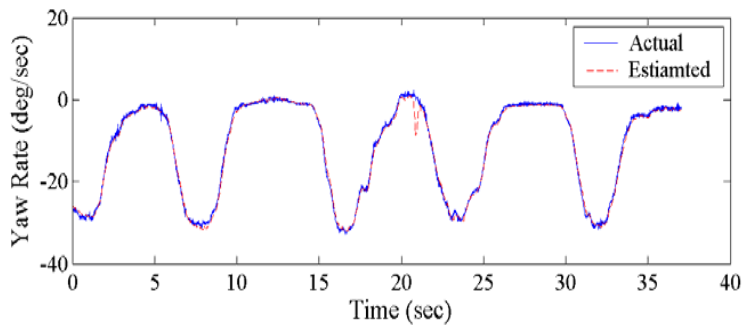
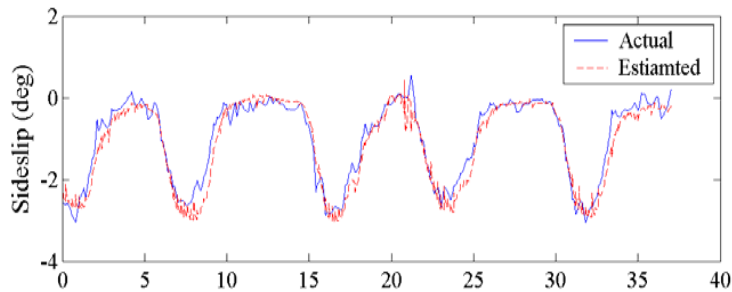


- Vehicle was driven in a flat parking lot performing 90° left turns
- Vehicle was driven at a constant speed of 20 mph (9m/s)

