Vehicle handling modification via steer-by-wire

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June 5, 2003

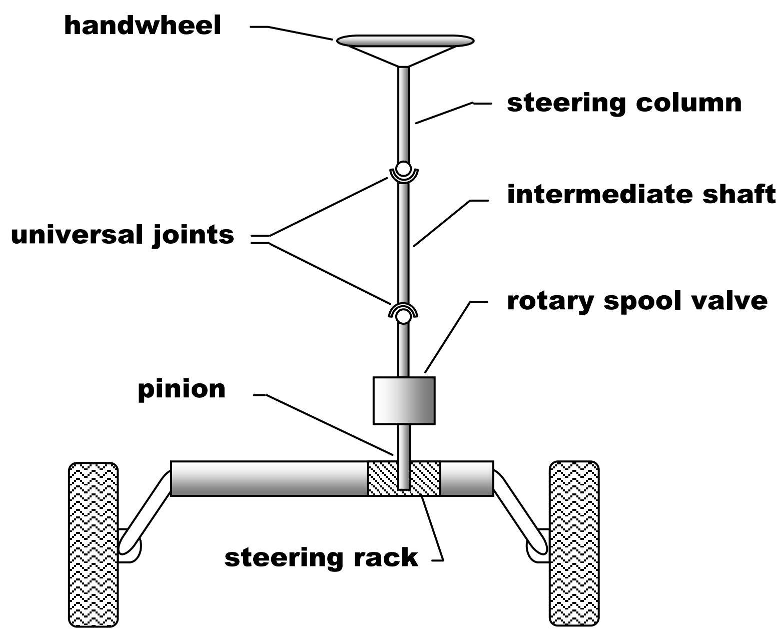
Outline

- Concept of handling modification
- Techniques for steer-by-wire control
- GPS-based state estimation
- A physically intuitive handling modification
- Experimental results

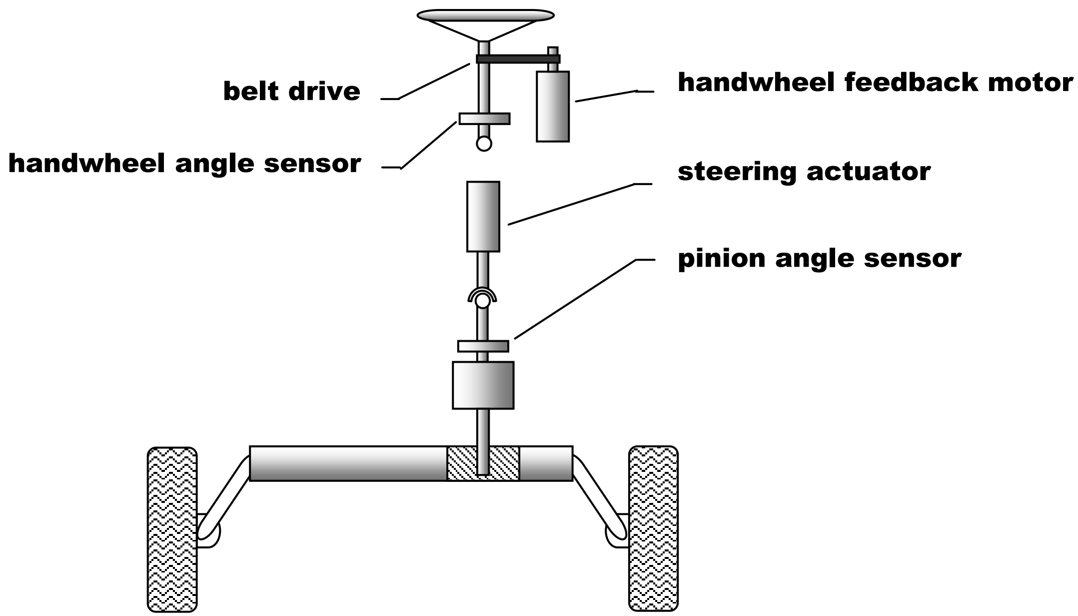
How do you make a Cavalier handle like a Corvette?

- Goal: tune handling behavior to driver preference or variations in operating conditions.
- Approach: artificially adjust tire characteristics with modified steering inputs.
- Implementation: precise active steering control and accurate vehicle state feedback.

Conventional steering system

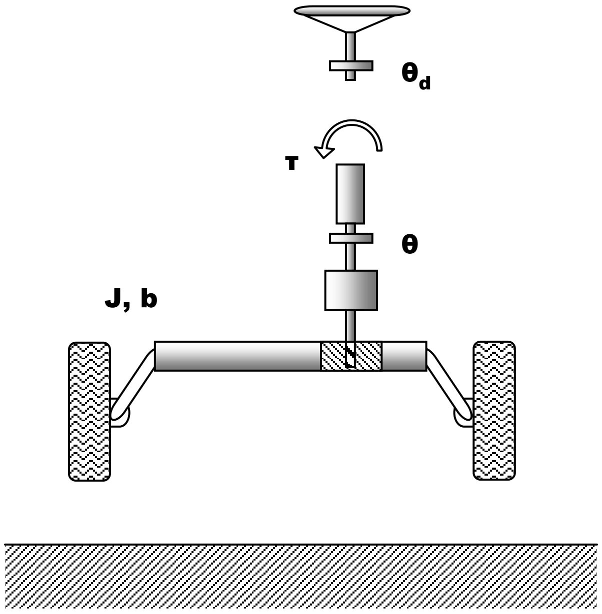


Steer-by-wire system



Steer-by-wire controller

- Actual steer angle should track commanded angle with minimal error.
- Initially consider no tire to ground contact.

