Rollover Prevention Using Active Suspension System

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Context: SYSCOVI project of the region Hauts-de-France

System of Systems approach for the COntrol of the dynamics of Intelligent Vehicles

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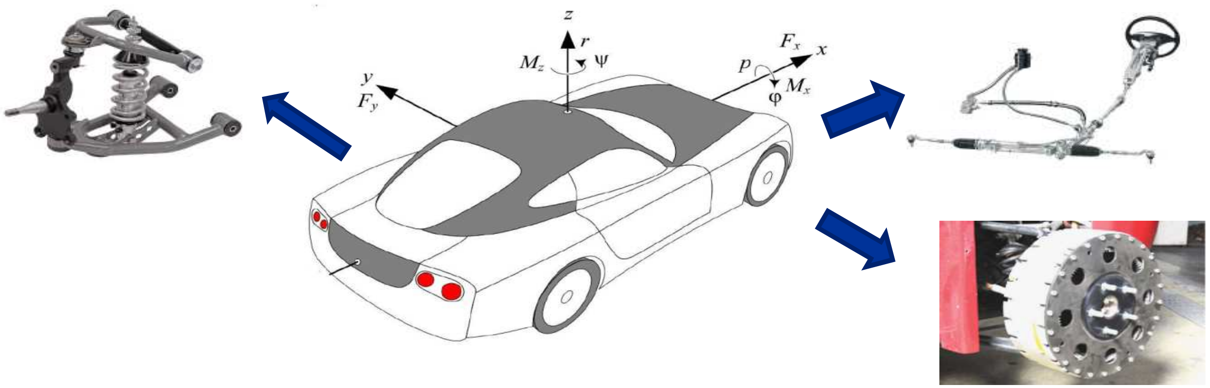
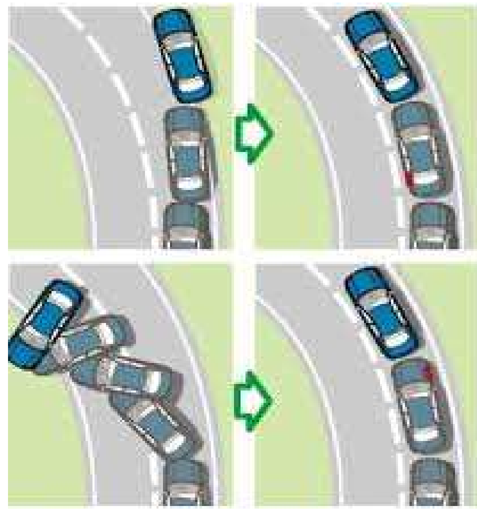




Several stabilization systems exist:
DYC ("Direct Yaw Control"), Active Steering (AS), (semi-)active suspensions

Each system has its own limitations with respect to the driving conditions.

Objectives

Global Chassis Control (GCC) **reliable**, **comfortable**, and **robust**

- Development of control architectures (decentralized or hierarchical) to ensure the cooperation of the actuators in the System of Systems (SoS).

- **Fault tolerant control** of the over-actuated system, for an improved reliability.

- Study of the technology of **In-wheel Electric Vehicles** (IEV), and consideration of the energy consumption.

Experimental evaluation of the results on real data acquired on the platforms of the Equipex Robotex project in Heudiasyc laboratory.

Plan

1. **Motivation**

2. **Rollover problem formulation**
   - **Rollover dynamics**
   - **Rollover avoidance possible solutions**

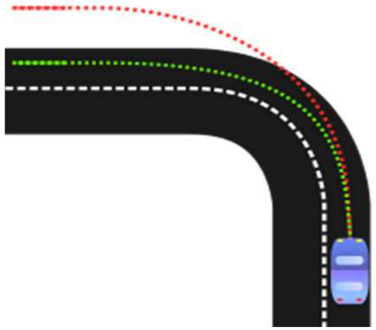
3. **Contribution**
   - **Vehicle Dynamics**
   - **Active Suspensions control for rollover prevention**

4. **Conclusion and perspectives**

Motivation

- 90% accidents ⟵ ⟶ human errors

Lateral skidding | Understeer | Rollover



Motivation

- Vehicle rollover constitutes ONLY 3% of all accidents !!

