Vehicle State Estimation Using Steering Torque

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Outline

- Introduction
  - Vehicle dynamics control with steer-by-wire
  - Need for sideslip estimation in vehicle dynamics control
- Vehicle model
- Steering system
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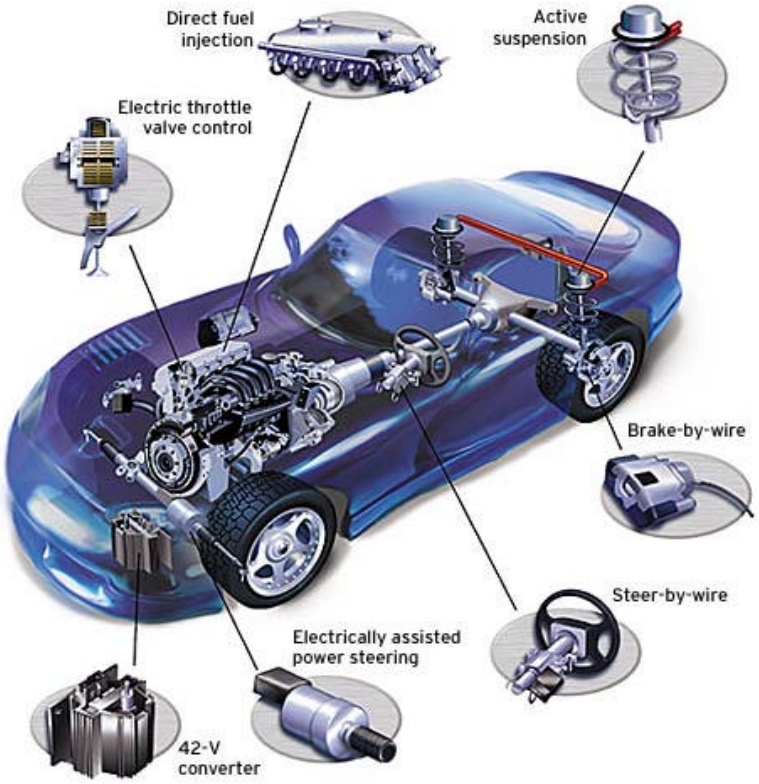
  - Role of aligning moment
  - Steering disturbance and vehicle state observers
- Conclusion and future work

Toward a by-wire future

- Throttle-by-wire and brake-by-wire already available on production cars.
- Steer-by-wire a more significant leap from conventional automotive systems—still several years away.
- Steer-by-wire promises to significantly improve vehicle handling and driving safety.



Source: Motorola

Example: handling modification demonstrated on experimental steer-by-wire vehicle

Need for sideslip estimation

- Handling modification relies on full vehicle state feedback (yaw rate and sideslip).
- In experiments, estimated from a combination of GPS and INS measurements.
- Drawbacks of GPS: loses signal under adverse conditions, cost.

- Knowledge of sideslip also critical for electronic stability control (ESC) systems.
- Often determined based on integration of lateral acceleration or model.
- Drawbacks: accumulation of error due to sensor drift, model uncertainty.

Steer-by-wire as a sideslip estimator

- Steer-by-wire system is a self-contained sensor for tire forces.
- Tire forces directly influence vehicle dynamics.
- Completely estimate sideslip using only steer-by-wire system and yaw rate sensor.
- Also works with electric power steering systems.

The car as a dynamic system

- Assume constant longitudinal speed, *V*, so only lateral forces.

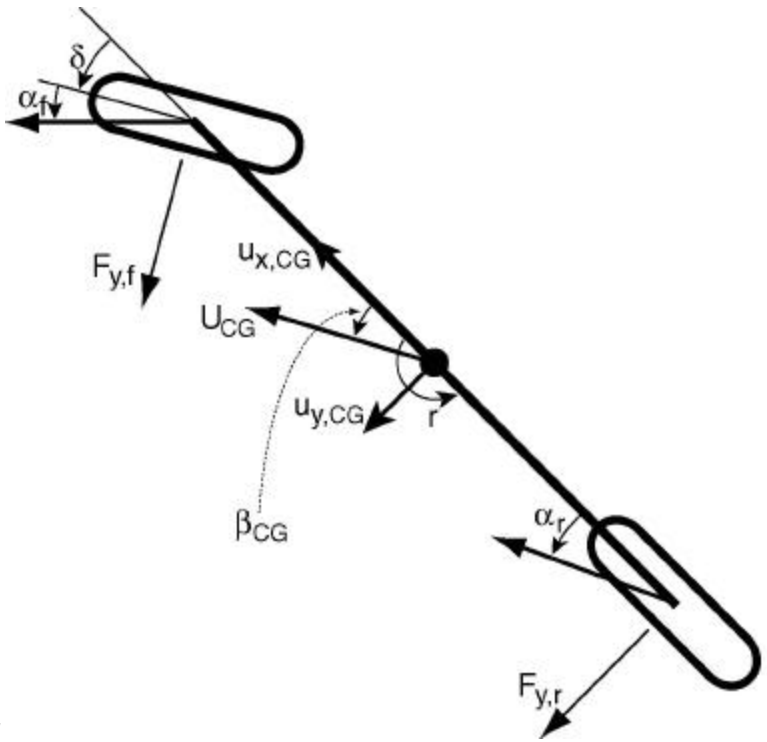
- Lateral forces generated by tire "slip."

$$F_y = -C_a a$$

- Force and mass balance:

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

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



Linearized vehicle model

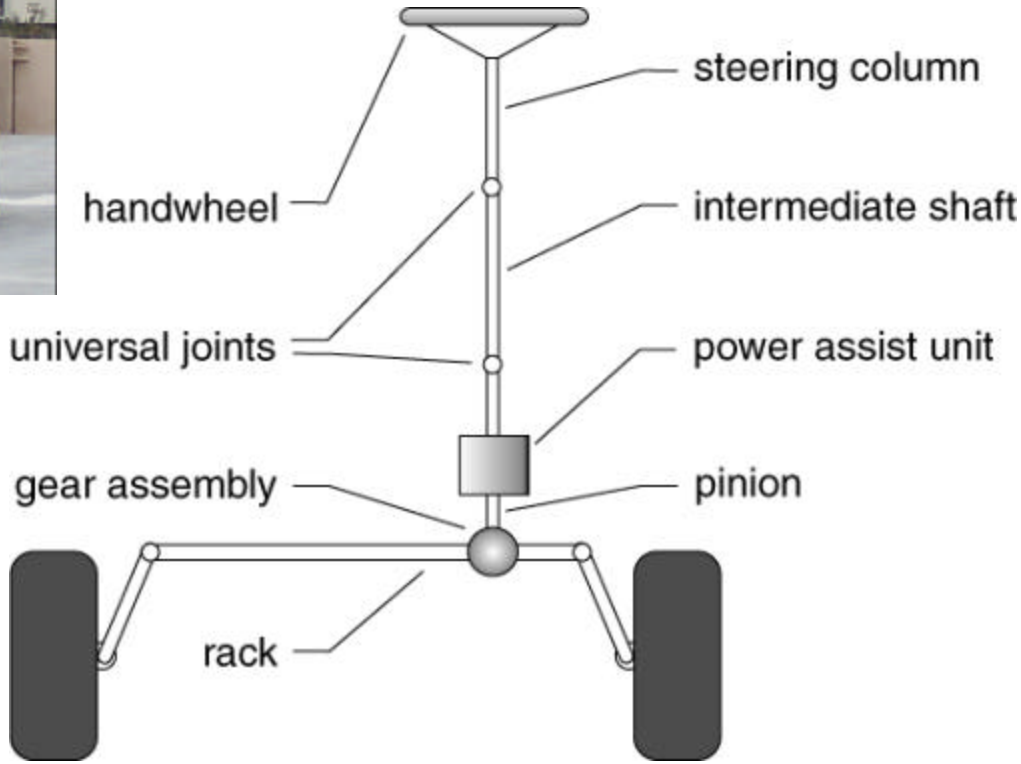
- Equations of motion:

$$\begin{bmatrix} \dot{b} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-C_{a,f} - C_{ar}}{mV} & -1 + \left(\frac{C_{a,r} b - C_{a,f} a}{mV^2} \right) \\ \frac{C_{a,r} b - C_{a,f} a}{I_z} & \frac{-C_{a,f} a^2 - C_{a,r} b^2}{I_z V} \end{bmatrix} \begin{bmatrix} b \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_{a,f}}{mV} \\ \frac{C_{a,f} a}{I_z} \end{bmatrix} d$$

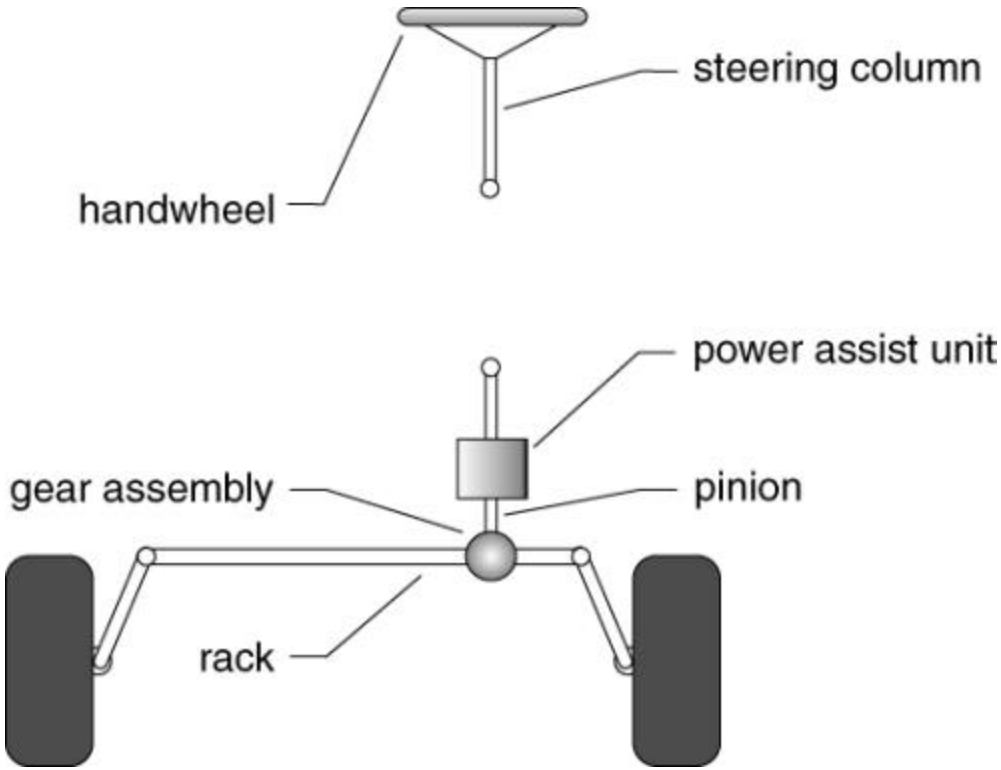
- Yaw rate, r, and sideslip angle, b, completely describe vehicle motion in plane.