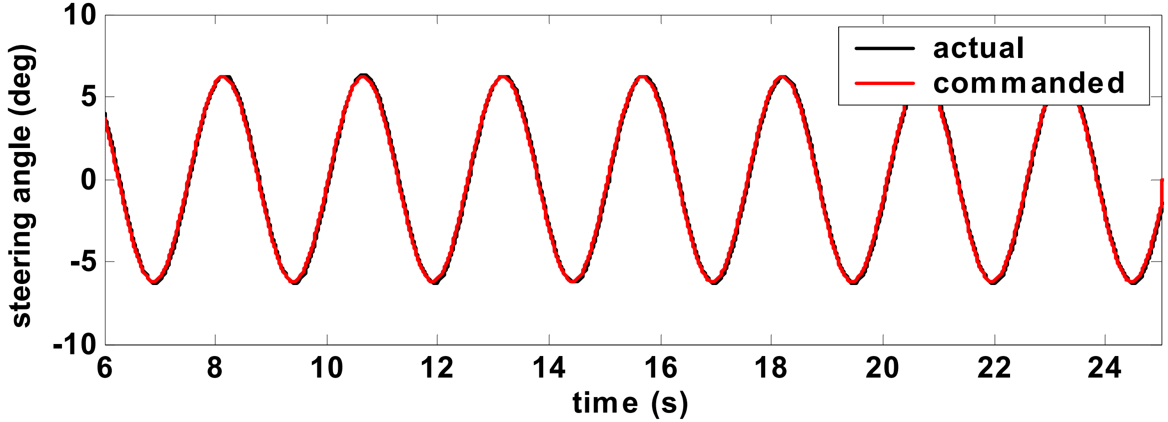


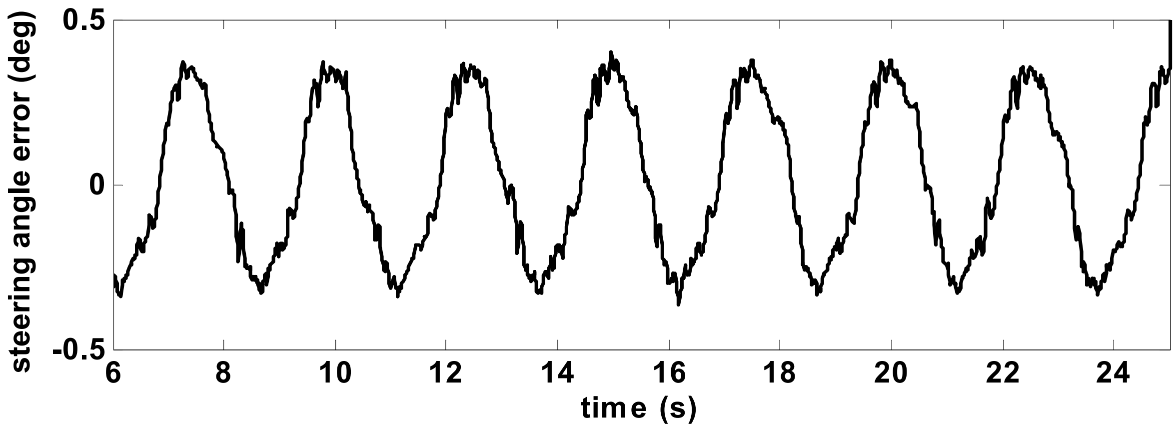
τ	actuator torque
θ_d	commanded angle (at handwheel)
θ	actual angle (at pinion)
J	effective moment of inertia
b	effective damping

Feedback control only

$$\tau = \tau_{feedback}$$

$$\tau_{feedback} = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta})$$





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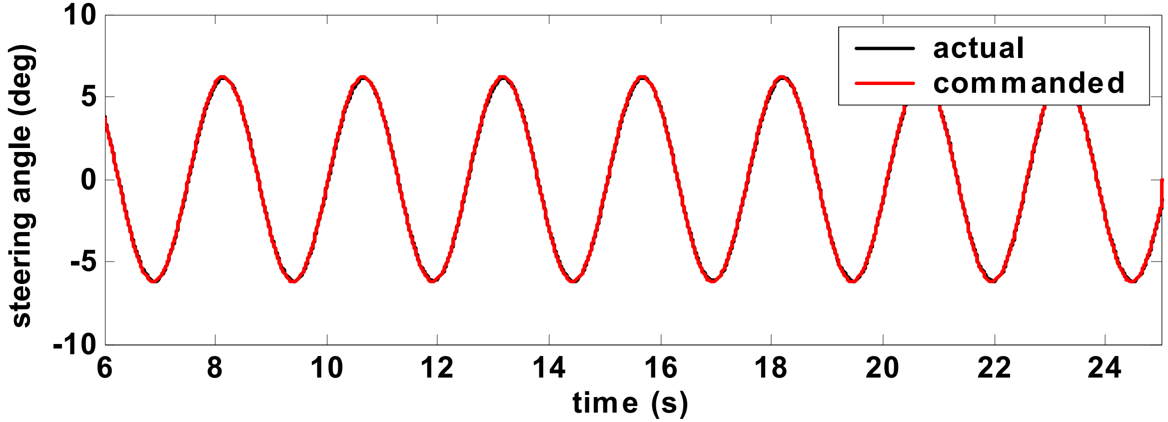
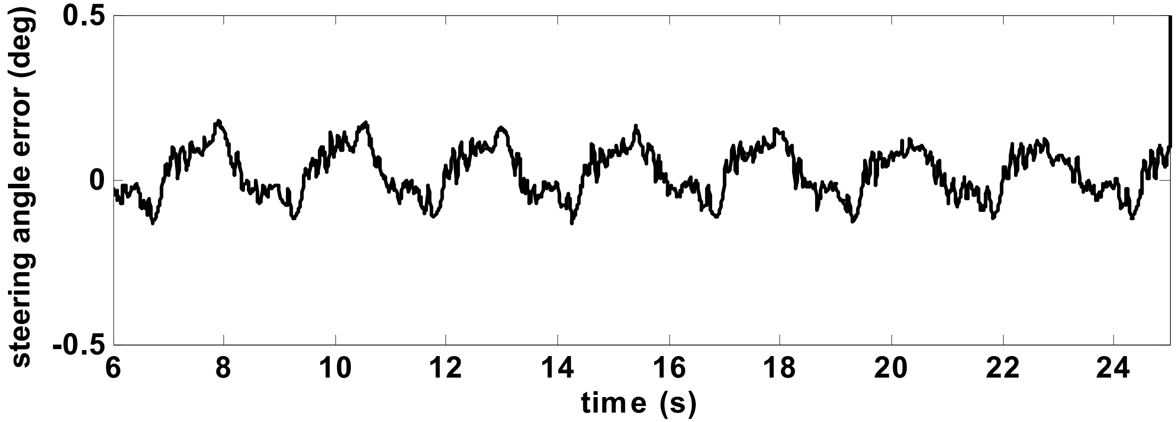
Feedback with feedforward compensation