But it causes:

  - Fatal injuries, nearly 33% of all deaths from passenger vehicle crashes (NHTSA, 2011)

NHTSA: National Highway Traffic Safety Administration

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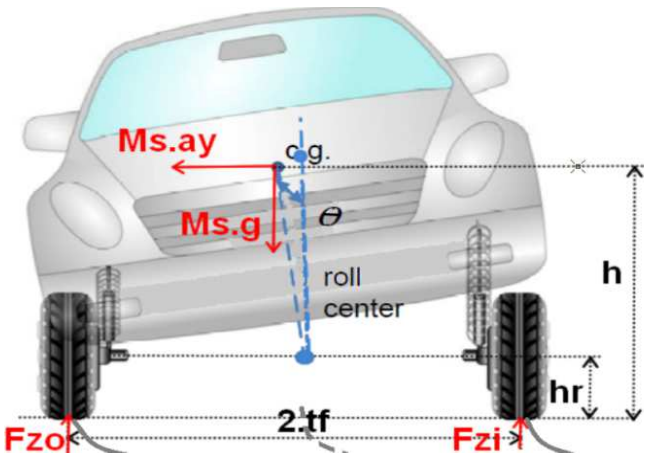
Rollover problem formulation

When cornering:

- The lateral acceleration induces a roll angle towards the outside of the corner.
- A vertical load transfer occurs toward the outside.
- The outside wheels vertical forces F_{z_o} increase, and the inside wheels vertical forces F_{z_i} decrease.



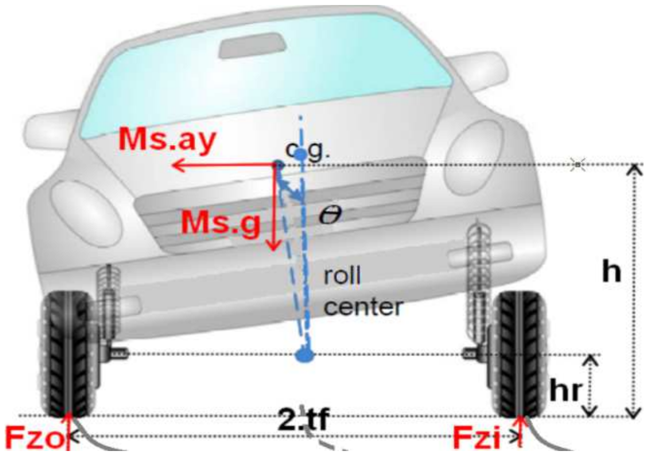
Equation of motion around outside wheels axis:

$$M_s.a_y.h - M_s.g.(t_f - (h - hr)\sin\theta) + F_{z_i}.2.t_f = 0$$

Rollover starts when F_{z_i} become 0

$$a_{y\_lift\_off} = \frac{t_f - (h - hr).\theta}{h} g$$

Rollover problem formulation



- Equation of motion around outside wheels axis:

$$M_s.a_y.h - M_s.\text{g}.(t_f - (h - hr)\sin\theta) + F_{z_i}.2.t_f = 0$$

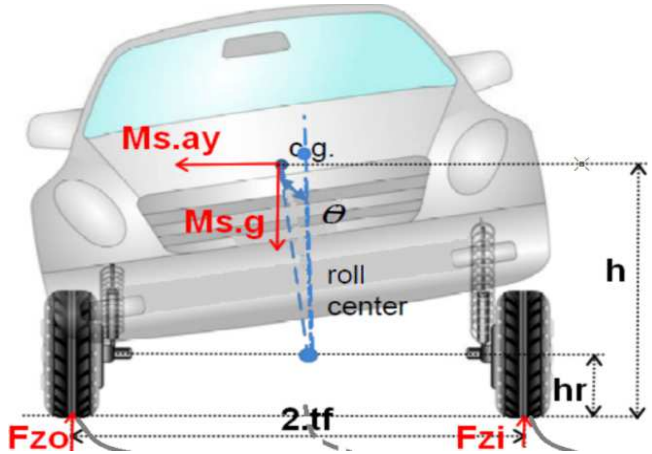
- Rollover starts when F_{z_i} become 0

$$a_{y\_lift\_off} = \frac{t_f - (h - hr).\theta}{h} g$$

$$a_{y\_safe} = 0.7 a_{y\_lift\_off}$$

- a_{y_safe} represents the maximal safe lateral acceleration a_y that the vehicle could handle before starting rollover.

Rollover avoidance possible solutions



- The vehicle lateral acceleration a_y should be kept below a_{y_safe} to avoid rollover

$$a_y < a_{y\_safe}$$

Possible actions

Diminish a_y

$$a_y = \frac{V^2}{R}$$

1. Braking to diminish V. (drawbacks on vehicle speed)
2. Steering to the outside of the corner to raise R. (drawbacks on vehicle trajectory)

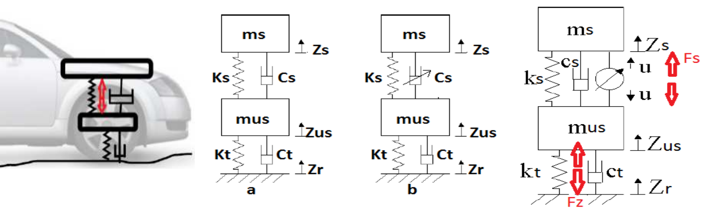
Raise $a_{y\_safe} = 0.7 a_{y\_lift\_off}$