- Steering angle, d, is the input.

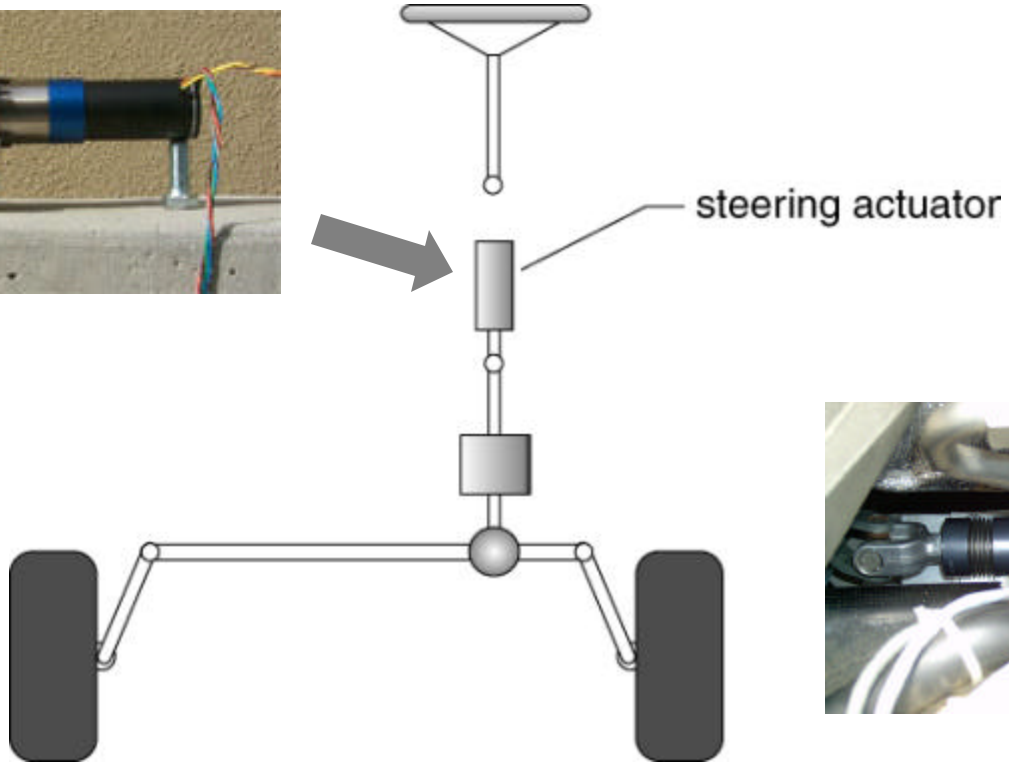
Conventional steering system



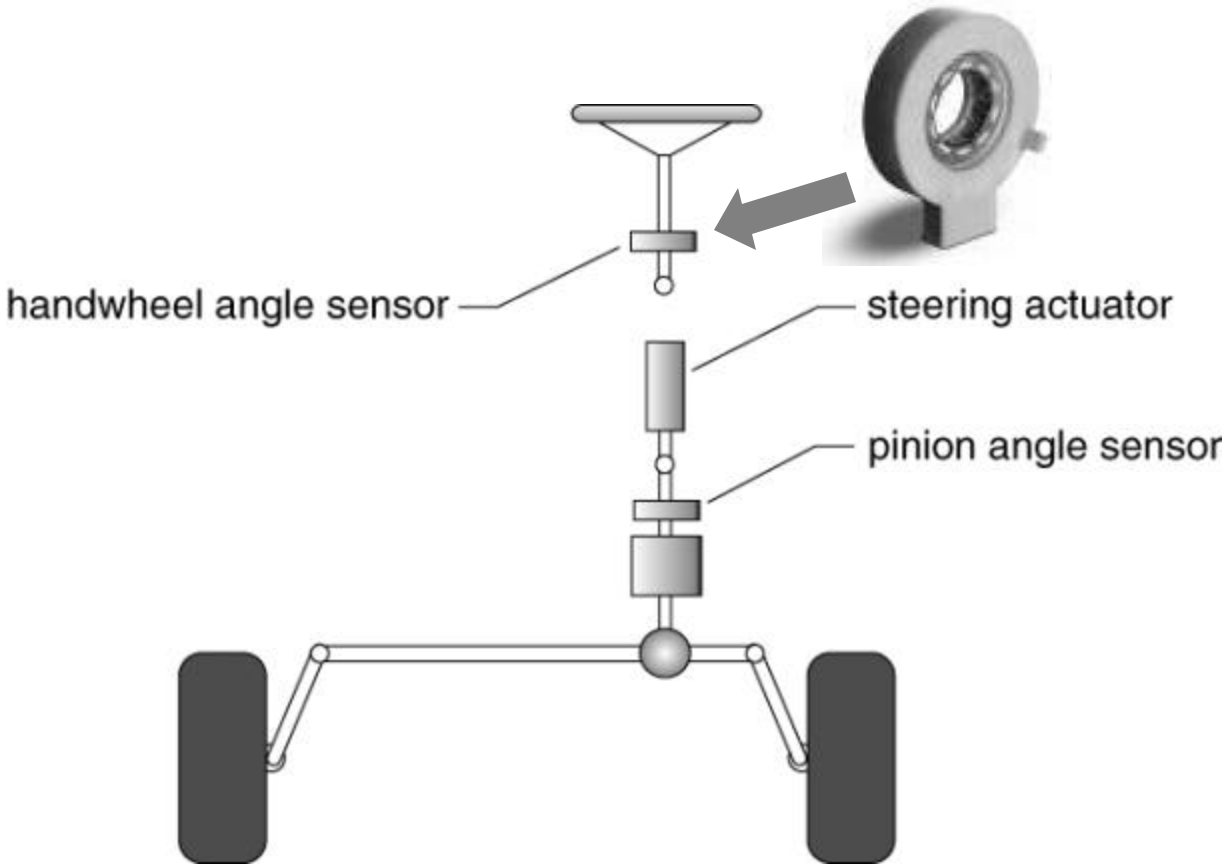
Conversion to steer-by-wire



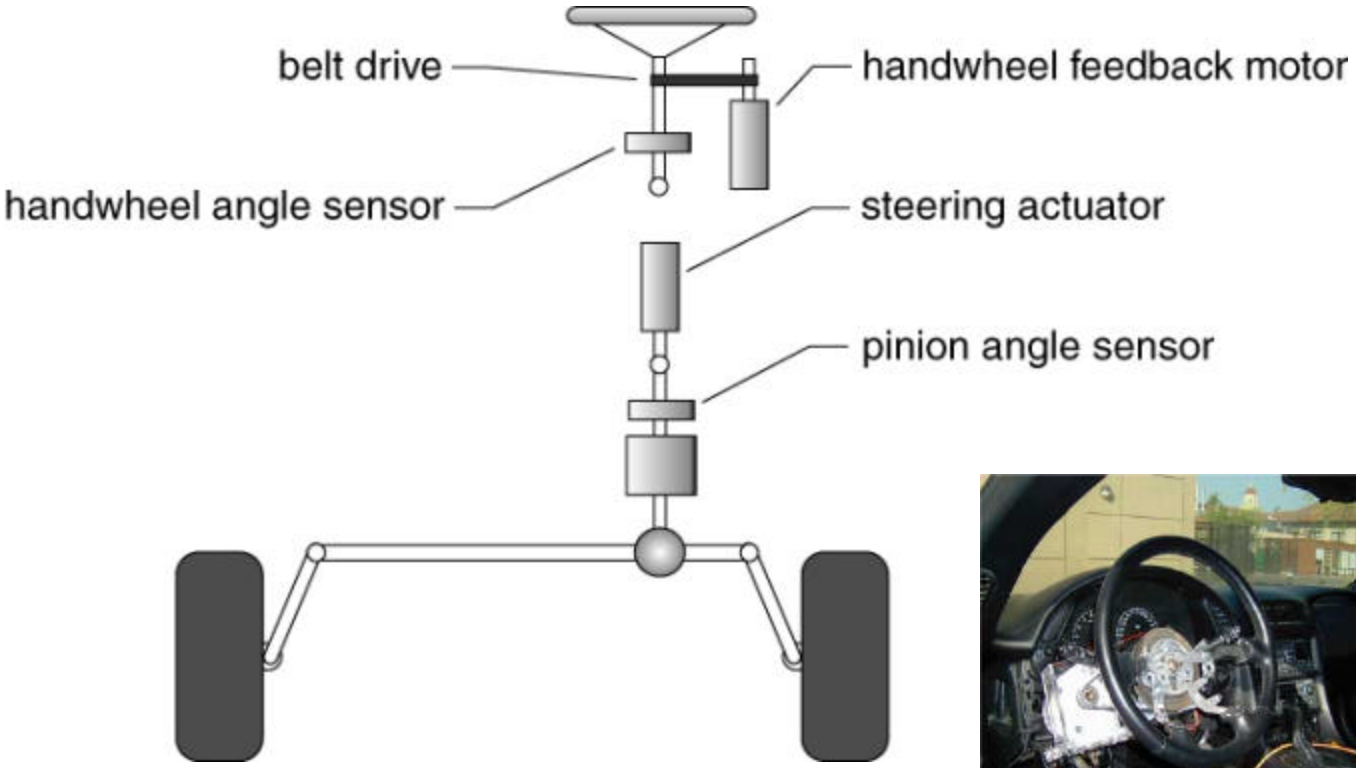
Steer-by-wire actuator



Steer-by-wire sensors

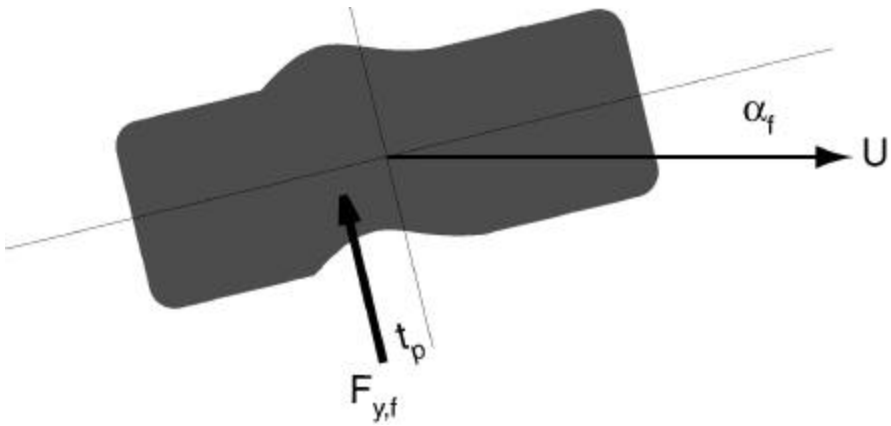


Force feedback system



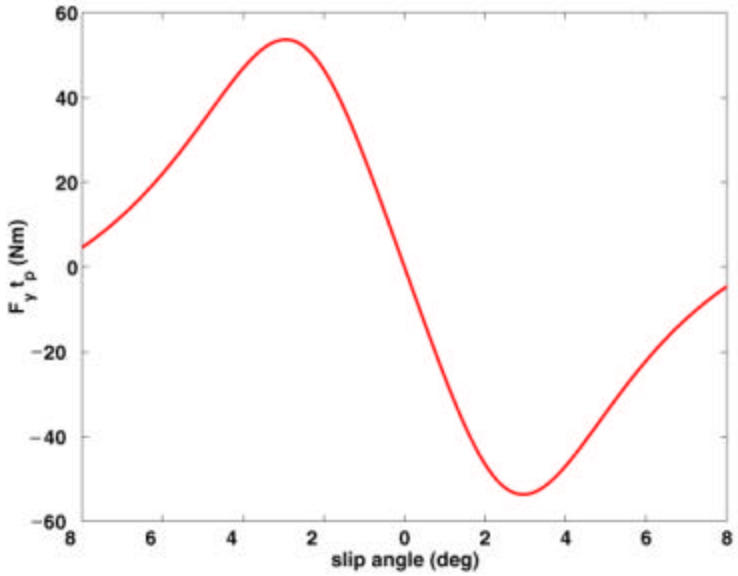
Aligning moment due to pneumatic trail

- Part of aligning moment comes from tire deformation during cornering.
- Point of application of resultant force occurs behind center of contact patch.
- Pneumatic trail generates moment about steer axis (usually against direction of steering).



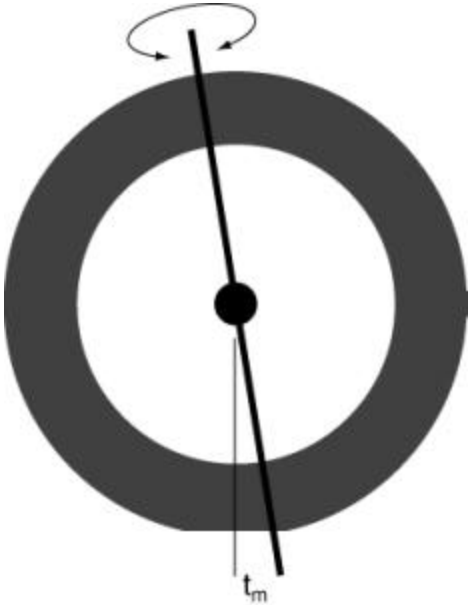
Aligning moment due to pneumatic trail

- Becomes nonlinear at larger slip angles.