$$\tau = \tau_{feedback} + \tau_{feedforward}$$

$$\tau_{feedforward} = J\ddot{\theta}_d + b\dot{\theta}_d$$





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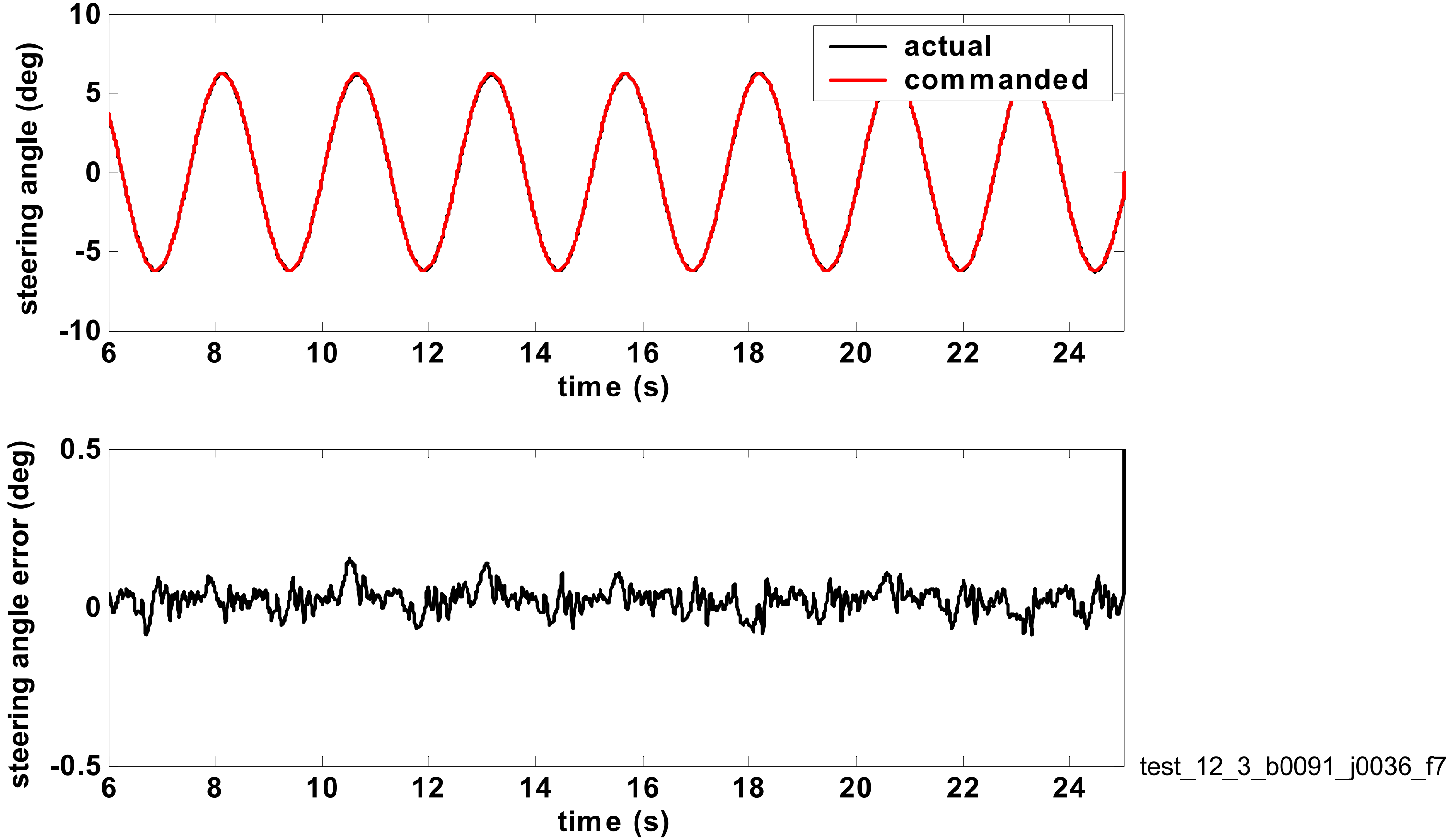
Feedforward and friction compensation

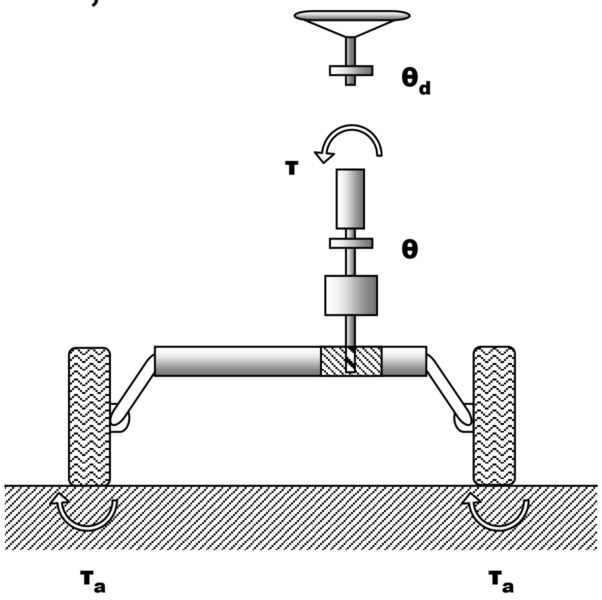
$$\tau = \tau_{feedback} + \tau_{feedforward} + \tau_{friction}$$

$$\tau_{friction} = F_c \operatorname{sgn}\left(\dot{\theta}_d\right)$$



Effects of tire self-aligning moment

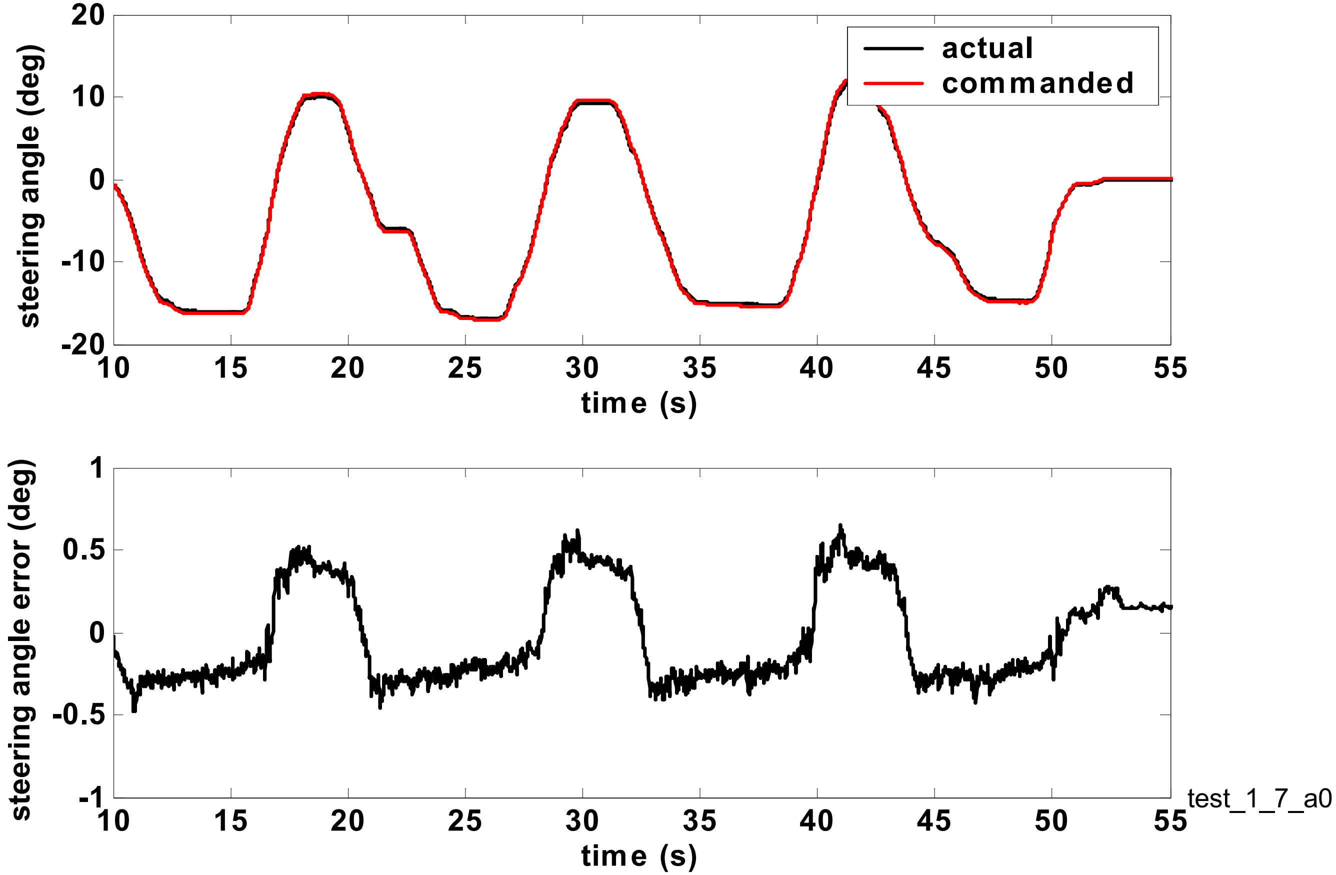
- Reintroduce tire to ground contact (vehicle moving at normal driving speeds).
- In a conventional steering system, self-centering tendency is due to aligning moment.
- Aligning moment acts as a (known) disturbance on steer-by-wire system.



