Expert Driving Techniques at the Limit of Handling

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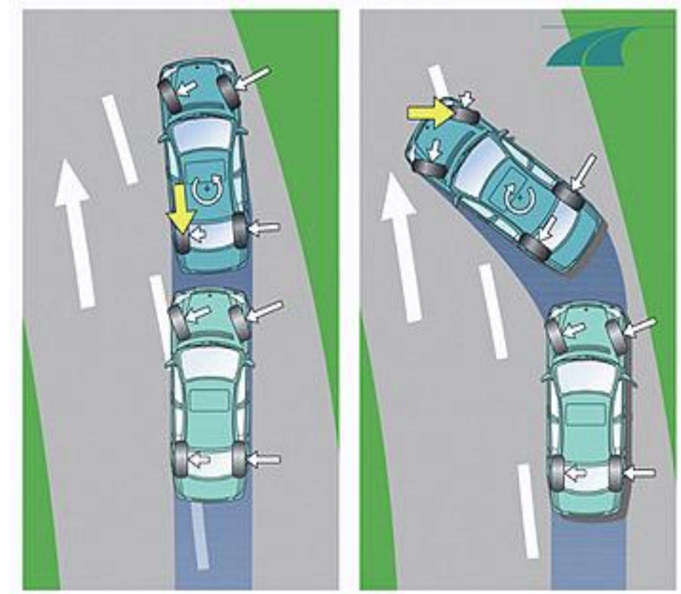
Motivation

- Stability control systems contribute considerably to the reduction of road traffic accidents
- Restrict the response of vehicles within linear region of operation of tyres
- Accident avoidance may require the exploitation of the full handling capacity
- Envision new generation of active safety systems employing expert driving skills
- Rally driving techniques: operation outside the stable envelope enforced by current systems
- Reproduce transient driving techniques – study optimality properties (Supported by Ford URP)
- Closed loop control formulation – stabilization of steady-state cornering at the limit (Supported by FP7 Marie Curie IRG)



