Optimal Vehicle Maneuvers for Different Road Conditions

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- Advancements in optimization technology and software unfolds new approaches in the development of active safety and driver assistant systems
  - Give valuable insight to a systems performance capabilities
  - The solution can be used as inspiration for new control strategies
  - Direct implementation in a system

- Regardless of application, the model configurations and optimization objectives will have an immense effect on the solution

- *Models and Methodology for Optimal Vehicle Maneuvers Applied to a Hairpin Turn.*
  Karl Berntorp, Björn Olofsson, Kristoffer Lundahl, Bo Bernhardsson, and Lars Nielsen.
  In ACC, USA, 2013.
- *Studying the Influence of Roll and Pitch Dynamics in Optimal Road-Vehicle Maneuvers.*
  Kristoffer Lundahl, Karl Berntorp, Björn Olofsson, Jan Åslund, and Lars Nielsen.
  In IAVSD, China, 2013.
- *An Investigation of Optimal Vehicle Maneuvers for Different Road Conditions.*
  Björn Olofsson, Kristoffer Lundahl, Karl Berntorp, and Lars Nielsen.
  In AAC, Japan, 2013.
- *Models and Methodology for Optimal Trajectory Generation in Safety-Critical Road-Vehicle Maneuvers.*
  Karl Berntorp, Björn Olofsson, Kristoffer Lundahl, and Lars Nielsen.
  Submitted to Vehicle System Dynamics.
- *Towards Lane-Keeping Electronic Stability Control for Road-Vehicles.*
  Kristoffer Lundahl, Björn Olofsson, Karl Berntorp, Jan Åslund, and Lars Nielsen.
  Accepted to IFAC-WC, South Africa, 2014.

- Look into two studies on optimal maneuvering
  - Chassis model comparison
  - Different road conditions

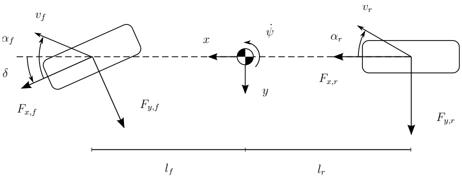
- Chassis model comparison
  - How does the optimal solution varies for different vehicle models?
  - In general a more complex model might be more accurate, but requires more parameters and is often heavier on the computational aspect
  - Comparison of two models:
    - Single-track model (simple model)
    - Double-track model (complex model)

- Different road conditions
  - How does the solution to a time-critical optimal maneuver change for different road-surfaces characteristics?
  - Four different road surfaces are compared:
    - Dry asphalt
    - Wet asphalt
    - Snow
    - Smooth ice

- Evaluated in a hairpin-turn maneuver:
  - Tight narrow 180 $^\circ$ turn with long straights prior and after
  - Triggers complex maneuvering
- Optimization objective: Minimize final time

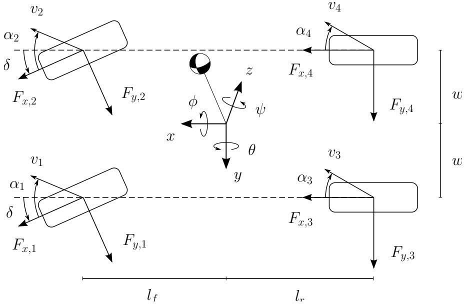
Single-track model:

- Left and right wheels lumped into a single front and a single rear wheel
- Static normal forces (i.e., no load transfer)



Double-track model:

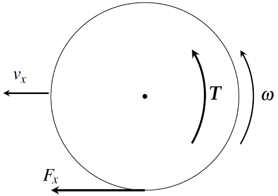
- 4 individually modeled wheels
- Pitch and roll dynamics
- Longitudinal and lateral load transfer



- Wheel dynamics:

$$T_i - I_w \dot{\omega}_i - F_{x,i} R_w = 0, \quad i \in \{f, r\} \text{ or } \{1, 2, 3, 4\}$$

  - ω – the wheel angular velocity
  - F_x – the longitudinal tire force
  - T – the driving/braking wheel torque



- Slip angles:

$$\dot{\alpha}_i \frac{\sigma}{v_{x,i}} + \alpha_i = -\arctan\left(\frac{v_{y,i}}{v_{x,i}}\right)$$

- Slip ratio:

$$\kappa_i = \frac{R_w \omega_i - v_{x,i}}{v_{x,i}}$$

- Nominal forces, $F_{x0,i}$ and $F_{y0,i}$, are described with *Magic Formula*
- *Weighting functions*, $G_{x\alpha}$ and $G_{y\kappa}$, are used for modeling the combined slip
- Longitudinal forces:

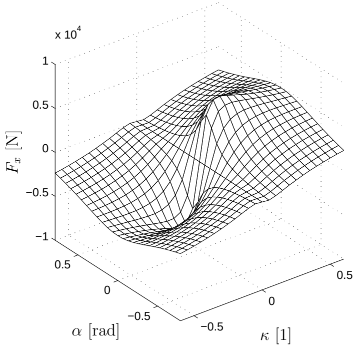
$$\begin{aligned}
F_{x0,i} &= \mu_x F_{z,i} \sin(C_{x,i} \arctan(B_{x,i}\kappa_i - E_{x,i}(B_{x,i}\kappa_i - \arctan B_{x,i}\kappa_i))) \\
B_{x\alpha,i} &= B_{x1,i} \cos(\arctan(B_{x2,i}\kappa_i)) \\
G_{x\alpha,i} &= \cos(C_{x\alpha,i} \arctan(B_{x\alpha,i}\alpha_i)) \\
F_{x,i} &= F_{x0,i} G_{x\alpha,i}
\end{aligned}$$

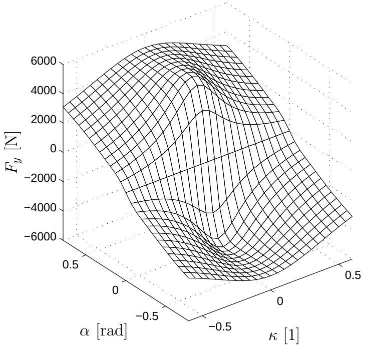
- Lateral forces:

$$\begin{aligned}
F_{y0,i} &= \mu_y F_{z,i} \sin(C_{y,i} \arctan(B_{y,i}\alpha_i - E_{y,i}(B_{y,i}\alpha_i - \arctan B_{y,i}\alpha_i))) \\
B_{y\kappa,i} &= B_{y1,i} \cos(\arctan(B_{y2,i}\alpha_i)) \\
G_{y\kappa,i} &= \cos(C_{y\kappa,i} \arctan(B_{y\kappa,i}\kappa_i)) \\
F_{y,i} &= F_{y0,i} G_{y\kappa,i}
\end{aligned}$$

- Tire parameters:
  $\mu_x, C_{x,i}, B_{x,i}, E_{x,i}, B_{x1,i}, B_{x2,i}, C_{x\alpha,i}, \mu_y, C_{y,i}, B_{y,i}, E_{y,i}, B_{y1,i}, B_{y2,i}, C_{y\kappa,i}$

- The tire forces (both longitudinal F_x and lateral F_y) are functions of three variables:
  - Slip ratio κ
  - Slip angle α
  - Normal force F_z





- The vehicle dynamics is formulated as a DAE system

$$\begin{aligned} \dot{x}(t) &= G(x(t), y(t), u(t)) \\ 0 &= h(x(t), y(t), u(t)) \end{aligned}$$

- Objective: Minimize the final time of the maneuver
  - Triggers extreme maneuvering, utilizing the tire forces to their maximum
  - Fixed start and end coordinates
  - Fixed initial velocity
  - Road constraints for the hairpin turn is formulated with superellipses

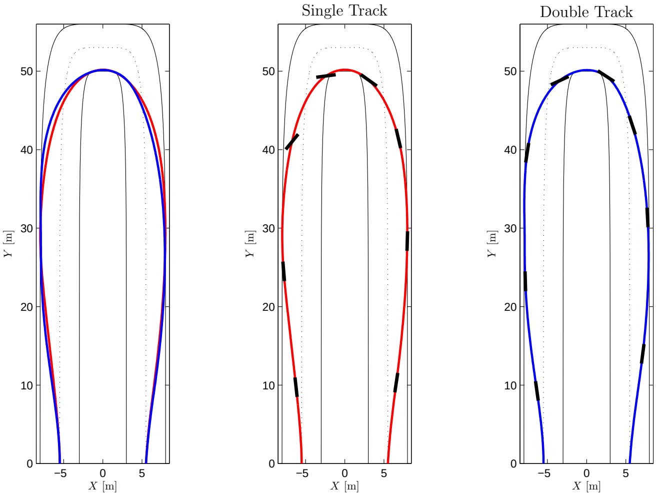
- Input variables (free variables in the optimization):
  - Steer angle (front wheels), $|\delta| \leq \delta_{max}$
  - Front wheel torque, $T_{f,min} \leq T_f \leq 0$
  - Rear wheel torque, $T_{r,min} \leq T_r \leq T_{r,max}$

- Software tool: JModelica.org

- The models are described with the *Modelica* language
- Optimization criterias described with *Optimica* (an extension to Modelica)
- The problem is discretized using direct collocation
  - 150 elements
  - 3 collocation points per element
- Jacobian and hessian computed with automatic differentiation (*CasADi*)
- The resulting NLP is solved with *Ipopt*