Error due to aligning moment disturbance

$$\tau = \tau_{feedback} + \tau_{feedforward} + \tau_{friction}$$

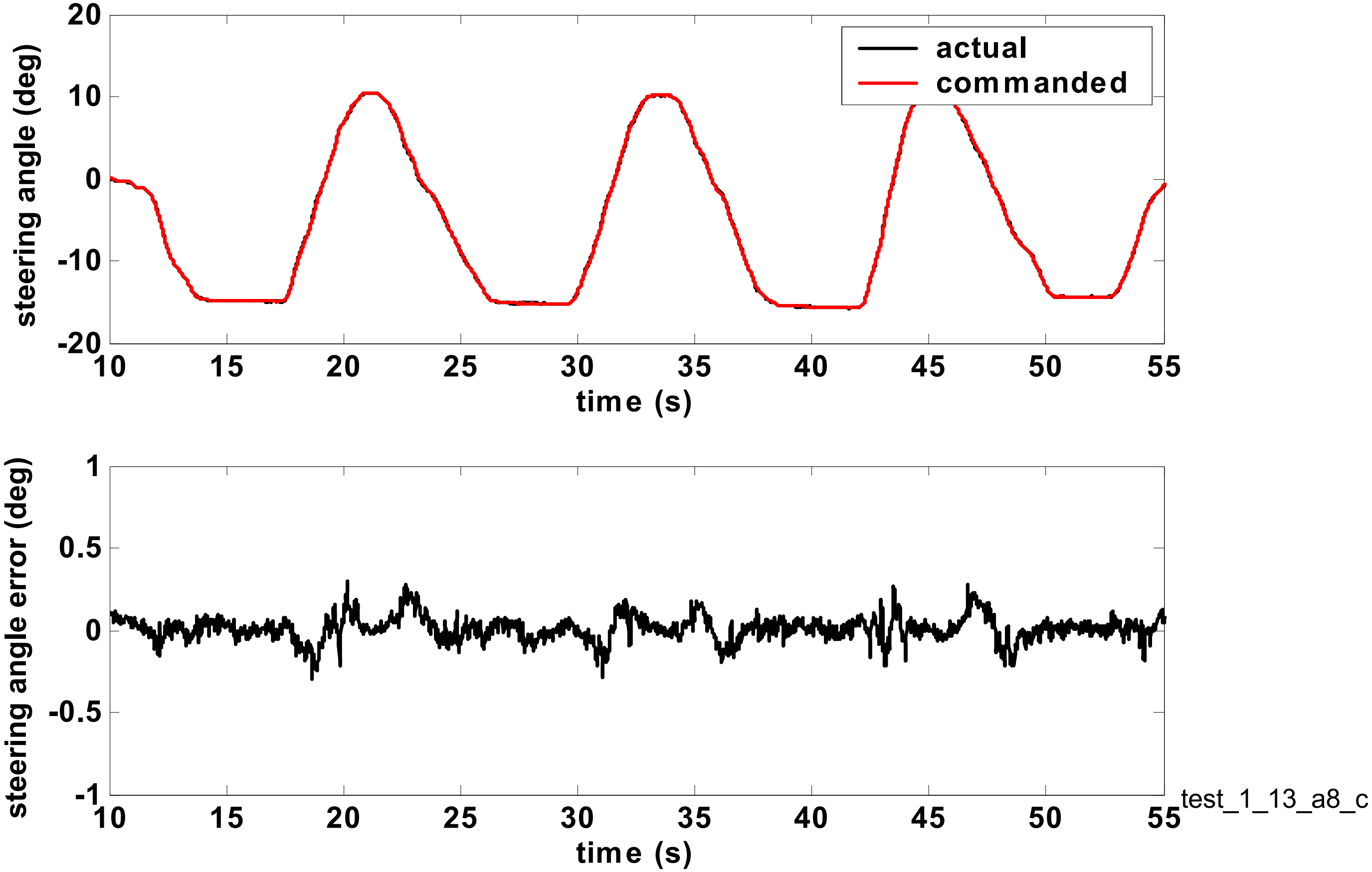
(Same controller as before)



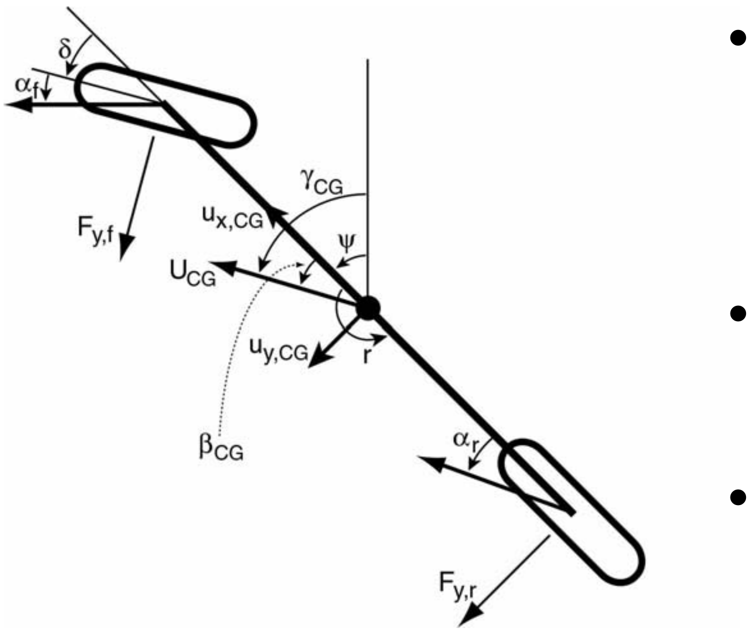
Controller with aligning moment correction