- In conventional steering system, change in steering feel alerts driver that vehicle is approaching limits of handling.



Aligning moment due to mechanical trail

- Other part from the wheel caster angle.
- Offset between intersection of steering axis with ground and center of tire contact patch.
- Lateral force acting on contact patch also contributes to moment about steer axis (against direction of steering).

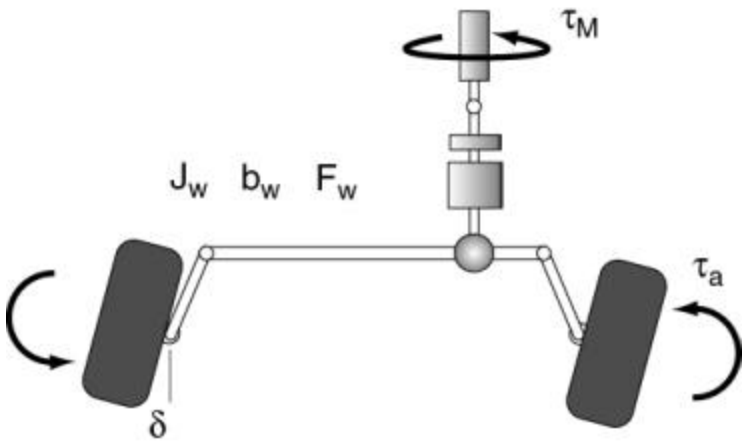


Steering system dynamics

d	road wheel angle
J_w	moment of inertia
b_w	damping constant
F_w	Coulomb friction
t_a	aligning moment
t_M	motor torque
k_M	motor constant
i_M	motor current

$$J_w \ddot{d} + b_w \dot{d} + F_w + t_a = r_s t_M$$

$$t_M = k_M i_M$$



Steering system as a disturbance observer

- Express in state space form. Choose steering angle as output (measured state). Motor current is input. Aligning moment is disturbance to be estimated.

$$\begin{bmatrix} \dot{d} \\ \ddot{d} \\ \dot{t}_a \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\dfrac{b_w}{J_w} & -\dfrac{1}{J_w} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} d \\ \dot{d} \\ t_a \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{r_s k_M}{J_w} \\ 0 \end{bmatrix} i_M$$

$$d = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} d \\ \dot{d} \\ t_a \end{bmatrix}$$

Link between aligning moment and sideslip angle

- Aligning moment can be expressed as function of the vehicle states, *b* and *r*, and the input, *d*.

$$
\begin{aligned}
t_a &= (t_p + t_m) F_{y,f} \\
&= -(t_p + t_m) C_{af} a_f \\
&= -(t_p + t_m) C_{af} \left(b + \frac{ar}{V} - d \right) \\
&= -(t_p + t_m) C_{af} b - \frac{a(t_p + t_m) C_{af}}{V} r + (t_p + t_m) C_{af} d
\end{aligned}
$$