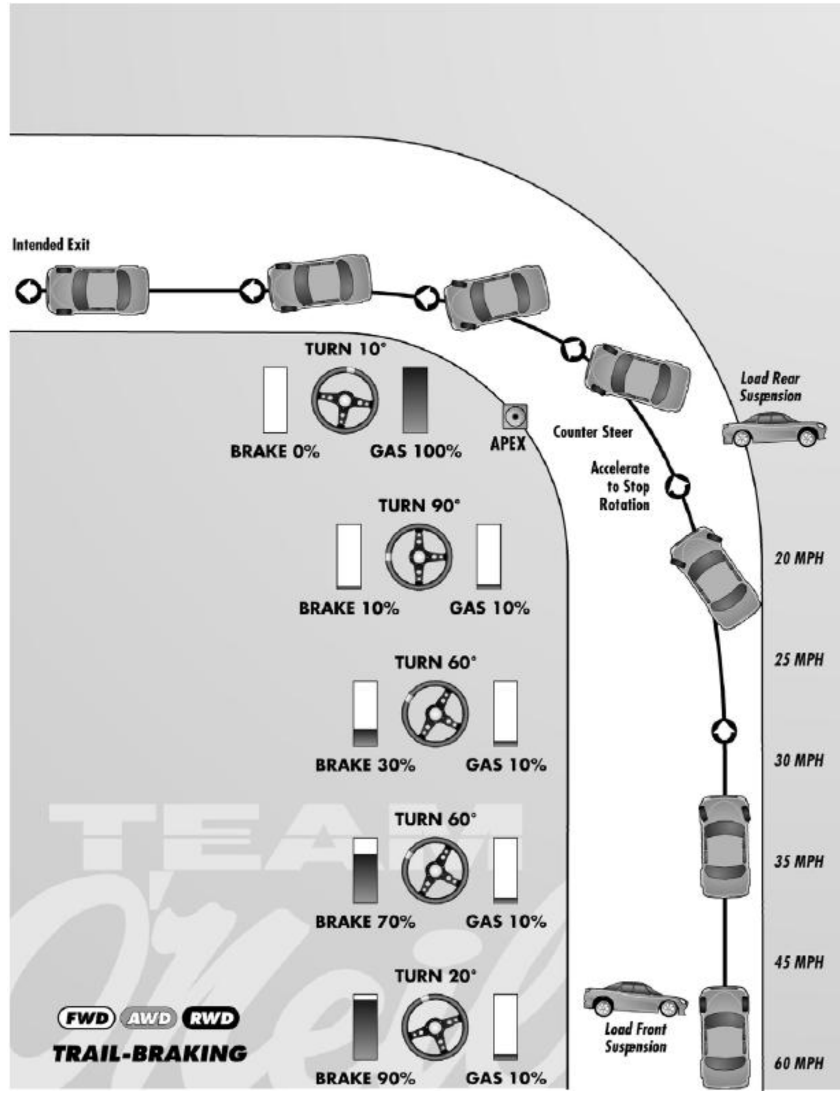
www.drive.com.au

www.drivingfast.net

Empirical Guidelines

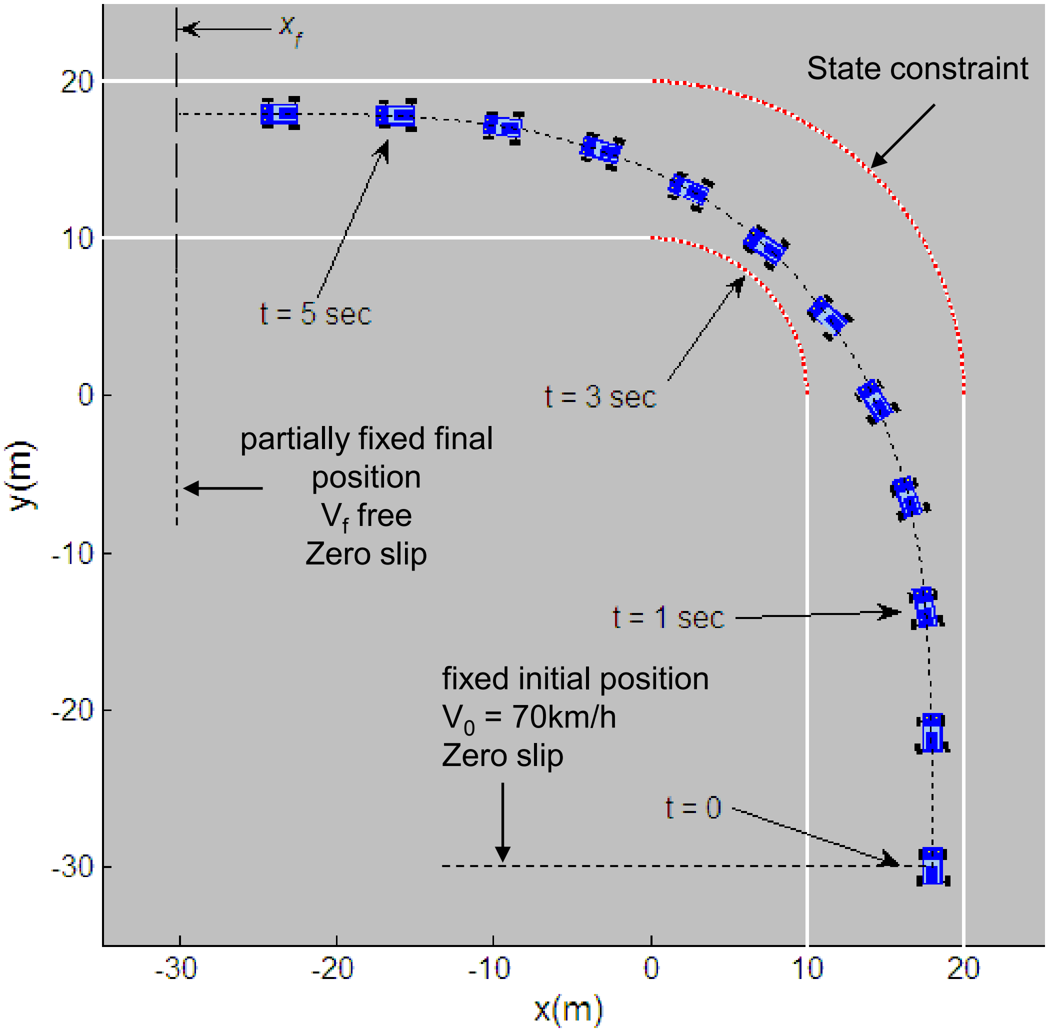
Trail-Braking

- Brake during cornering
- Load transfer effect
- Aggressive sideslip
- “Late Apex” line



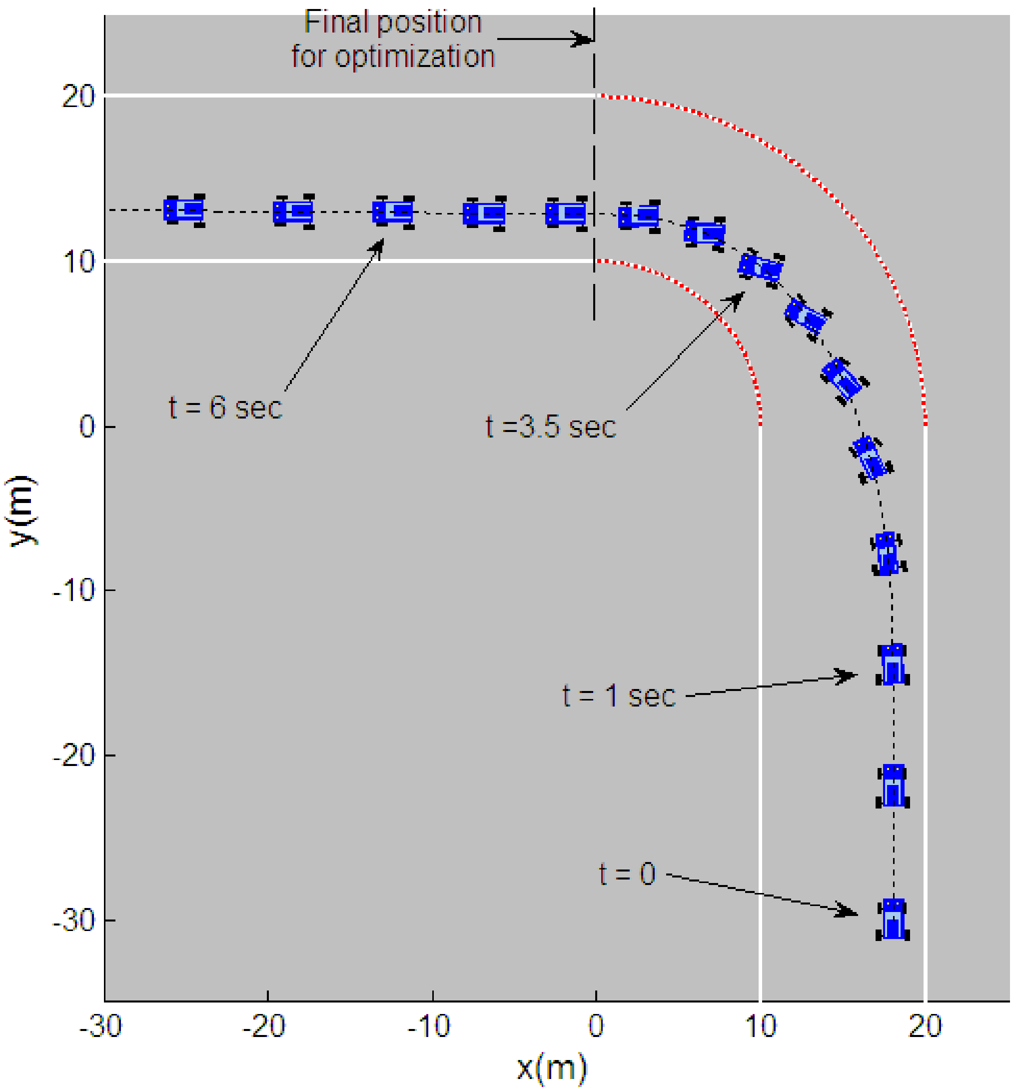
T. O’Neil. *Rally Driving Manual. Team O’Neil Rally School and Car Control Center, 2006.*