- The vehicle lateral acceleration a_y should be kept below a_{y_safe} to avoid rollover

$a_y < a_{y\_safe}$

Possible actions

1. Semi-active suspensions to diminish θ to 0
2. Active suspensions to turn the θ toward the inside of the corner.



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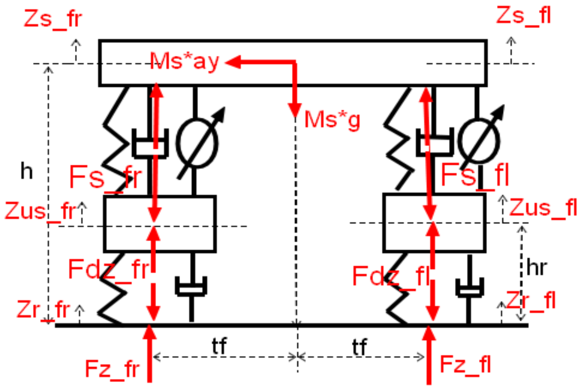
Full-vehicle Vertical dynamics



$$z_{s_{fr}} = z - t_f \sin\theta - l_f \sin\varphi$$
$$z_{s_{fl}} = z + t_f \sin\theta - l_f \sin\varphi$$
$$z_{s_{rr}} = z - t_r \sin\theta + l_r \sin\varphi$$
$$z_{s_{rl}} = z + t_r \sin\theta + l_r \sin\varphi$$

$$F_{s_{ij}} = -k_{s_{ij}}\left(z_{s_{ij}} - z_{us_{ij}}\right) - c_{s_{ij}}\left(\dot{z}_{s_{ij}} - \dot{z}_{us_{ij}}\right) + U_{ij}$$

$$F_{z_{ij}} = F_{dz_{ij}} + F_{Z\_LT_{ij}} + m_{ij}.g$$

$$\ddot{z}_{us_{ij}} = -F_{s_{ij}} + F_{dz_{ij}}$$

$$F_{Z\_LT_{ij}} = \pm m_{ij}.\left(\frac{h}{tf}\right).ay.$$

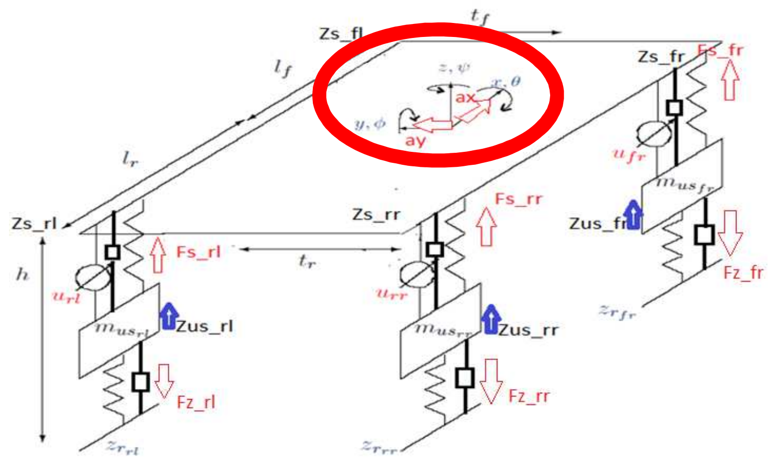
$$F_{dz_{ij}} = -k_{t_{ij}}\left(z_{us_{ij}} - z_{r_{ij}}\right) - c_{t_{ij}}\left(\dot{z}_{us_{ij}} - \dot{z}_{r_{ij}}\right)$$

Full-vehicle Vertical dynamics

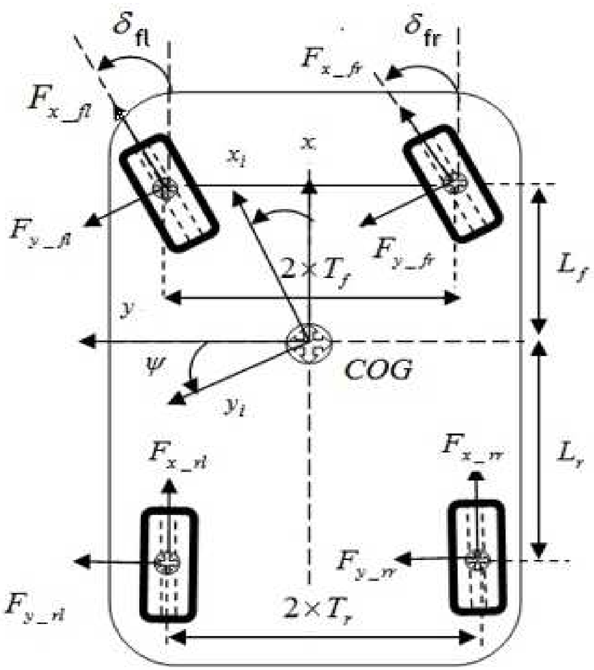
$$\ddot{\theta} = \frac{1}{I_x + M_s {h_\theta}^2}\begin{pmatrix} \left(-F_{s_{fr}} + F_{s_{fl}}\right) t_f + \left(-F_{s_{rr}} + F_{s_{rl}}\right) t_r \\ +M_s(h_\theta \cos\theta + z).\,a_y + M_s(h_\theta \sin\theta + z).\,g \end{pmatrix}$$