Vehicle state observer

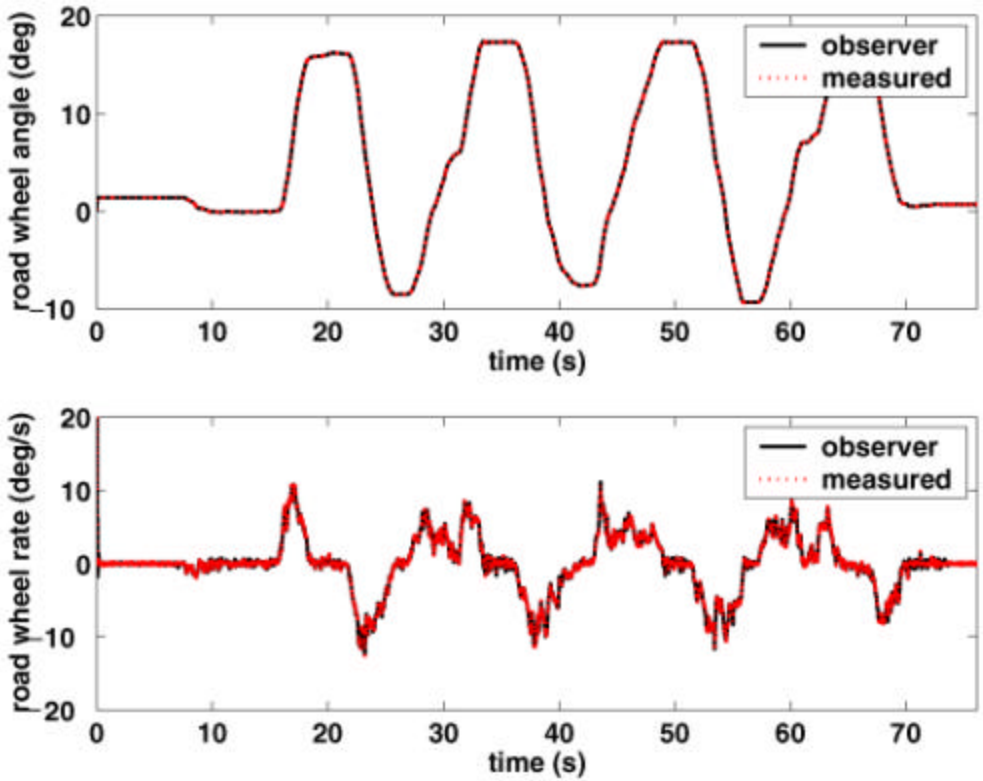
- Express in state space form. Steering angle is input. Yaw rate and aligning moment (from the disturbance observer) are outputs (measurements).

$$\begin{bmatrix} \dot{b}_{CG} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-C_{af}-C_{ar}}{mV} & -1+\left(\frac{C_{ar}b-C_{af}a}{mV^2}\right) \\ \frac{C_{ar}b-C_{af}a}{I_z} & \frac{-C_{af}a^2-C_{ar}b^2}{I_zV} \end{bmatrix} \begin{bmatrix} b_{CG} \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_{af}}{mV} \\ \frac{C_{af}a}{I_z} \end{bmatrix} d$$

$$\begin{bmatrix} r \\ t_a \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ (t_p+t_m)C_{af} & \frac{a(t_p+t_m)C_{af}}{V} \end{bmatrix} \begin{bmatrix} b_{CG} \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ (t_p+t_m)C_{af} \end{bmatrix} d$$

- Apply standard Luenberger observer.

Estimated steer angle and rate



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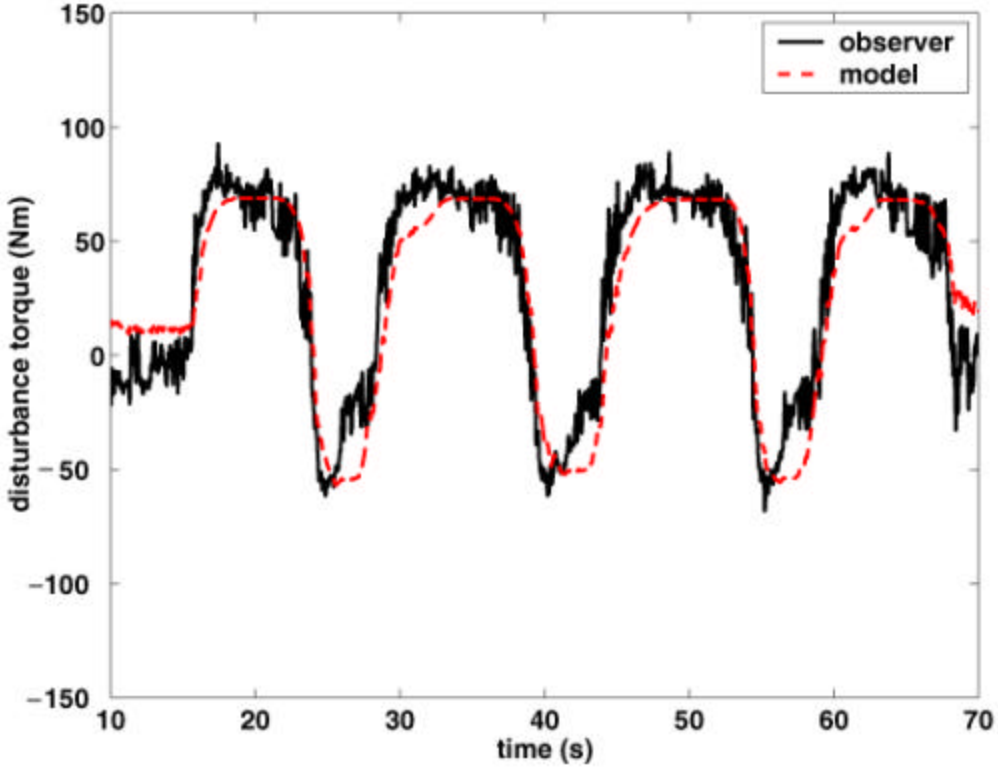
- Steering angle is measured, so observer should give exact estimate.