$$\tau = \tau_{feedback} + \tau_{feedforward} + \tau_{friction} + \tau_{aligning}$$

$$\tau_{aligning} = K_a \hat{\tau}_a$$



Linear vehicle model



- Force and moment equations

$$m \cdot a_y = F_{y,f} \cdot \cos\delta + F_{y,r}$$

$$I_z \cdot \dot{r} = a \cdot F_{y,f} \cdot \cos\delta - b \cdot F_{y,r}$$

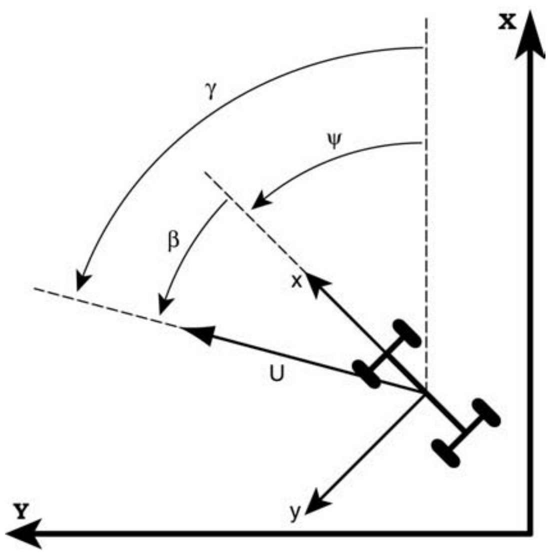
- Side forces (linear tire model)

$$F_{y,f} = -C_f \alpha_f, \quad F_{y,r} = -C_r \alpha_r$$

- Steering angle

$$\delta = \frac{1}{r_{steering}} \theta$$

Vehicle sideslip



- Angle between vehicle heading and direction of velocity at CG

$$\beta = \gamma - \psi = \tan^{-1}\left(\frac{u_y}{u_x}\right) \approx \frac{u_y}{u_x}$$

- Sideslip angle (*β*) at CG and yaw rate (*r*) as state variables

$$\begin{bmatrix} \dot{\beta}_{CG} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-C_{\alpha f} - C_{\alpha r}}{mV} & -1 + \left(\frac{C_{\alpha r} b - C_{\alpha f} a}{mV^2}\right) \\ \frac{C_{\alpha r} b - C_{\alpha f} a}{I_z} & \frac{-C_{\alpha f} a^2 - C_{\alpha r} b^2}{I_z V} \end{bmatrix} \begin{bmatrix} \beta_{CG} \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_{\alpha f}}{mV} \\ \frac{C_{\alpha f} a}{I_z} \end{bmatrix} \delta$$

Physically motivated handling modification

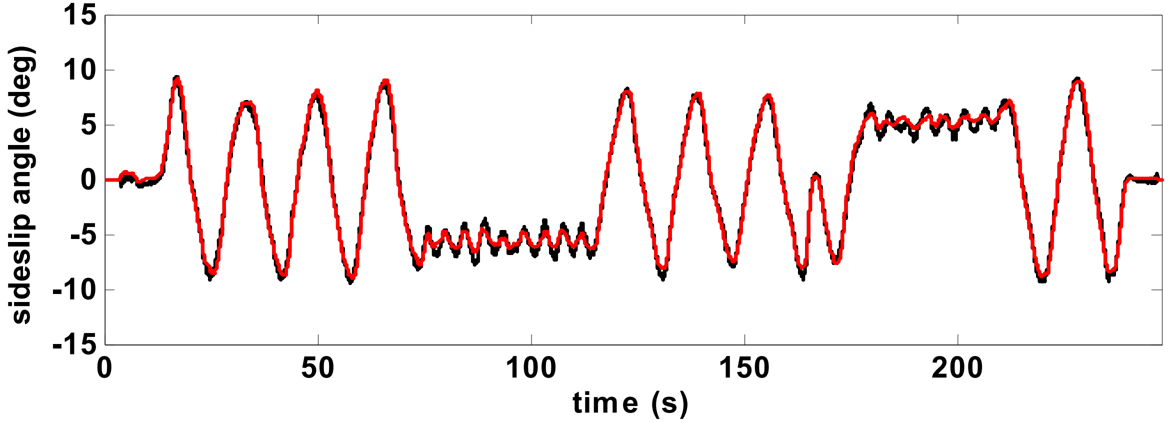
- Steer angle is linear combination of states and driver command angle $\delta = K_r r + K_\beta \beta + K_d \delta_d$
- Define new cornering stiffness as $\hat{C}_{\alpha f} = C_{\alpha f}(1+\eta)$
- Choose gains such that state space equation is exactly the same as before with new cornering stiffness $K_\beta = -\eta \quad K_r = -\frac{a}{V}\eta \quad K_d = (1+\eta)$

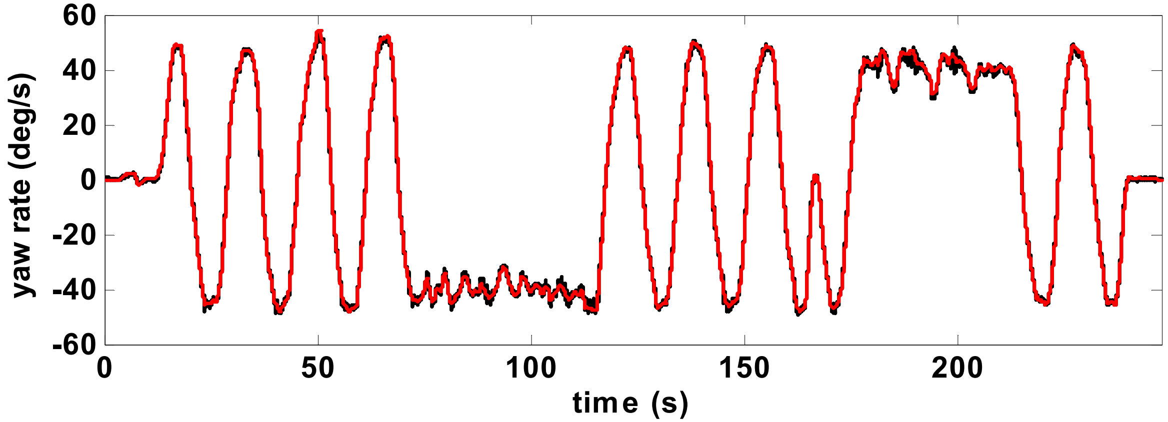
$$\Rightarrow \begin{bmatrix} \dot{\beta}_{CG} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-\hat{C}_{\alpha f} - C_{\alpha r}}{mV} & -1 + \left(\frac{C_{\alpha r} b - \hat{C}_{\alpha f} a}{mV^2}\right) \\ \frac{C_{\alpha r} b - \hat{C}_{\alpha f} a}{I_z} & \frac{-\hat{C}_{\alpha f} a^2 - C_{\alpha r} b^2}{I_z V} \end{bmatrix} \begin{bmatrix} \beta_{CG} \\ r \end{bmatrix} + \begin{bmatrix} \frac{\hat{C}_{\alpha f}}{mV} \\ \frac{\hat{C}_{\alpha f} a}{I_z} \end{bmatrix} \delta_d$$

GPS-based state estimation

- Accurate estimates of sideslip angle and yaw rate are available from combined Global Positioning System (GPS) and inertial navigation sensor (INS) measurements.
- Multiple-antenna GPS receivers provide absolute velocity and heading information.