$$\ddot{\varphi} = \frac{-\left(F_{s_{fr}} + F_{s_{fl}}\right) l_f + \left(F_{s_{rr}} + F_{s_{rl}}\right) l_r \\ +M_s\left(h_\varphi \cos\varphi + z\right).\,a_x + M_s\left(h_\varphi \sin\varphi + z\right).\,g}{I_y + M_s {h_\varphi}^2}$$

$$\ddot{z} = \left\{F_{s_{fr}} + F_{s_{fl}} + F_{s_{rr}} + F_{s_{rl}}\right\} / M_s$$



Full-vehicle longitudinal / lateral dynamics



$$\ddot{x} = \dot{y}\dot{\Psi} + (F_{x_{fl}}\cos\delta_{fl} + F_{x_{fr}}\cos\delta_{fr} + F_{x_{rl}} + F_{x_{rr}} - F_{y_{fl}}\sin\delta_{fl} - F_{y_{fr}}\sin\delta_{fr})/M$$

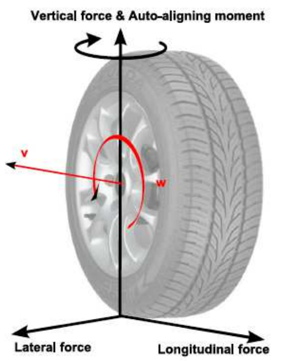
$$a_x = \ddot{x} - \dot{y}\dot{\Psi}$$

$$\ddot{y} = -\dot{x}\dot{\Psi} + (F_{x_{fl}}\sin\delta_{fl} + F_{x_{fr}}\sin\delta_{fr} + F_{y_{rl}} + F_{y_{rr}} + F_{y_{fl}}\cos\delta_{fl} + F_{y_{fr}}\cos\delta_{fr})/M$$

$$a_y = \ddot{y} + \dot{x}\dot{\Psi}$$

$$\begin{aligned}\ddot{\Psi} = \{&-t_f(\cos\delta_{fl} F_{x_{fl}} - \cos\delta_{fr} F_{x_{fr}} + \sin\delta_{fr} F_{y_{fr}} - \sin\delta_{fl} F_{y_{fl}}) \\ &+ l_f(\sin\delta_{fl} F_{x_{fl}} + \sin\delta_{fr} F_{x_{fr}} + \cos\delta_{fl} F_{y_{fl}} + \cos\delta_{fr} F_{y_{fr}}) \\ &- l_r\left(F_{y_{rl}} + F_{y_{rr}}\right) - t_r(F_{x_{rl}} - F_{x_{rr}})\}/I_z\end{aligned}$$

Tire-road contact (Dugoff model)



$$F_{x_{ij}} = C_\sigma \frac{\sigma_{x_{ij}}}{1-\sigma_{x_{ij}}} f(\lambda_{ij})$$

$$F_{y_{ij}} = C_\alpha \frac{\tan(\alpha_{ij})}{1-\sigma_{x_{ij}}} f(\lambda_{ij})$$

$$f(\lambda_{ij}) = \begin{cases} (2-\lambda_{ij})\lambda_{ij} & for\ \lambda_{ij} < 1 \\ 1 & for\ \lambda_{ij} > 1 \end{cases}$$