Estimated aligning moment



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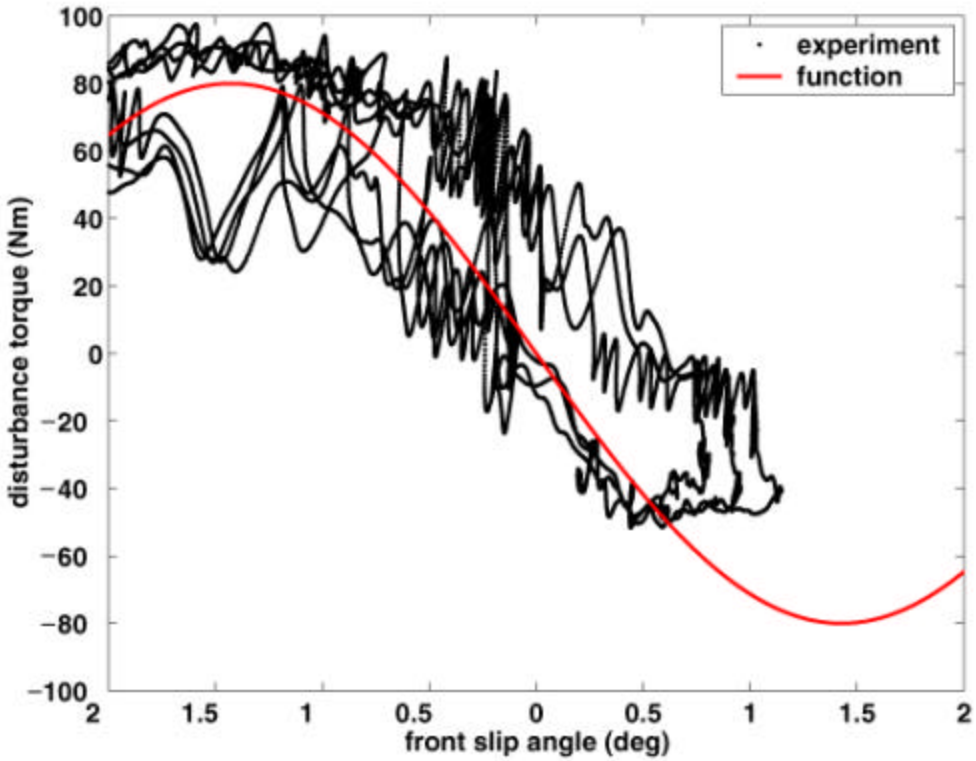
- Some error present can be explained by...

Estimated aligning moment



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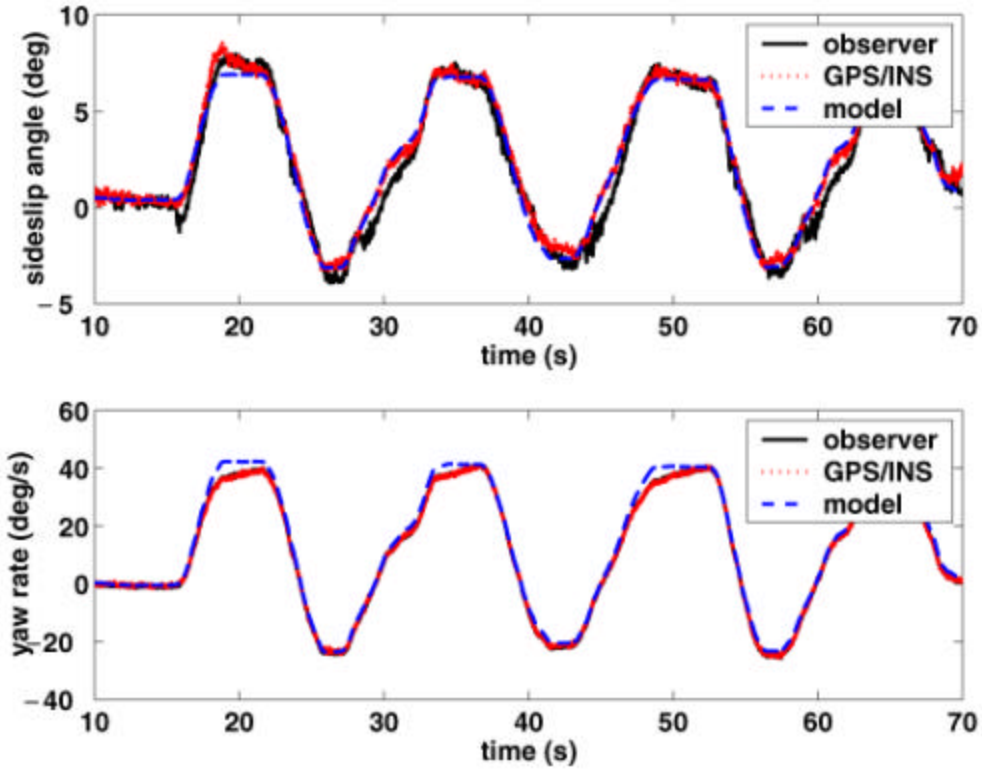
- …hysteresis due to power steering dynamics and other unmodeled characteristics of the steering system.