Velocity and steer angle from extreme cornering experiments



Model-Based Estimator Experimental Results

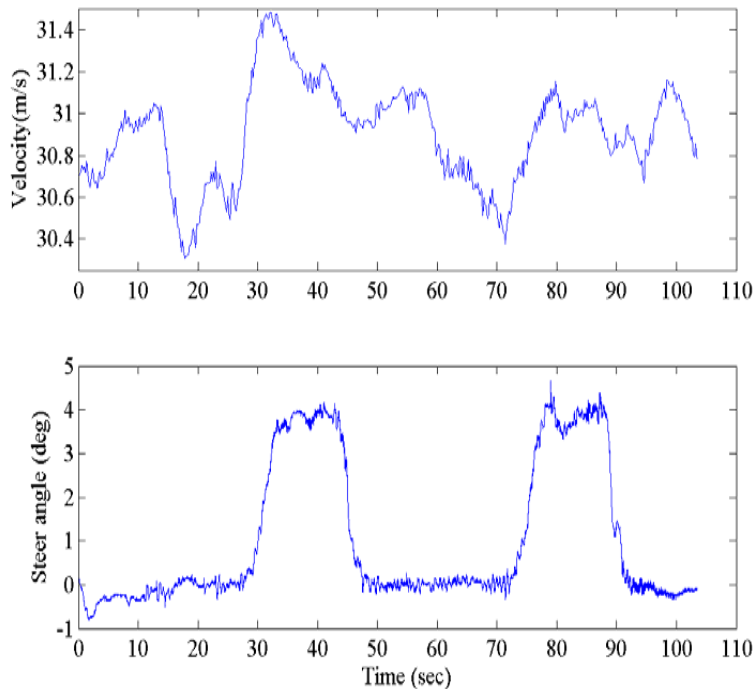


Sideslip and yaw rate
from extreme cornering
experiment

Residuals from yaw rate
and GPS for extreme
cornering experiment



Test Track Experiments

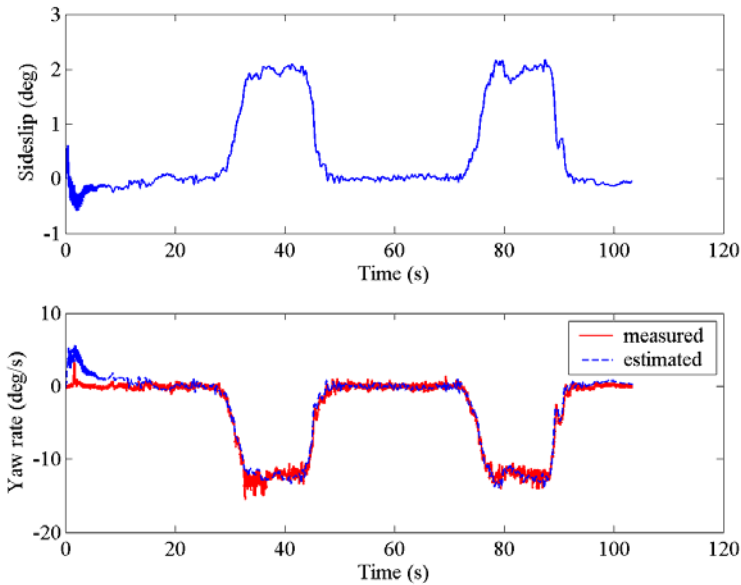


Velocity and steer angle
from test track

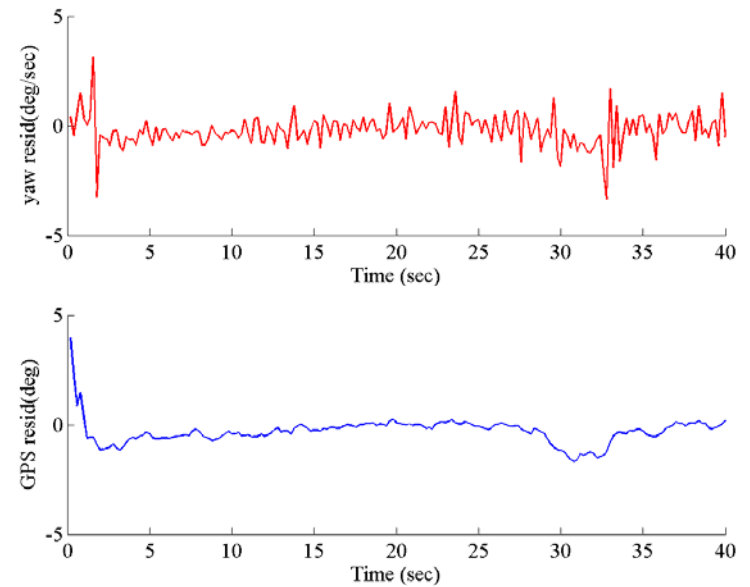
- Vehicle was driven around NCAT's 180 degree fixed radius pavement test track with an 8 degree bank turn
- Vehicle was driven at a constant velocity of 70 mph