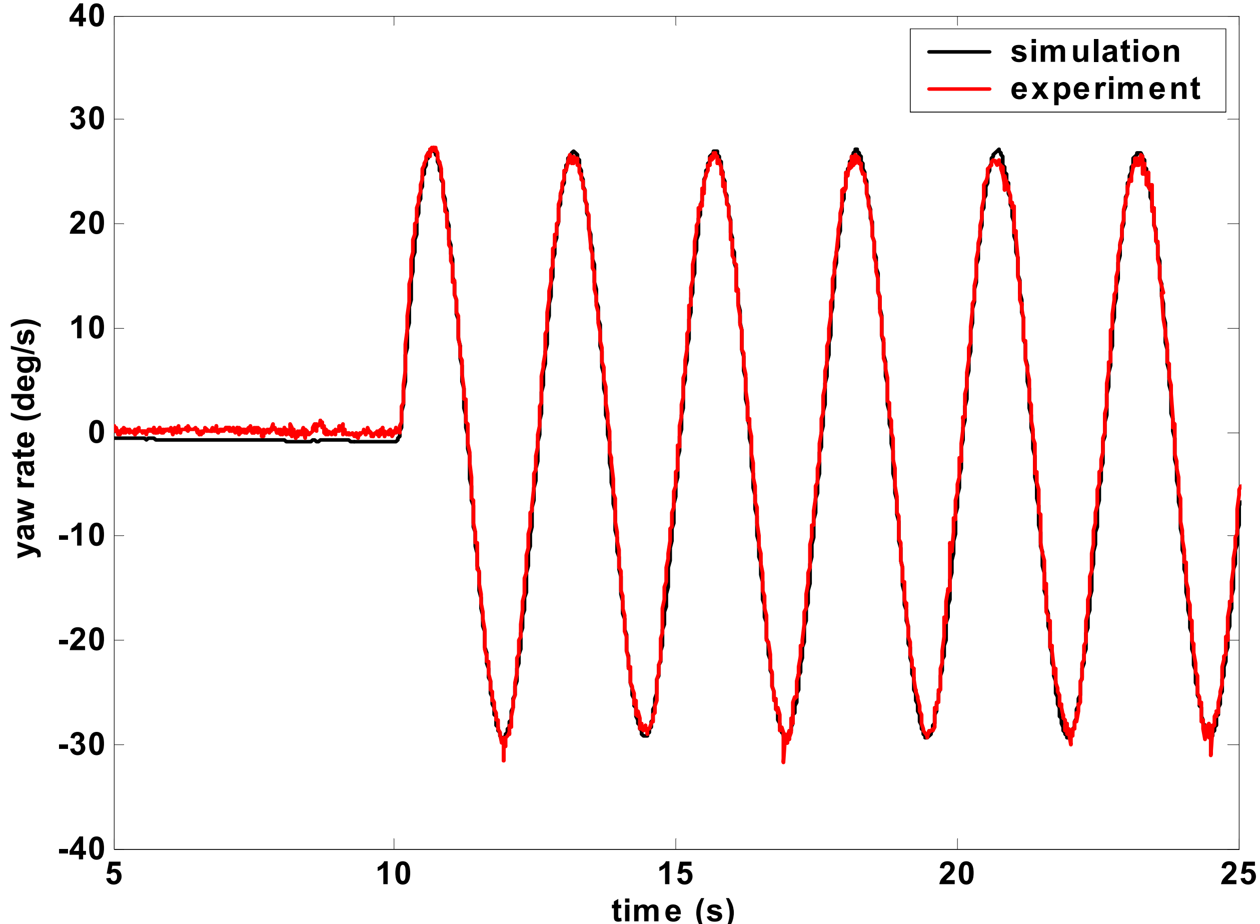
Validation of state estimation: experiment vs. model





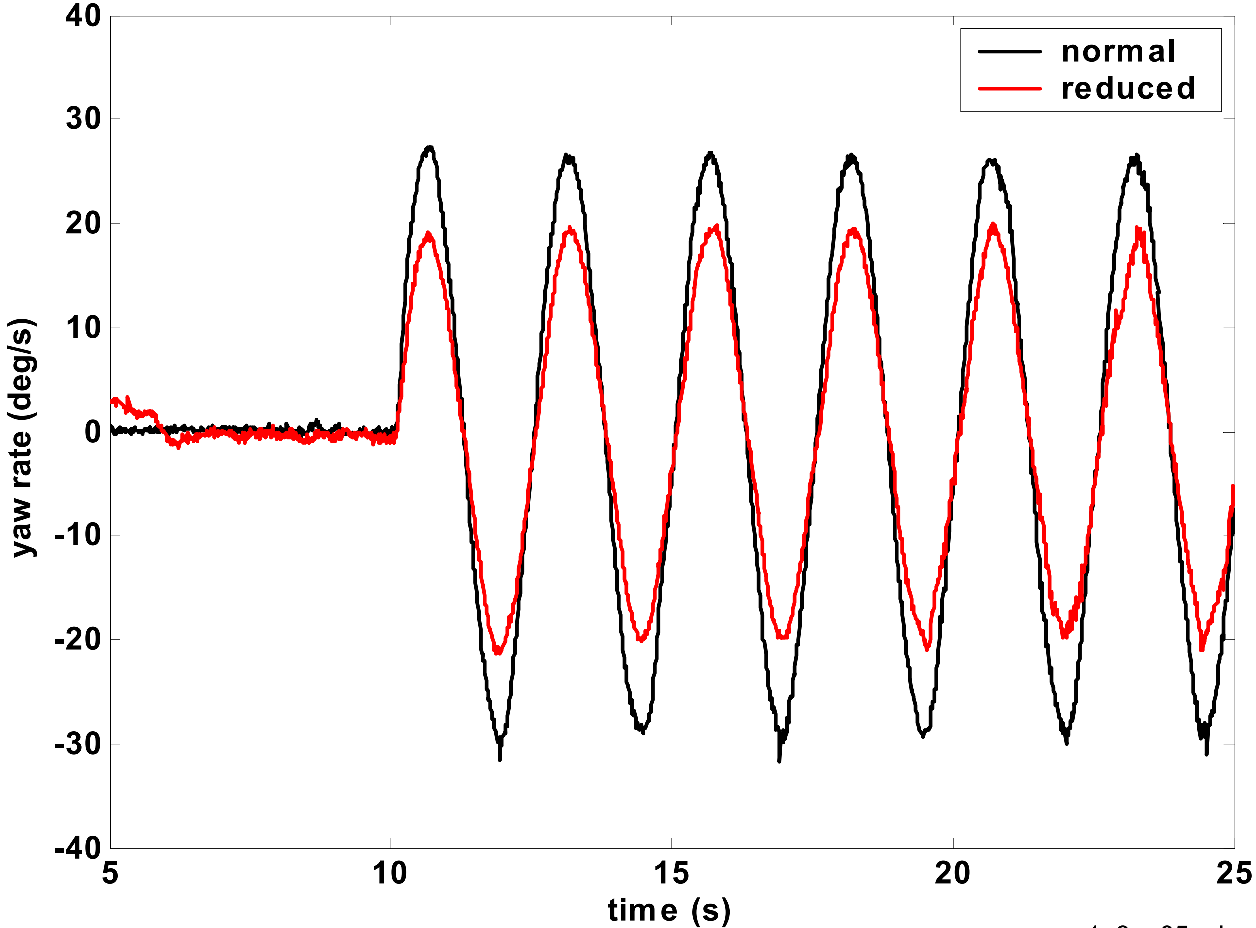
Handling modification tests at Moffett Federal Airfield