Estimated sideslip and yaw rate



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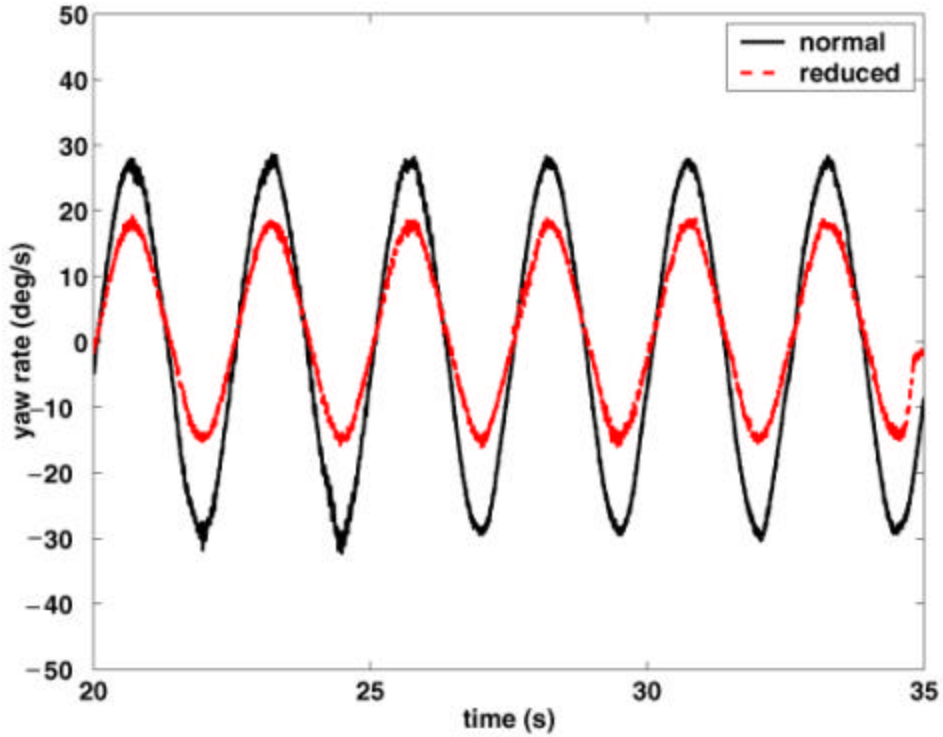
- Sideslip estimate from observer is comparable to estimate from GPS.

Experiment: handling modification to understeering



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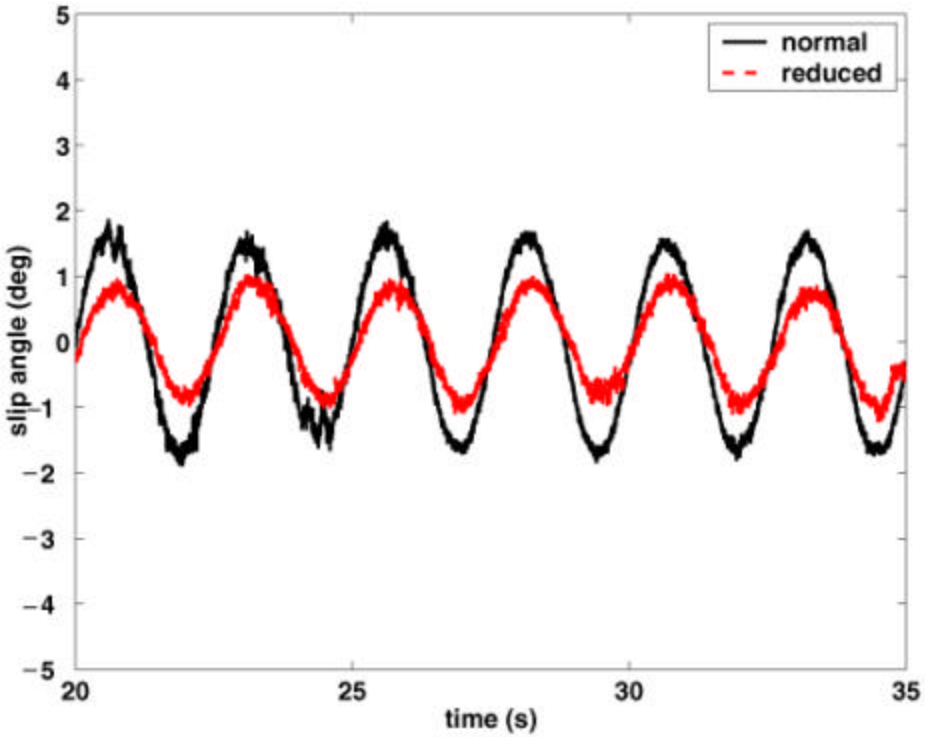
- Sideslip estimation successfully applied to full state feedback vehicle control.

Experiment: handling modification to understeering



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- Steer-by-wire system provides both actuation for control and sensing for sideslip estimation.

Conclusion

- Knowledge of vehicle sideslip is necessary for advanced steering control made possible with steer-by-wire.
- Steer-by-wire system provides convenient way to estimate vehicle sideslip.
- A two-observer structure has been developed linking the steering system dynamics and vehicle dynamics through the tire forces.

Future work

- Apply control and estimation techniques to a dedicated by-wire vehicle.
- Can avoid nonlinear and other undesirable steering system characteristics with a clean sheet design.