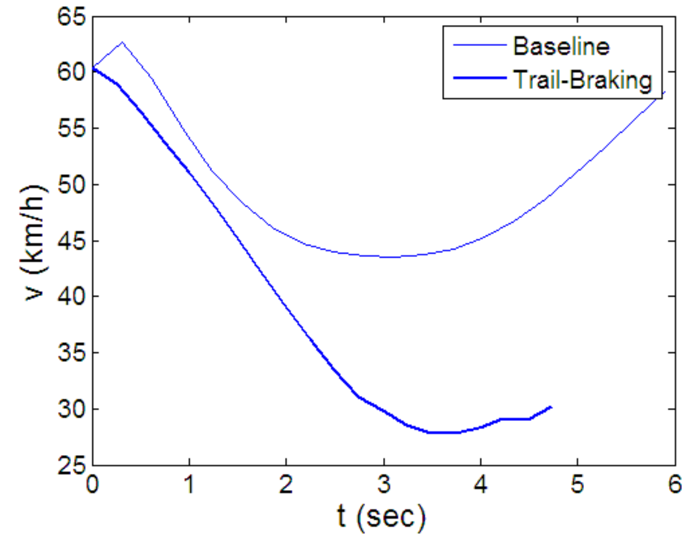
Optimal Control Formulation - Baseline Solution

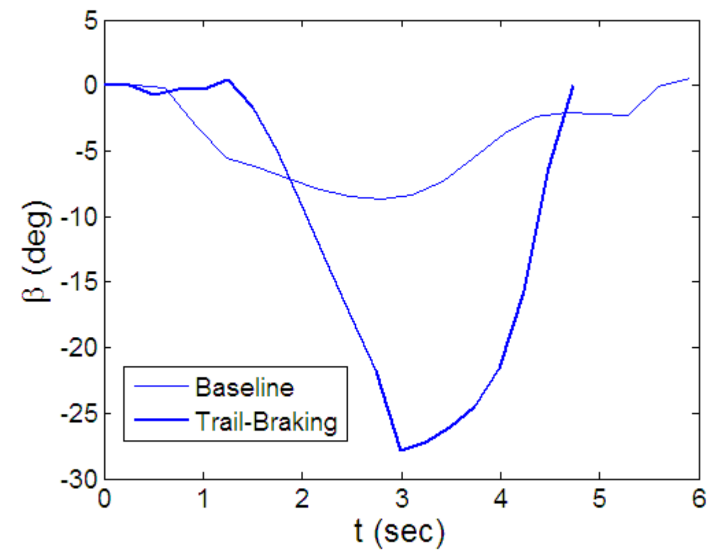


- Dynamics of a "bicycle" vehicle model with nonlinear tyre force characteristics
- State/Control constraints
- Boundary conditions
- Cost function – time minimization
- Convert optimal control problem to a nonlinear programming problem (NLP)
- Use NLP solver software for numerical solution (EZopt).