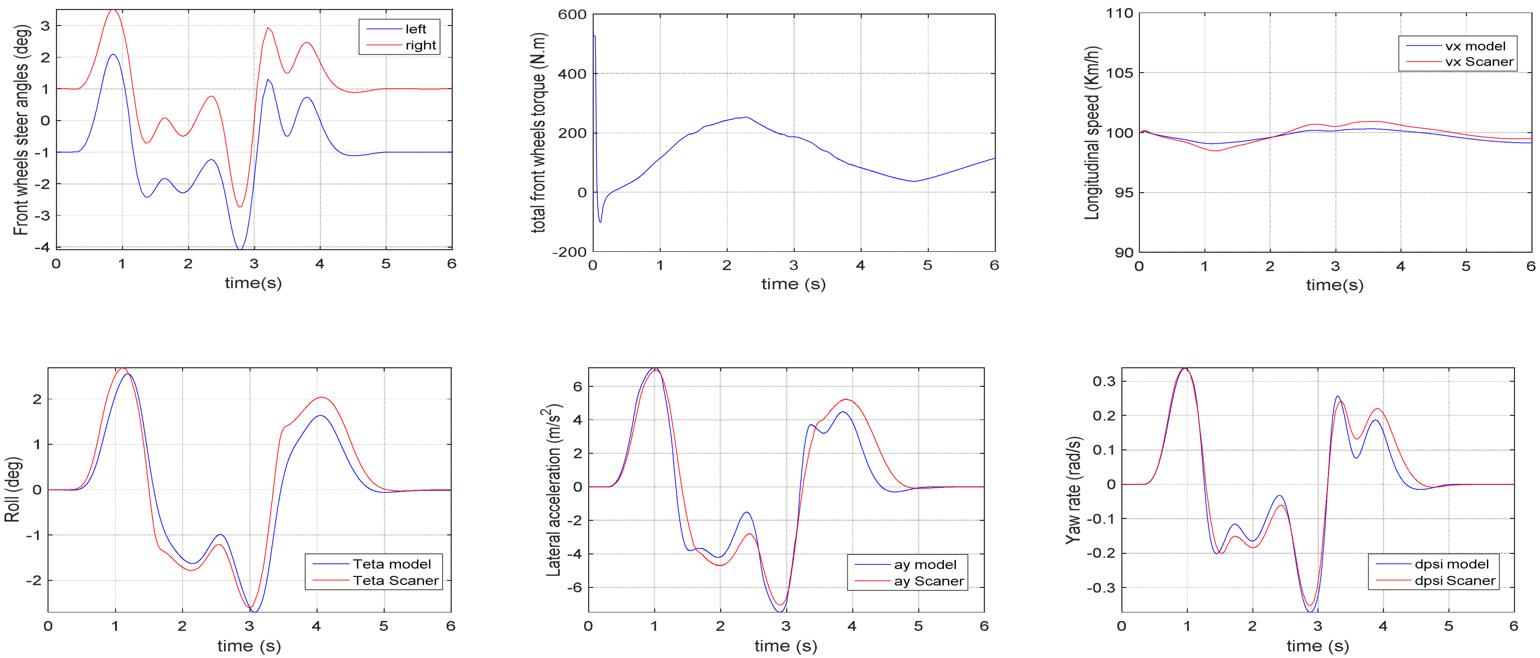
$$\lambda_{ij} = \frac{\mu F_{z_{ij}}(1-\sigma_{x_{ij}})}{2.\sqrt{(C_\sigma \sigma_{x_{ij}})^2 + (C_\alpha \tan(\alpha_{ij}))^2}}$$