- Inital guess generated with a lane-keeping driver-model

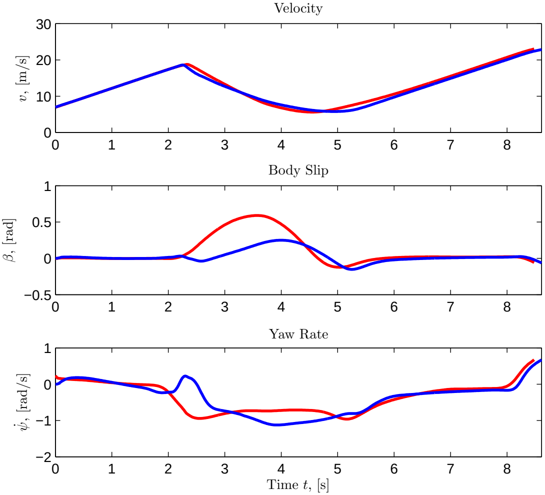
Vehicle Trajectories



red – Single track
blue – Double track

- Slightly different trajectories, but overall similar
- Most significant difference: The body-slip through the turn

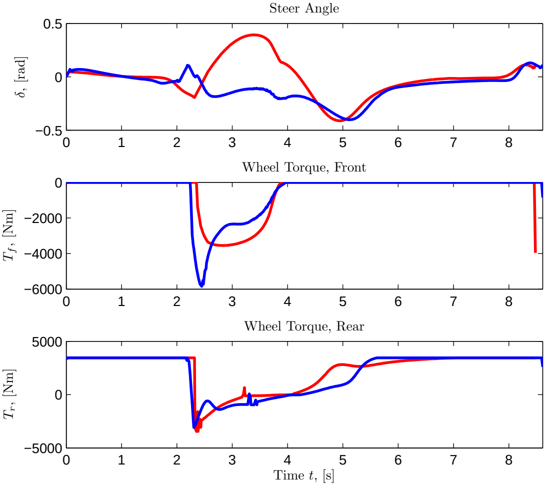
Vehicle Variables



red – Single track
blue – Double track

- Velocity profile very similar
- Body slip significantly larger for ST in corner-entry
- Differences in yaw rate (especially when initiating the turn)

Control Signals (free variables)



red – Single track
blue – Double track

- Different steer-angle trajectories due to the body slip
- Front wheel braking strategy quite different
- Quite similar braking and accelerating strategies for rear wheel

Conclusions

Chassis Model Comparison

- Global trajectories and overall dynamics fairly similar
- For control signals and internal variables the two models are not interchangeable

- The single-track model should be sufficient for quantitative studies

Road-Surface Modeling

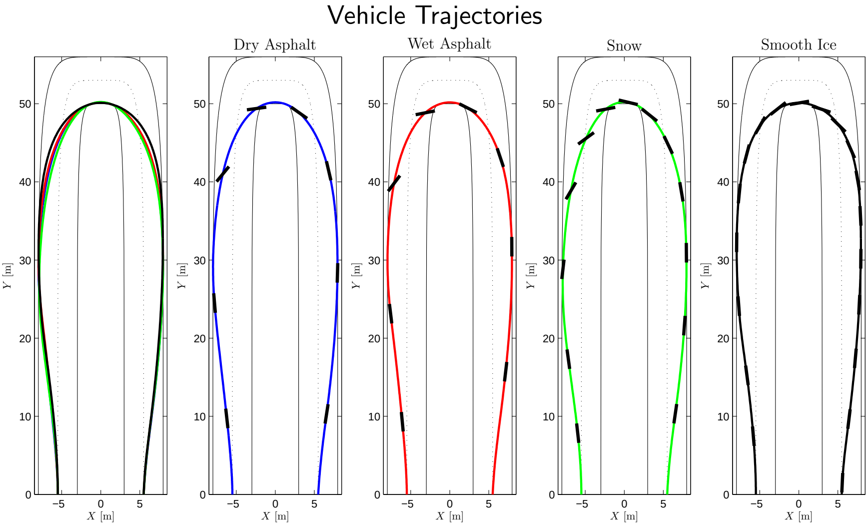
- The tire parameters are scaled/modified to represent different surfaces

- *Braghin et al.* presents a study extracting scaling parameters for different road surfaces

  Environmental effects on Pacejka's scaling factors
  F. Braghin, F. Cheli, and E Sabbioni
  Vehicle System Dynamics, 2006.