Trail-Braking

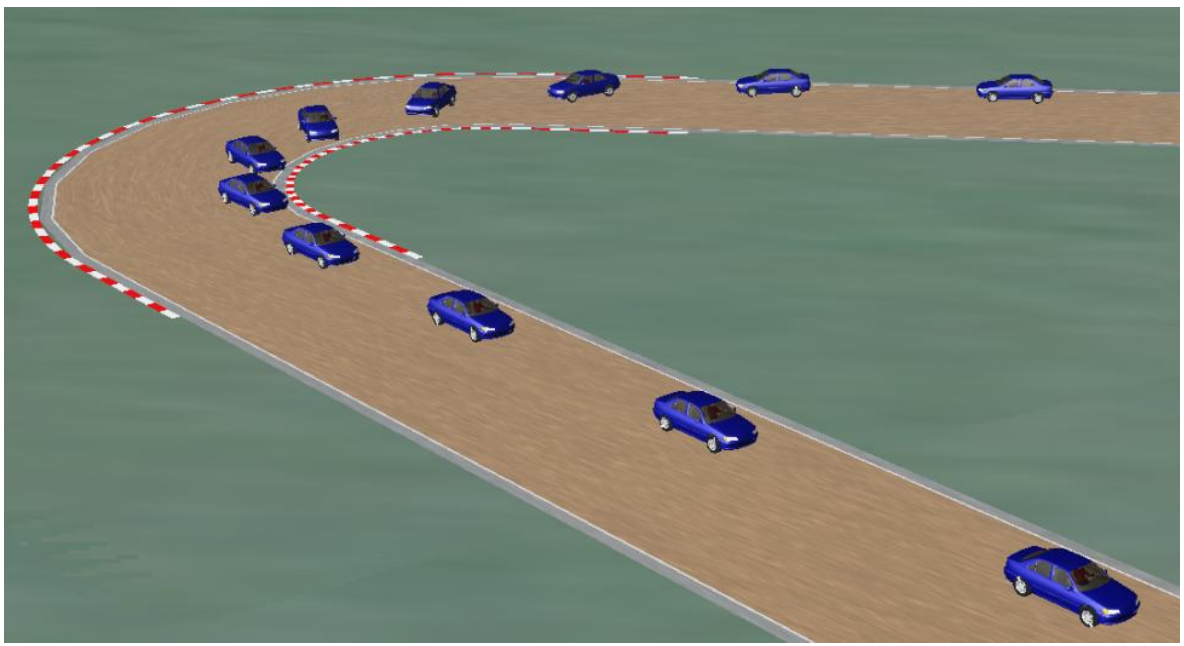


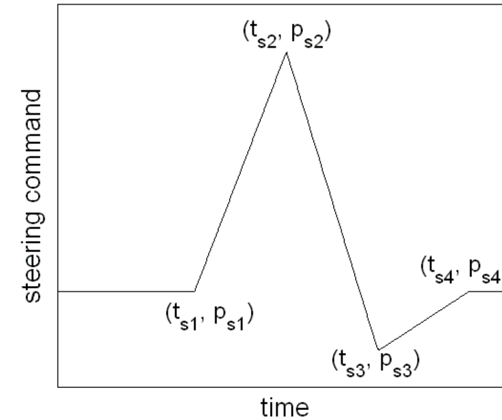


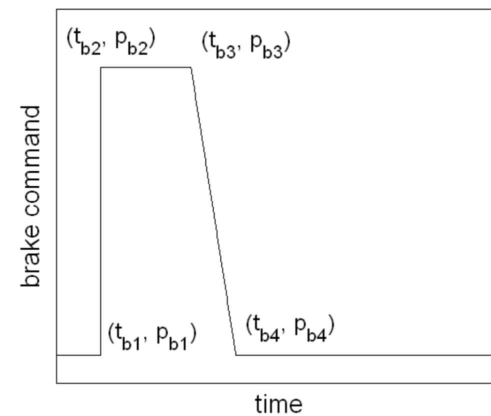


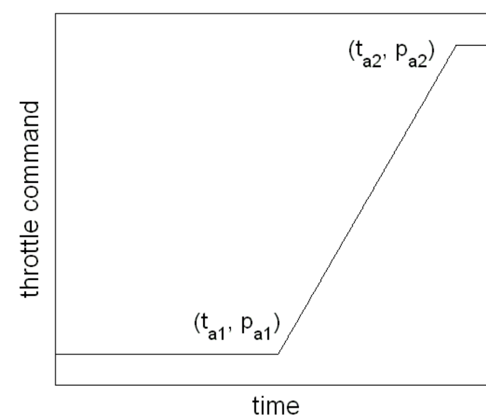
Alternative Optimization Scheme

- Introduce simple parameterization of control inputs.
- Reduce optimization search space.
- Increased vehicle model fidelity.









Vehicle Testing

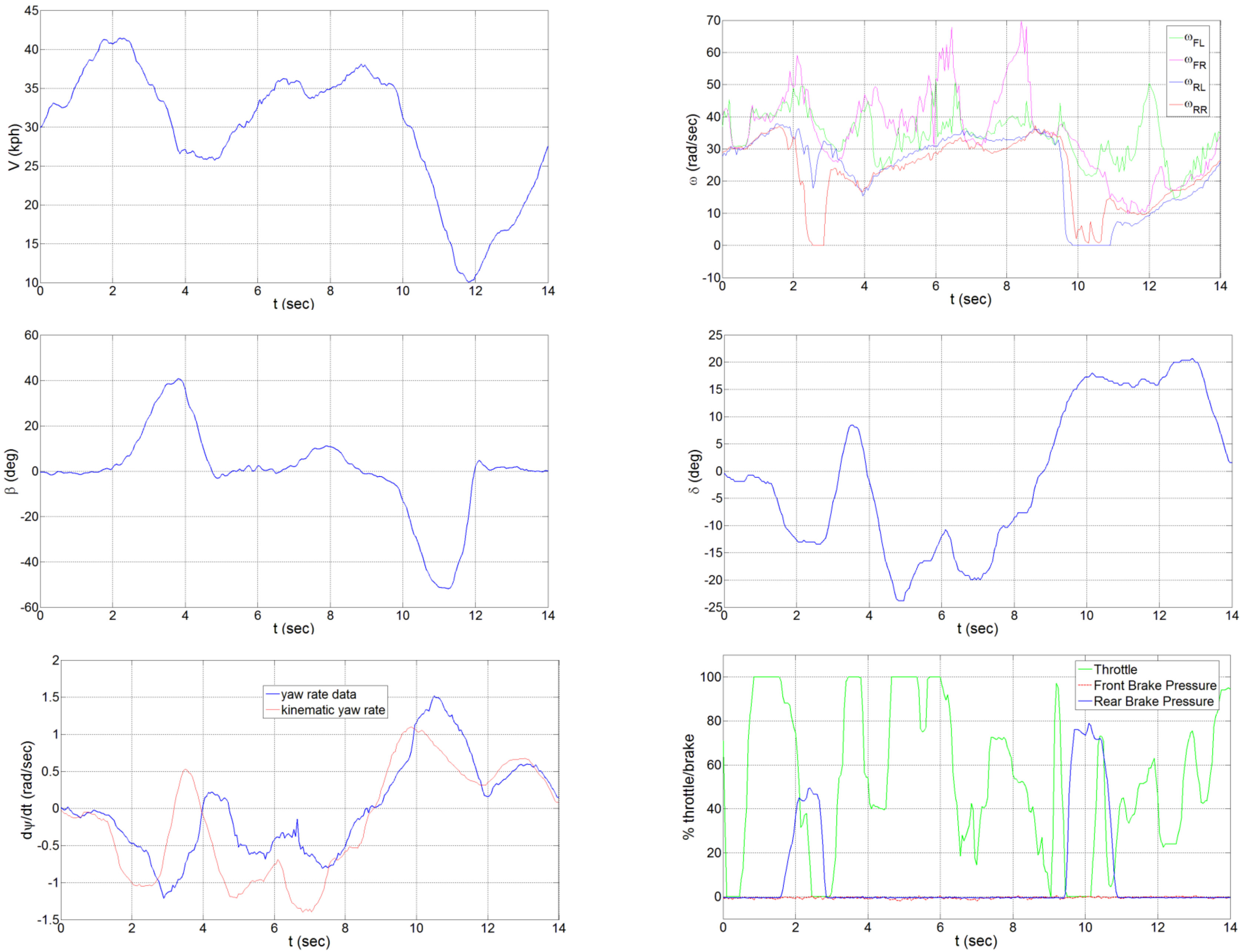
Testing Facilities – Test Driver

- Bill Gwynne Rally School, Brakley, UK
- 2006 Ford Fiesta (FWD, 2.0lt engine)
- Bill Gwynne, rally driver and instructor