Simulation – Renault Megane Parameters

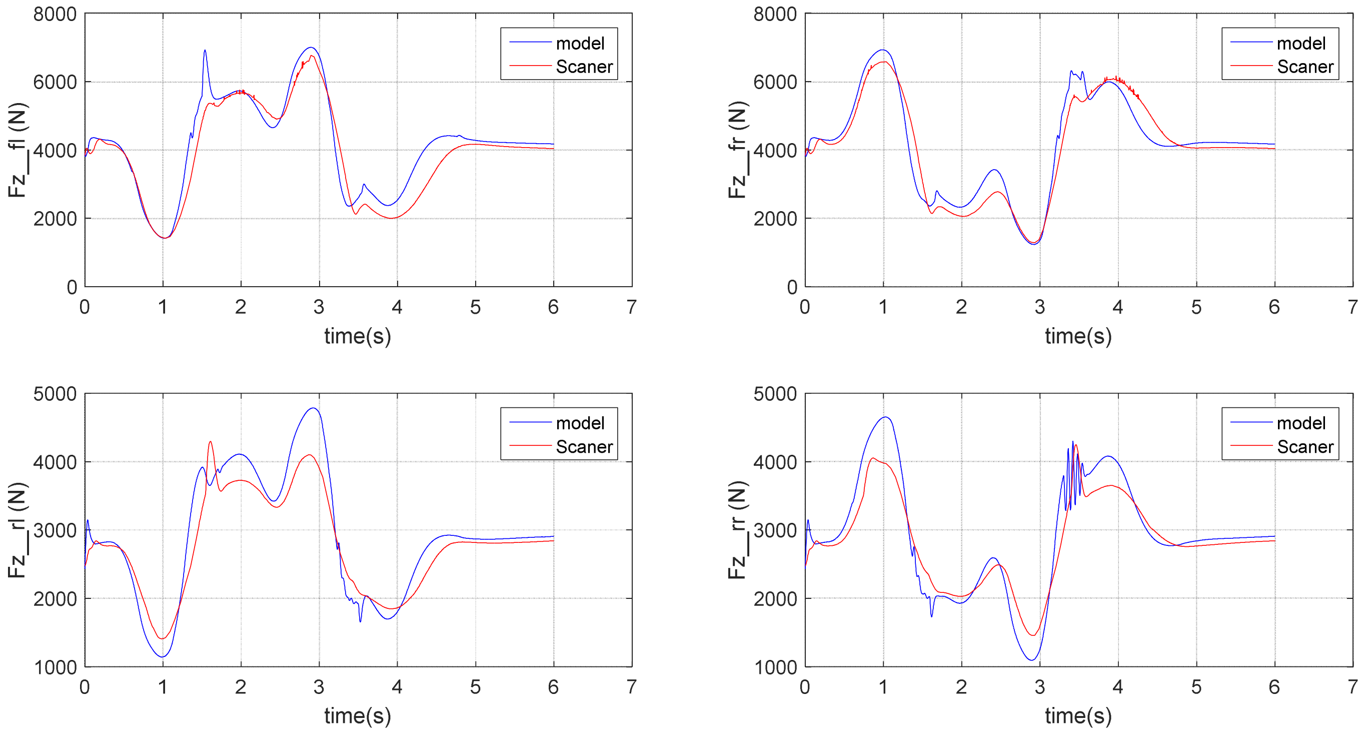
h=0,58 m

M	1286.4	$t_f = t_r$	0.773
$m_{us_{ij}}$	40	l_f& l_r	1 & 1.6
I_x	534	$k_{s_{fl}} = k_{s_{fr}}$	22639
I_y	1860	$k_{s_{rl}} = k_{s_{rr}}$	12548
I_z	1970	$c_{s_{ij}}$	700

Model Validation- Scaner Studio



Model Validation- Scaner Studio



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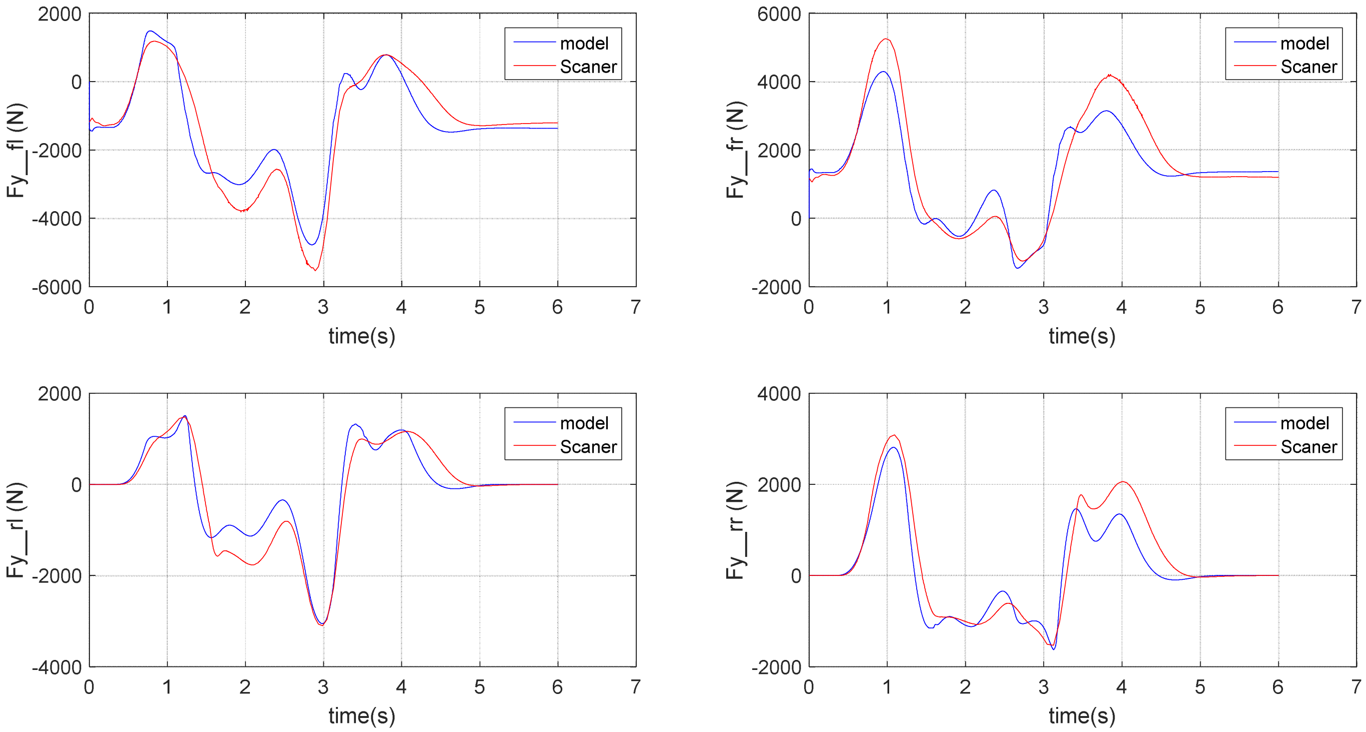