Model: normal front cornering stiffness



mo_1_3_eta0_d

Experiment: effectively reduced front cornering stiffness



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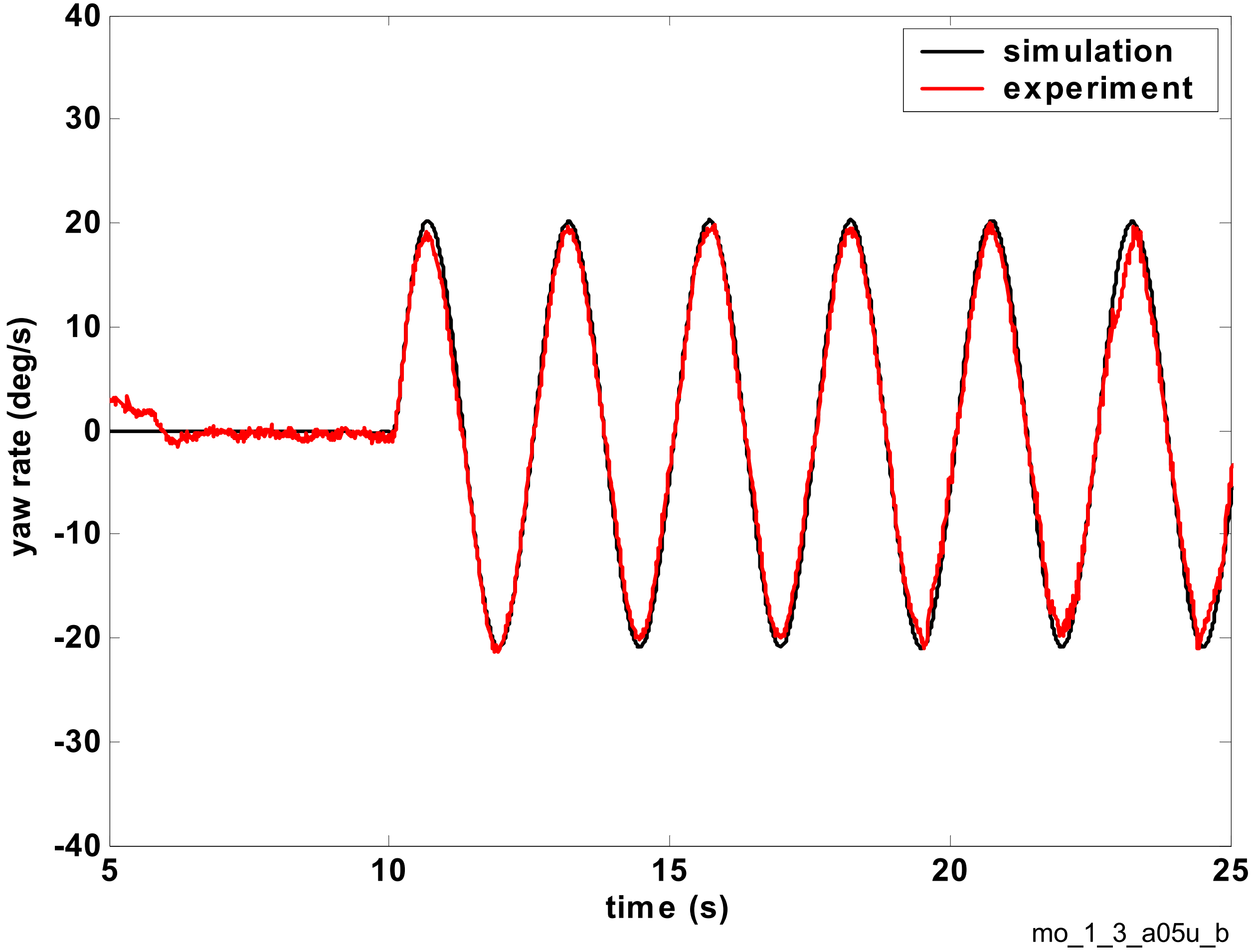
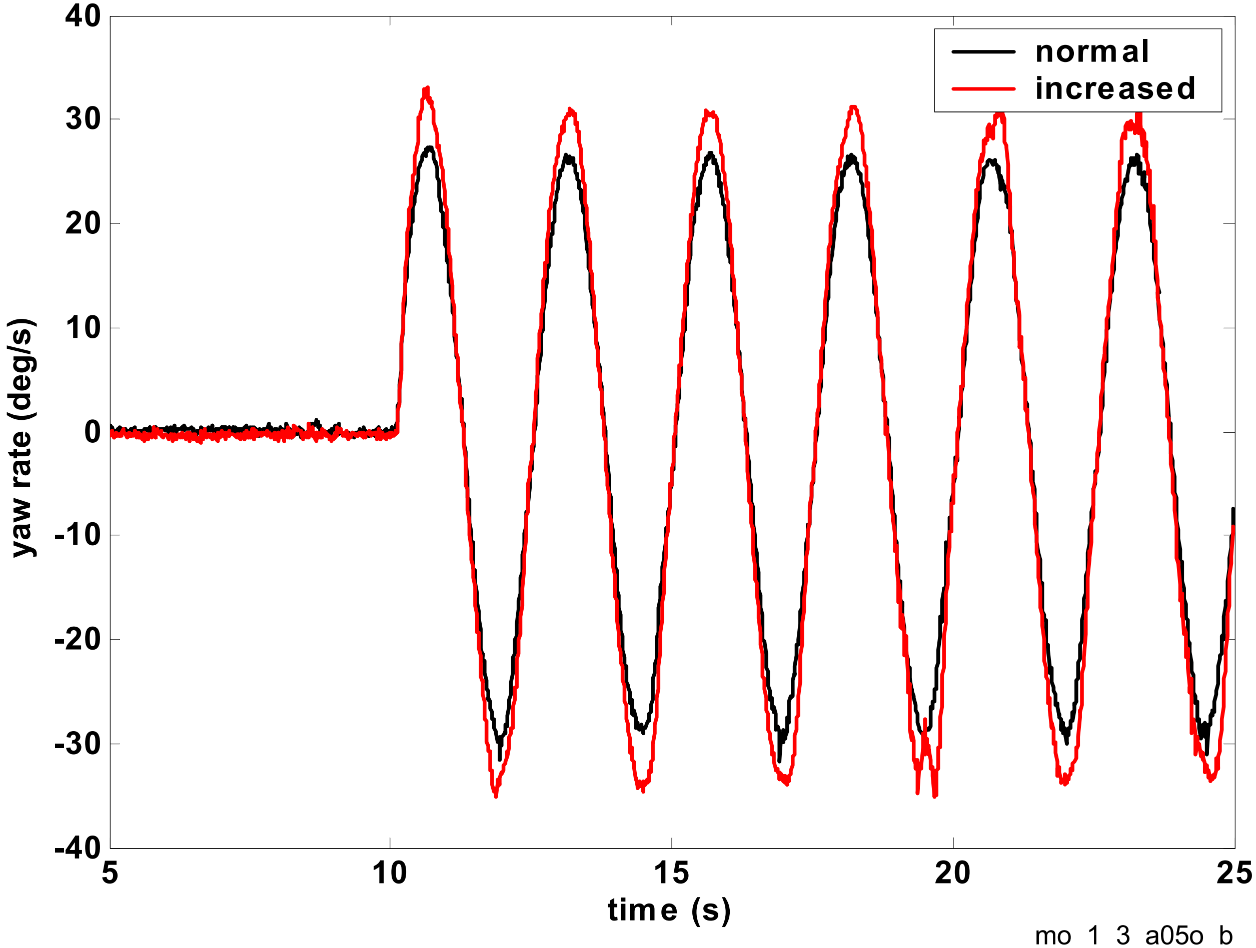
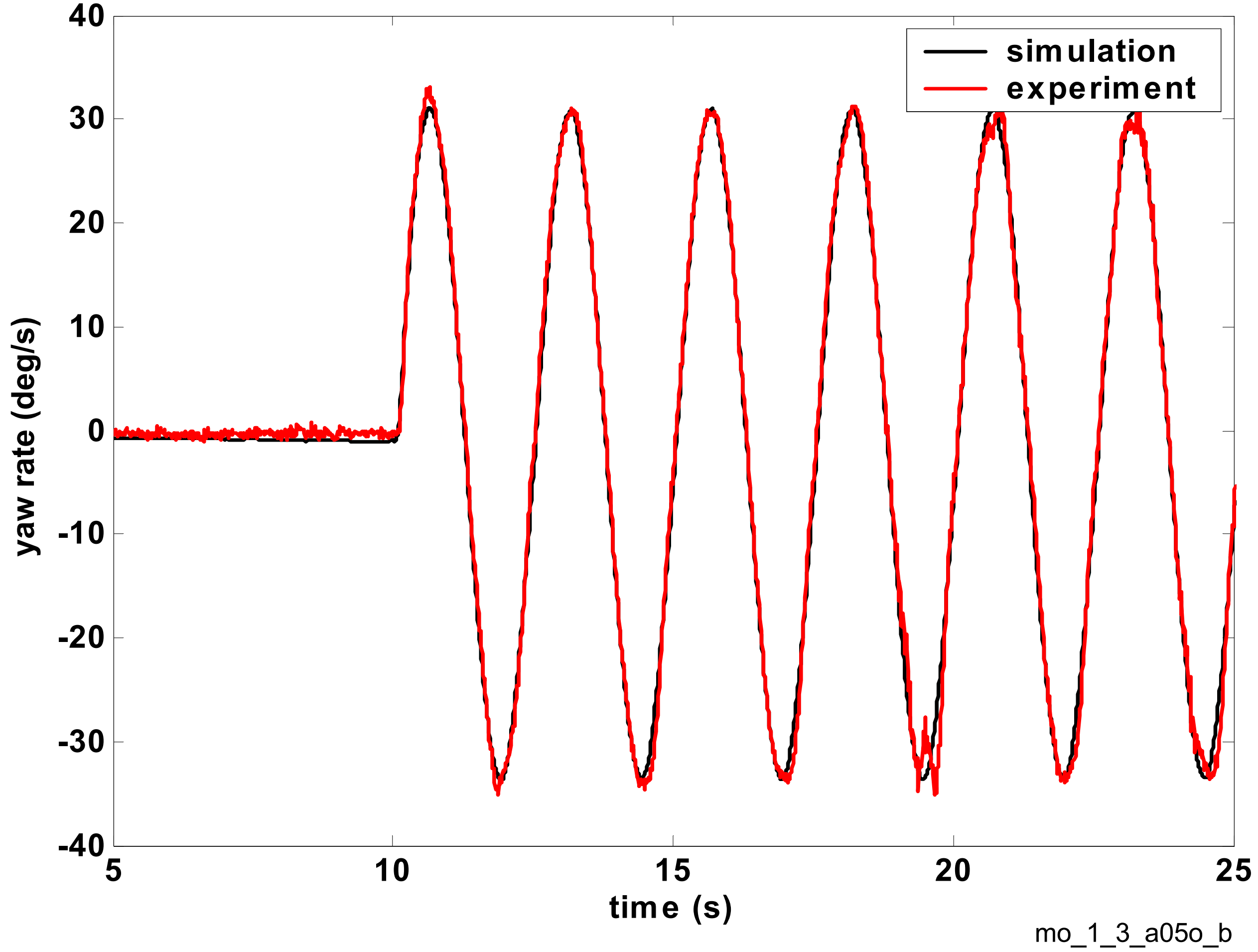
Model: effectively reduced front cornering stiffness



Experiment: effectively increased front cornering stiffness



Model: effectively increased front cornering stiffness



Conclusion

- The combination of steer-by-wire and full state feedback provides a way to modify vehicle handling characteristics for improved driving feel and safety.
- By effectively changing front cornering stiffness, the same vehicle can be made to handle differently.
- Therefore, it is possible to maintain consistent handling characteristics under variable operating conditions.

Future work

- What happens outside the linear region of operation and when tires reach the limits of adhesion?
- In some situations, active steering intervention is an effective means of stability control.
- What are the limitations of active steering intervention and how can it be combined with other control inputs such as differential braking?