Instrumentation

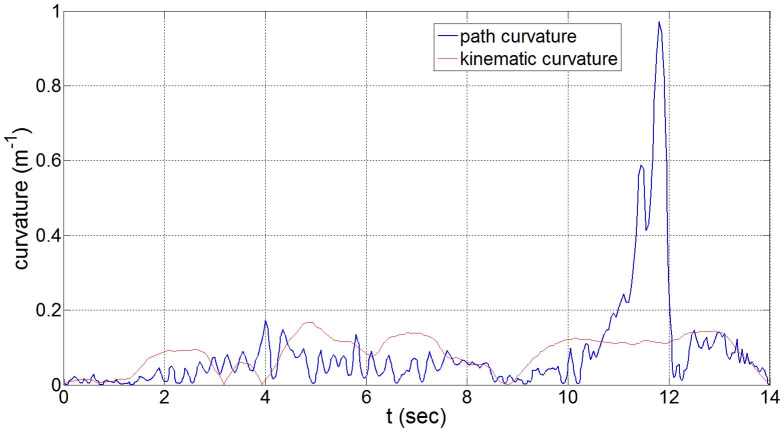
- Racelogic VBOX twin antenna GPS
- DGPS base station
- 3-axis accelerations, 3-axis rotational rates
- CAN-Bus interface: 4 wheel speed, throttle position, engine rpm
- fitted steering angle, front/rear axle brake pressure sensors

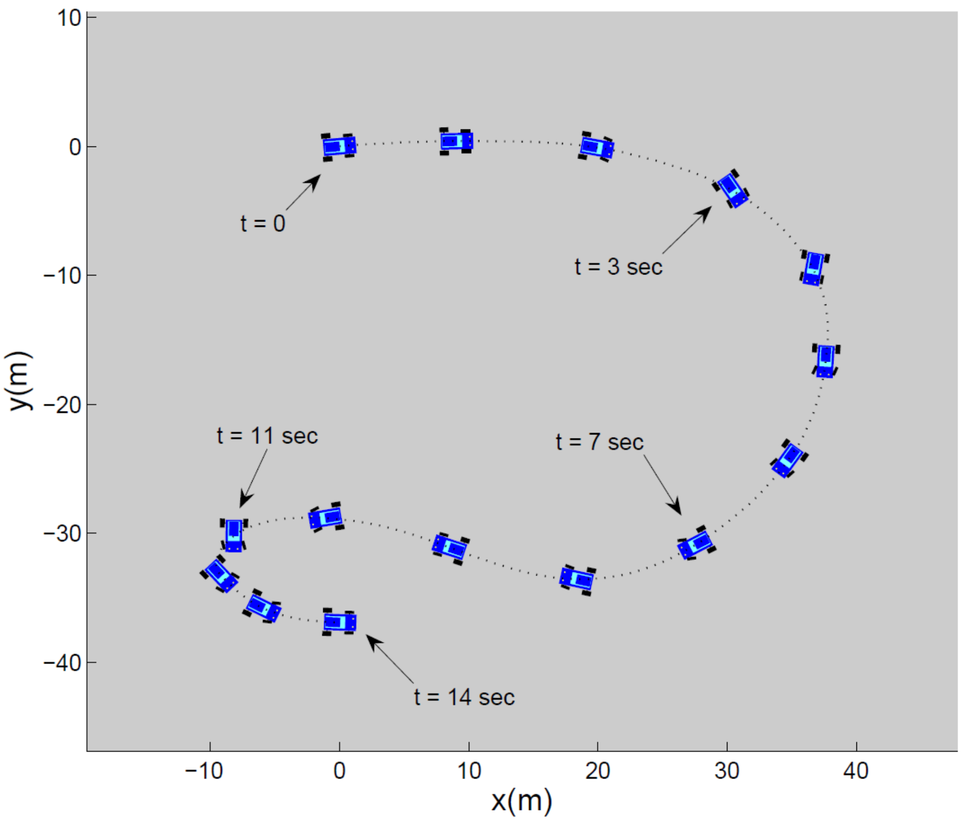
Handbrake-Cornering Data



Handbrake-Cornering Data

- Application of handbrake during cornering:
  $1.5 \le t \le 3$sec and $9.5 \le t \le 11$sec
- Eliminate understeer
- Achieve lower turning radius
- Locking the wheel (increase of slip ratio) eliminates cornering tyre force
- The resultant yaw moment increases, which is experienced by increased yaw rate and sideslip.

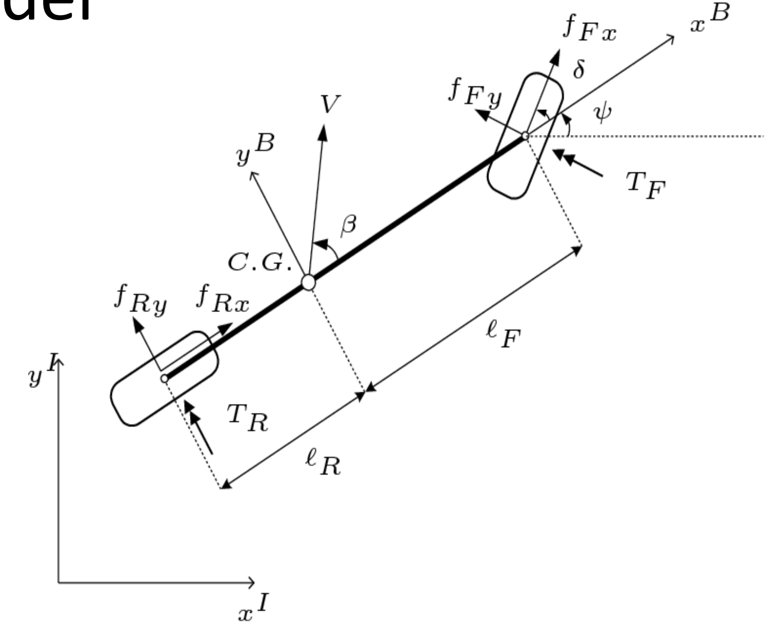




Vehicle Model

Equations of Motion

$$\begin{aligned}
m\dot{V}_x &= f_{Fx}\cos\delta - f_{Fy}\sin\delta + f_{Rx} + mV_y\dot{\psi}, \\
m\dot{V}_y &= f_{Fx}\sin\delta + f_{Fy}\cos\delta + f_{Ry} - mV_x\dot{\psi}, \\
I_z\ddot{\psi} &= (f_{Fy}\cos\delta + f_{Fx}\sin\delta)\,\ell_F - f_{Ry}\ell_R, \\
I_{wi}\dot{\omega}_i &= T_i - f_{ix}r_i, \qquad i = F, R
\end{aligned}$$