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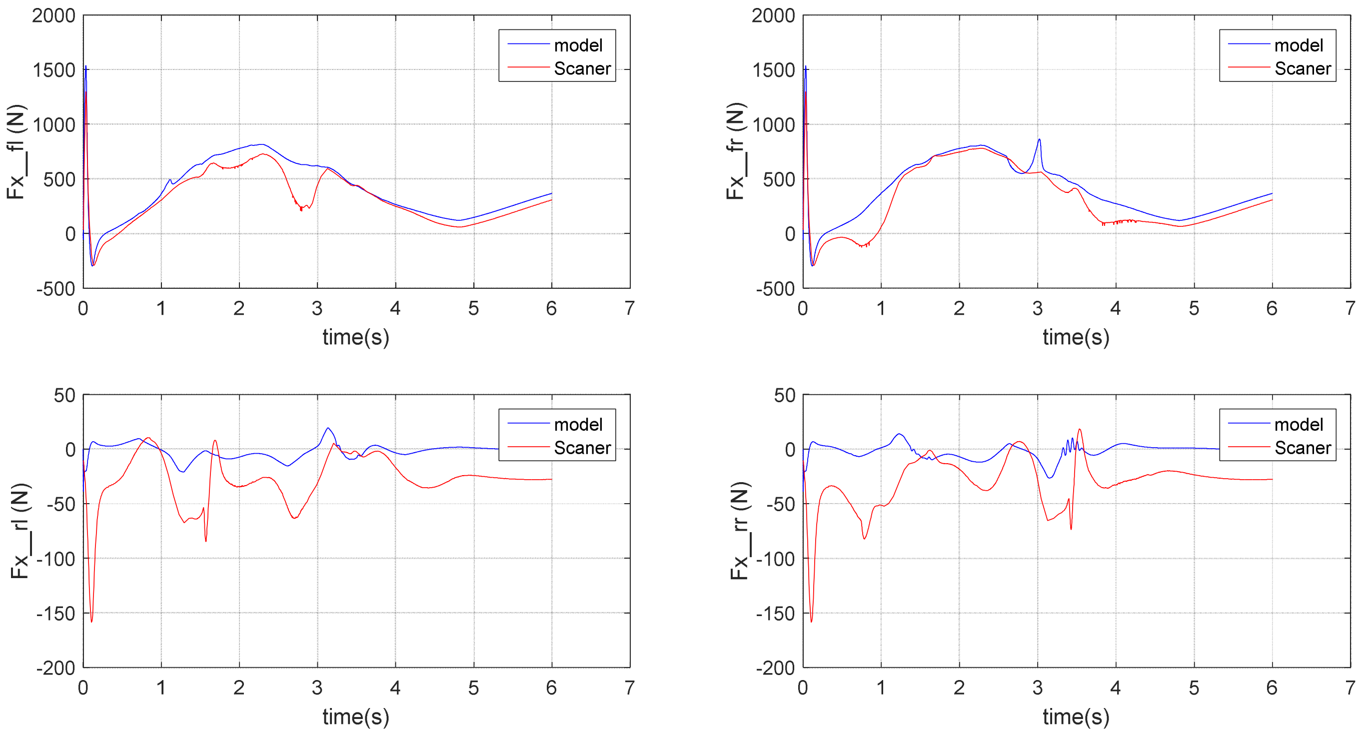

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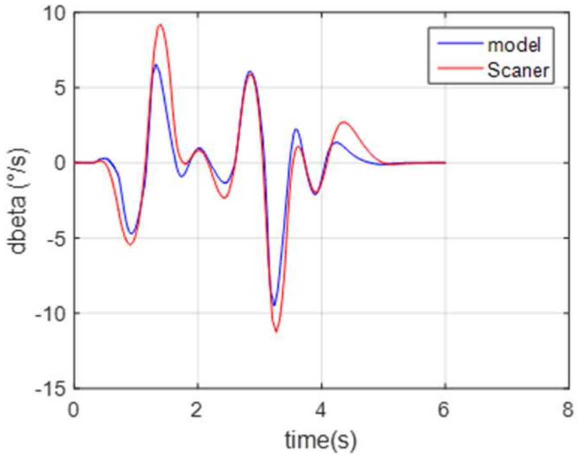
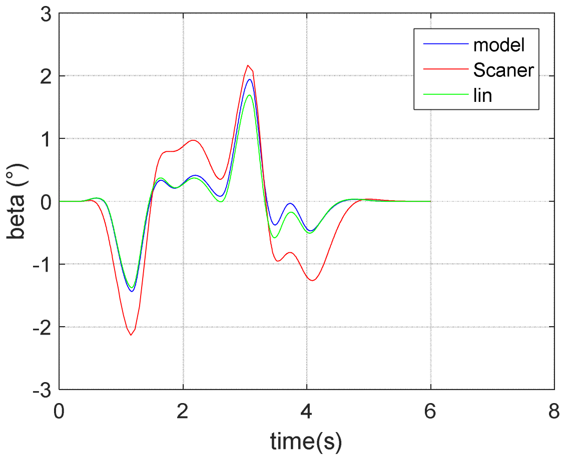
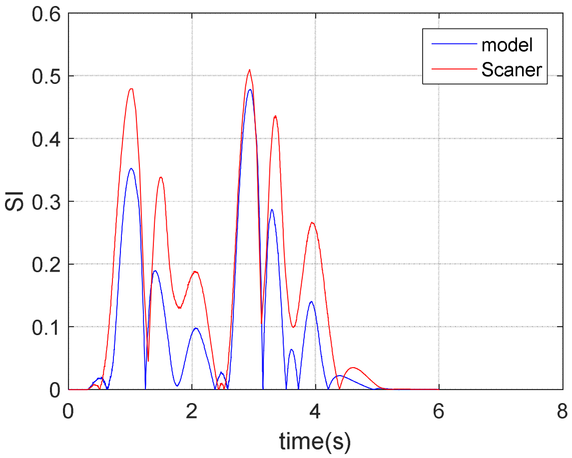
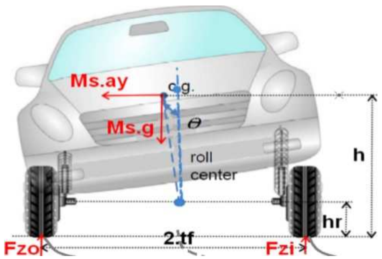