Model-Based Estimator Experimental Results



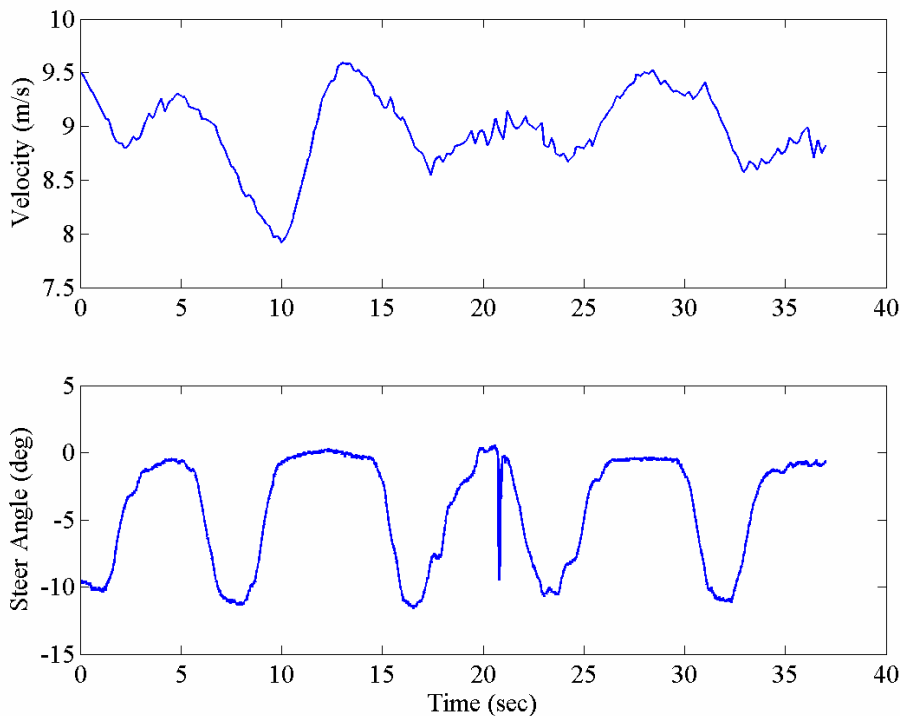
Sideslip and yaw rate
for test track



Residuals for yaw rate
and GPS from
test track



Combining Kinematic and Model-Based

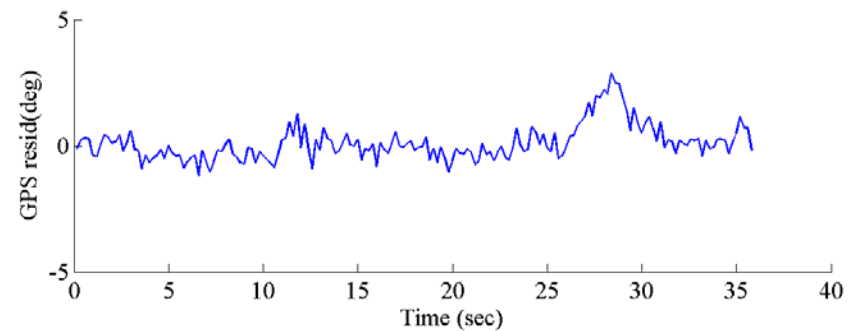
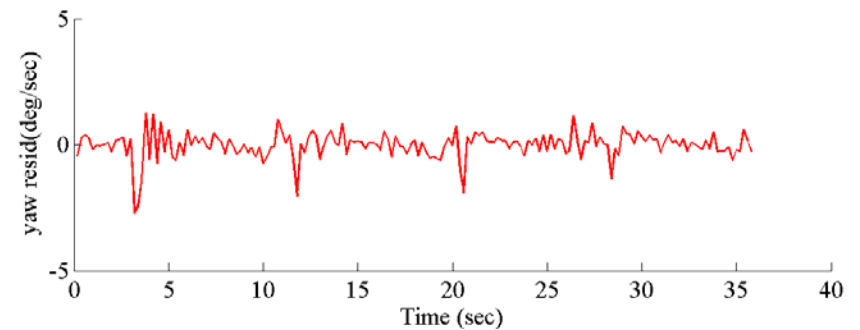
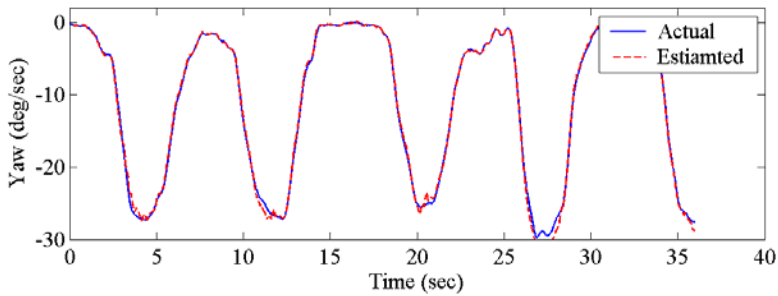
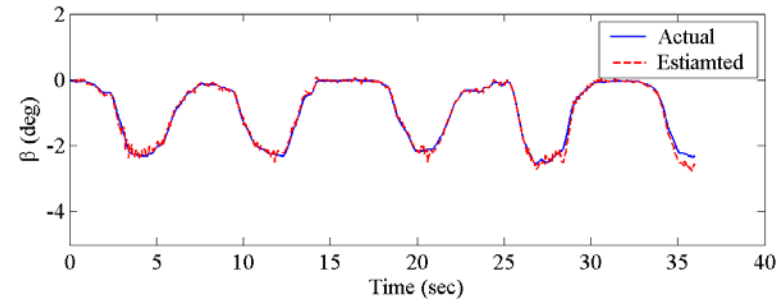


Velocity and steer angle

- Gyro scale factor was removed
- Kinematic Kalman filter was used to estimate sideslip
- Tire cornering stiffness was then calculated and feed into model based estimator



Combination Estimator Experimental Results



Sideslip and yaw rate
from combine the two
estimators

Residuals from yaw rate
and GPS measurements



Future work

- Investigate the possibility of using a nonlinear method to accurately estimate the tire cornering stiffness and weight split.
- Include a higher fidelity dynamic model of the vehicle to include nonlinear tire model
- Investigate the advantages of adding dual antenna GPS attitude measurements with a Model-Based estimator



Questions????