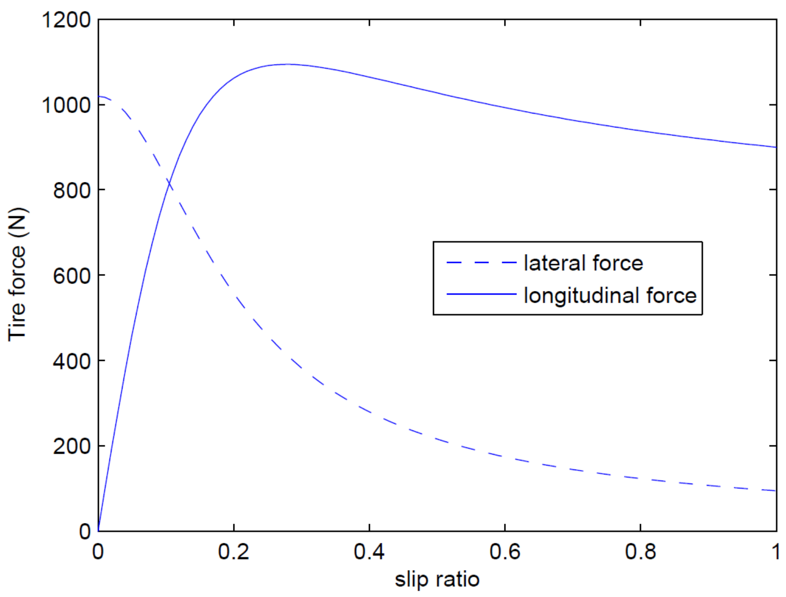
Tyre Forces

$$\mu_i = f_i/f_{iz}, \quad \mu_{ij} = f_{ij}/f_{iz}, \qquad i = F, R, \quad j = x, y$$

$$s_{ix} = \frac{V_{ix} - \omega_i r_i}{\omega_i r_i}, \qquad s_{iy} = \frac{V_{iy}}{\omega_i r_i} = (1 + s_{ix})\tan\alpha_i$$

$$\mu_i(s_i) = \mathrm{MF}(s_i) = D\ \sin(C\ \mathrm{atan}(B\ s_i))$$

$$\mu_{ij} = -(s_{ij}/s_i)\mu(s_i)$$



Normal Load Transfer

$$\begin{aligned}
f_{Fz} &= \frac{\ell_R mg - hmg\mu_{Rx}}{L + h\,(\mu_{Fx}\cos\delta - \mu_{Fy}\sin\delta - \mu_{Rx})}, \\
f_{Rz} &= mg - f_{Fz}.
\end{aligned}$$

Steady-State Handbrake-Cornering Conditions

- Enforce equilibrium conditions in the EOM

$$R = R^{ss},\ V = V^{ss},\ \dot{\psi} = \dot{\psi}^{ss} = \frac{V^{ss}}{R^{ss}},\ \beta = \beta^{ss}$$

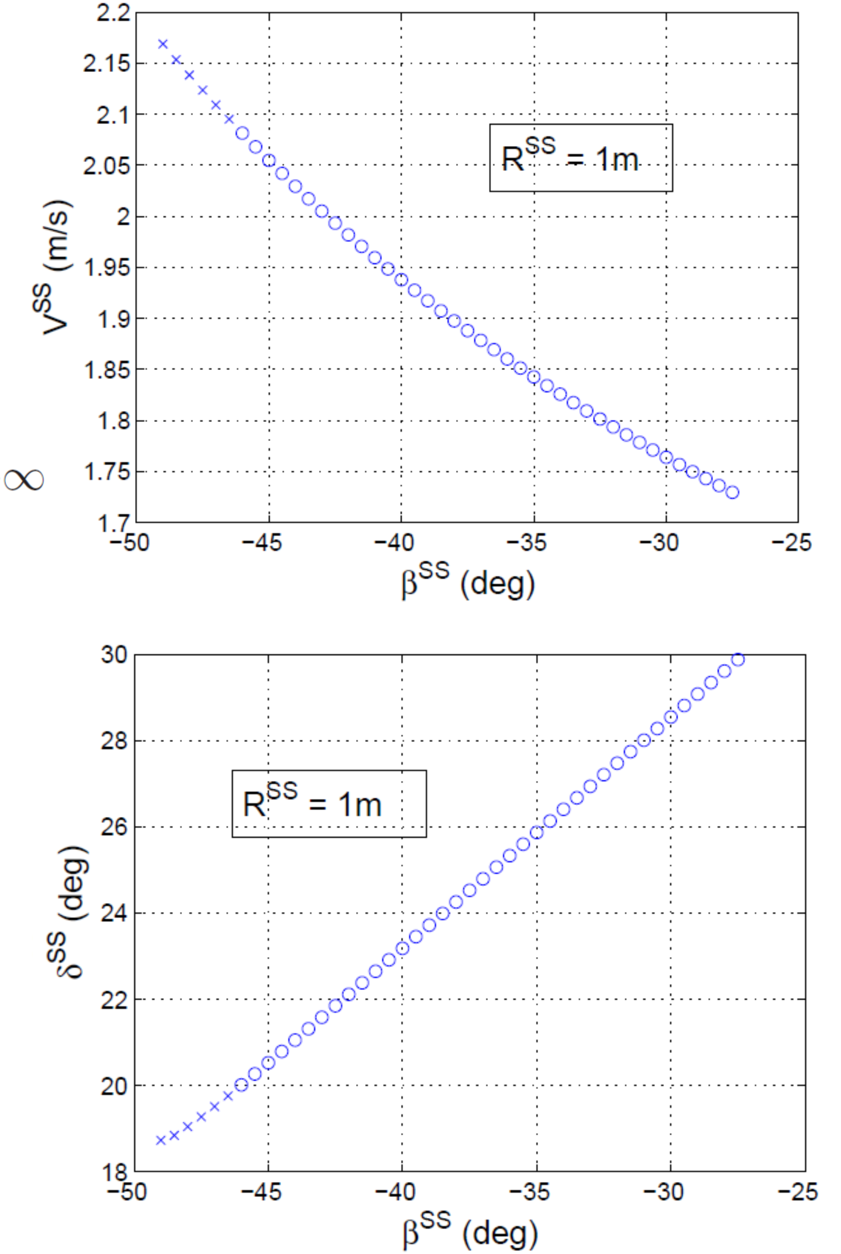
$$\omega_i = \omega_i^{ss},\ s_{ij} = s_{ij}^{ss},\ f_{ij} = f_{ij}^{ss},\ \delta = \delta^{ss},\ T_i = T_i^{ss}$$