- This data is used as a basis to form tire/surface models for;
  - Dry asphalt
  - Wet asphalt
  - Snow
  - Smooth ice

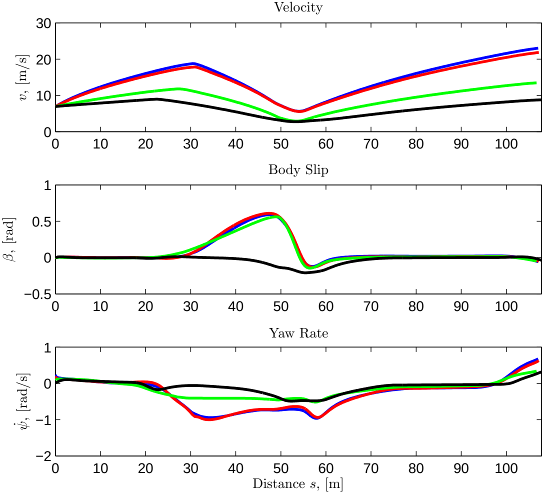
- Model inconsistencies arise, demanding some manual adjustments of a few parameters
  - Base model parameters not public



- The trajectories through the turn are very similar for all surfaces
- The body-slip characteristics differ considerably for ice

Results

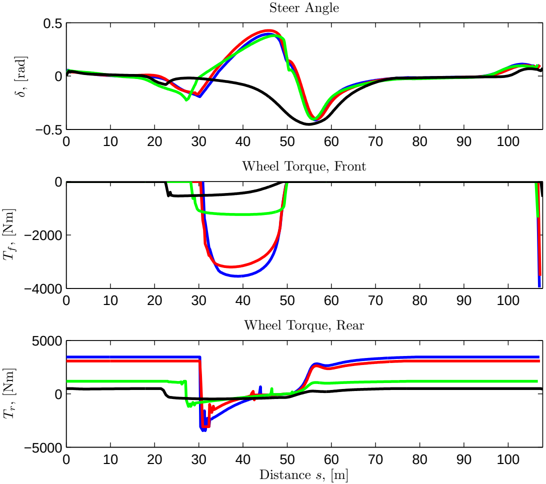
Vehicle Variables



blue – dry asphalt
red – wet asphalt
green – snow
black – smooth ice

- Illustrated as functions of driven distance
- Speed differs in amplitude
- Body slip similar for dry, wet, and snow
- Ice show a low-slip maneuver strategy

Control Signals (free variables)



blue – dry asphalt
red – wet asphalt
green – snow
black – smooth ice

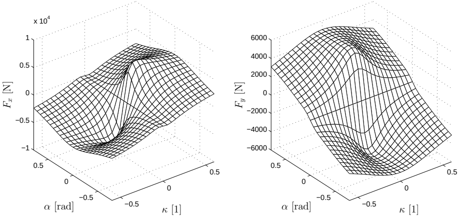
- Steer angle δ very similar for dry/wet asphalt and snow
- Due to the small-slip approach on ice, no counter steering is experienced
- Earlier actuation for snow and ice
- Differences in amplitude for the applied wheel torques (explained by the various friction limits)

Results
Naive surface modeling

- The results for *smooth ice* stands out
- Investigating the tire force, as functions over both slip quantities, show a much narrower force surface for the ice model (especially for F_x)

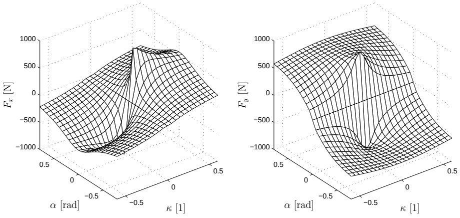
Dry Asphalt

F_x F_y



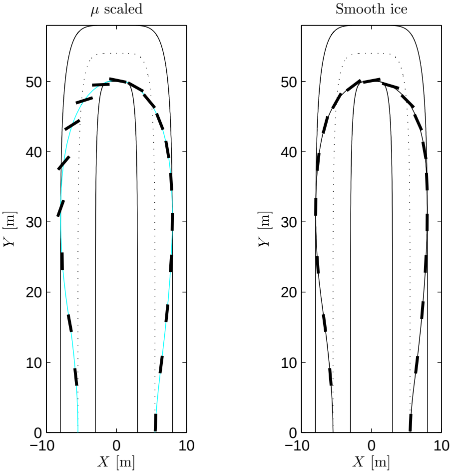
Smooth Ice

F_x F_y



Results

Comparison with a more primitive road-surface scaling method



- μ *scaled* – only adjusting μ (the friction coefficient), otherwise parametrized as *dry asphalt*
- Compared with *smooth ice* (same model as before)
- The two approaches results in very different maneuvering

Conclusions

- Observations:
  - The vehicle path through the turn is (almost) invariant to the road-surface conditions
  - The optimal driving techniques (control actions) can be fundamentally different for different tire-road characteristics
  - Only scaling the friction coefficient is insufficient

- Future system needs to be more versatile to fully benefit from improved sensor information
- Since the paths are similar, inspires to look for strategies using path formulations

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