- Enforce rear wheel lock: $\omega_R^{ss} = 0$

$$s_{Rx}^{ss} = \lim_{\omega_R \to 0}(s_{Rx}) = +\infty,\ s_R^{ss} = \lim_{\omega_R \to 0}(s_R) = +\infty$$

$$\mu_R^{ss} = \lim_{\omega_R \to 0} \mathrm{MF}(s_R) = D\ \sin(C\ \mathrm{atan}(B\ \pi/2))$$

- For a given pair (R^{ss}, β^{ss}), one can calculate numerically the remaining equilibrium states and control inputs, under rear wheel lock conditions.
- Sample calculations for steady-state radius 5m and 1m ('o' unstable; '+' stable).
- Higher speeds at higher sideslip angles; Counter-steering required in higher radii.



Steering and Front Wheel Speed Control

- Consider EOM with steering angle and front wheel speed inputs (and rear wheel lock)

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}V &= f_1(V,\beta,\dot{\psi},\hat{\omega}_F,\hat{\delta}) \\
\frac{\mathrm{d}}{\mathrm{d}t}\beta &= f_2(V,\beta,\dot{\psi},\hat{\omega}_F,\hat{\delta}) \\
\frac{\mathrm{d}}{\mathrm{d}t}\dot{\psi} &= f_3(V,\beta,\dot{\psi},\hat{\omega}_F,\hat{\delta})
\end{aligned}
$$

- Calculate equilibrium point: $(V^{\mathrm{ss}},\beta^{\mathrm{ss}},\dot{\psi}^{\mathrm{ss}})$ and $(\omega_F^{\mathrm{ss}},\delta^{\mathrm{ss}})$

- Linearize EOM with respect to equilibrium:

$$
\begin{aligned}
\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} &= \mathbf{A}^{\mathrm{ss}}\mathbf{x}+\mathbf{B}^{\mathrm{ss}}\mathbf{u} \\
\mathbf{y} &= \mathbf{C}\mathbf{x},
\end{aligned}
\qquad
\mathbf{x} = \begin{bmatrix} V - V^{\mathrm{ss}} \\ \beta - \beta^{\mathrm{ss}} \\ \dot{\psi} - \dot{\psi}^{\mathrm{ss}} \end{bmatrix},\ \mathbf{u} = \begin{bmatrix} \hat{\omega}_F - \omega_F^{\mathrm{ss}} \\ \hat{\delta} - \delta^{\mathrm{ss}} \end{bmatrix},\ \mathbf{C} = \mathcal{I}^{3\times 3}
$$

- Design LQR controller: $\mathbf{u} = -\mathbf{K}\mathbf{x}$

Drive/Brake Torque Control

- Wheel speed error: $z_F = \omega_F - \hat{\omega}_F(\mathbf{x}), \quad \dot{z}_F \;=\; \dot{\omega}_F - \dfrac{\partial \hat{\omega}_F(\mathbf{x})}{\partial \mathbf{x}}\dot{\mathbf{x}}.$

- Consider the controller: $T_F = T_F^{\mathrm{eq}} + I_w v_F$

with $$T_F^{\mathrm{eq}} \;=\; f_{Fx} r + I_w \left(\frac{\partial \hat{\omega}_F}{\partial V} f_1 + \frac{\partial \hat{\omega}_F}{\partial \beta} f_2 \frac{\partial \hat{\omega}_F}{\partial \dot{\psi}} f_3 \right)$$

- Results in feedback linearization: $\dot{z}_F = v_F$

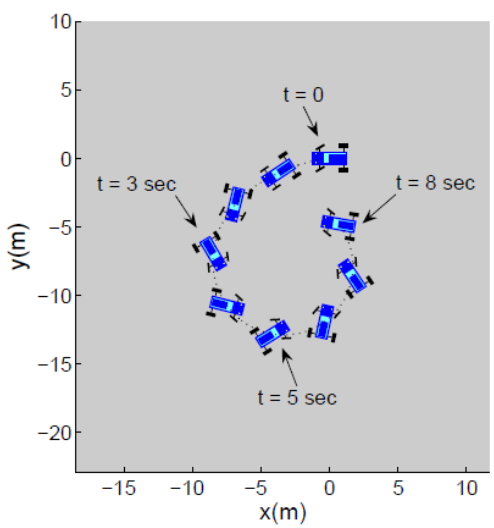
- Linear controller to stabilize wheel speed error dynamics: $v_F = -k_F\, z_F, \quad k_F > 0$

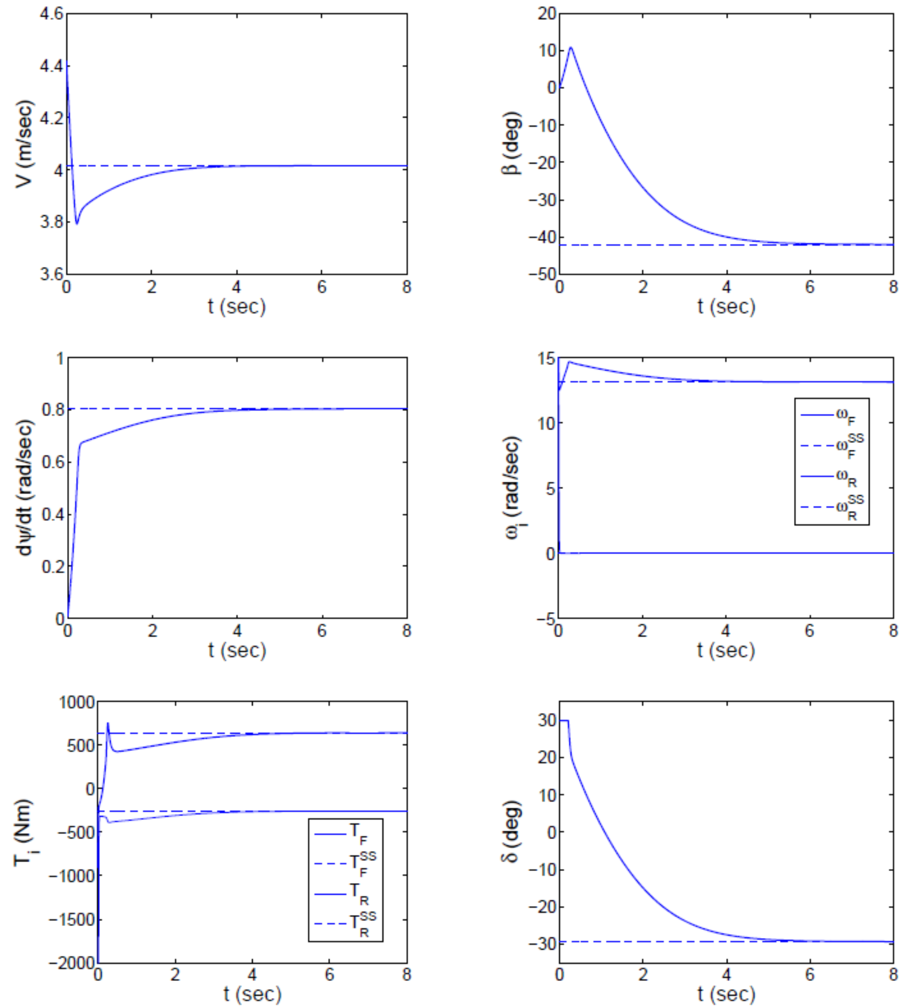
- Similarly, a rear brake torque controller to maintain wheel lock is implemented:

$$T_B = f_{Rx} r + I_w v_R, \quad v_R = -k_R \omega_R, \quad k_R > 0$$

Simulation Results

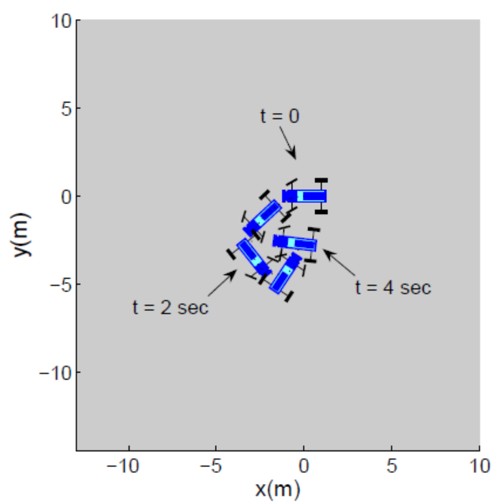
- Stabilization of 5m radius equilibrium
- Simulation starts with vehicle travelling along a straight line with $V_0 = 1.1\ V^{SS}$
- Steering is saturated at 30deg
- Steady-state is maintained with counter-steering.

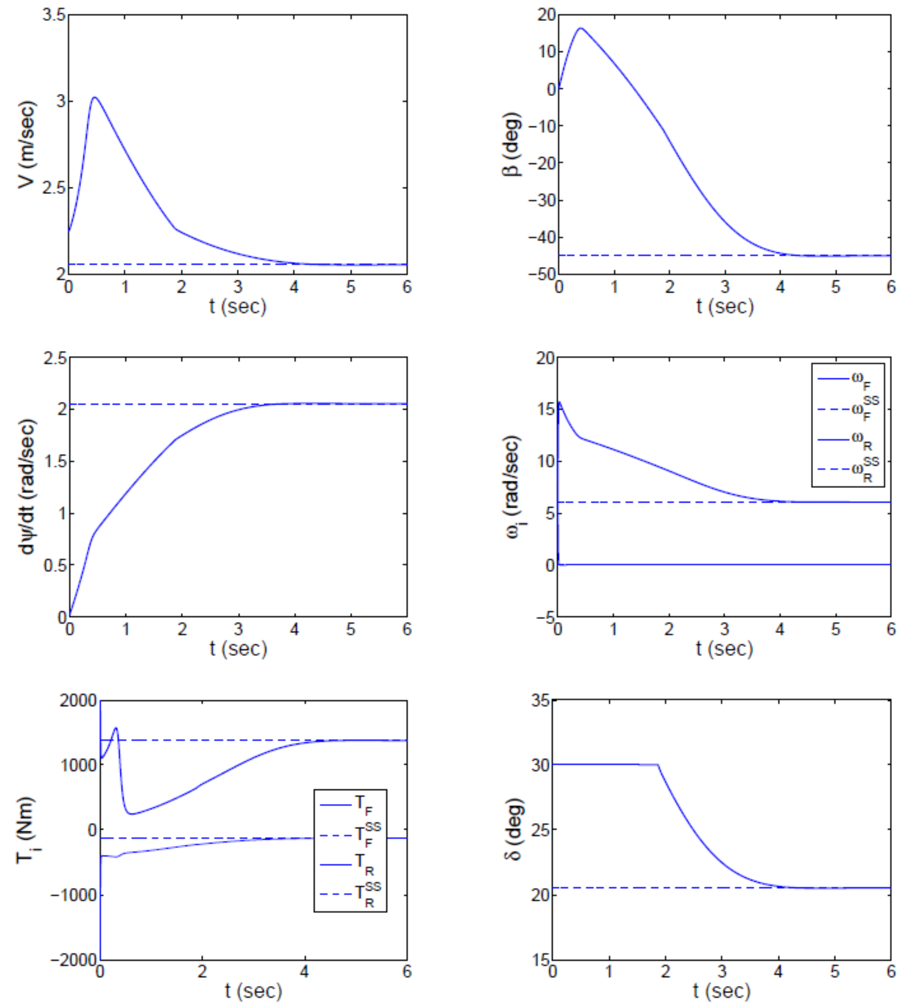




Simulation Results

- Stabilization of 1m radius equilibrium
- Simulation starts with vehicle travelling along a straight line with $V_0 = 1.1\ V^{SS}$
- Steering is saturated at 30deg
- Steady-state is maintained with steering along the direction of the corner.





Future Work

- Validate controller using high fidelity vehicle models
- Incorporate tyre friction estimation
- Implement control scheme in transient cornering scenarios
- Extensions to safety