Active suspensions design for rollover avoidance



- θ_{des} = 0 when a_y=0;
- θ_{des} decreases linearly to attain -10° (the maximal possible roll angle) when a_y reaches its maximal safe value $0.7 * \frac{t_f}{h}.g.$

$$\ddot{\theta} = \frac{1}{I_x + M_s {h_\theta}^2}\begin{pmatrix}\left(-F_{s_{fr}} + F_{s_{fl}}\right)t_f + \left(-F_{s_{rr}} + F_{s_{rl}}\right)t_r \\ +M_s(h_\theta \cos\theta + z).a_y + M_s(h_\theta \sin\theta + z).g\end{pmatrix}$$

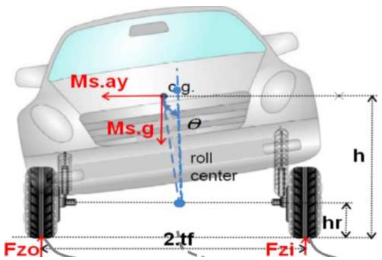
$$\theta_{des} = -\frac{10.\pi/180}{0.7 * \frac{t_f}{h}.\mathrm{g}} a_y$$

$$F_{s_{ij}} = -k_{s_{ij}}\left(z_{s_{ij}} - z_{us_{ij}}\right) - c_{s_{ij}}\left(\dot{z}_{s_{ij}} - \dot{z}_{us_{ij}}\right) + U_{ij}$$

$$\ddot{\theta} = \frac{1}{I_x + M_s {h_\theta}^2}\begin{pmatrix}M_\theta + (-F_{fr} + F_{fl})t_f + (-F_{rr} + F_{rl})t_r \\ +M_s(h_\theta \cos\theta + z).a_y + M_s(h_\theta \sin\theta + z).g\end{pmatrix}$$

$$F_{ij} = -k_{s_{ij}}\left(z_{s_{ij}} - z_{us_{ij}}\right) - c_{s_{ij}}\left(\dot{z}_{s_{ij}} - \dot{z}_{us_{ij}}\right)$$

Active Suspensions controller design



$$\ddot{\theta} = \frac{1}{I_x + M_s {h_\theta}^2}\begin{pmatrix} \mathcal{M}_\theta + (-F_{fr} + F_{fl})t_f + (-F_{rr} + F_{rl})t_r \\ +M_s(h_\theta \cos\theta + z).a_y + M_s(h_\theta \sin\theta + z).g \end{pmatrix}$$

$$\theta_{des} = -\frac{10.\pi/180}{0.7 * \frac{t_f}{h}.\mathrm{g}} a_y$$

Lyapunov Based controller

$$e_\theta = \theta - \theta_{des},$$

$$s_\theta = \dot{e}_\theta + k_{1\theta} e_\theta + k_{2\theta}\int_0^t e_\theta d\tau,$$

$$V_\theta = \frac{1}{2}{s_\theta}^2,$$

$$\dot{s}_\theta = -\alpha_\theta s_\theta,$$

$$\begin{aligned} \mathcal{M}_\theta \\ &= -(\alpha_\theta + k_{1\theta})(I_x + M_s {h_\theta}^2)(\dot{\theta} - \dot{\theta}_{des}) - (\alpha_\theta k_{1\theta} + k_{2\theta})(I_x + M_s {h_\theta}^2)(\theta - \theta_{des}) \\ &- \alpha_\theta k_{2\theta}(I_x + M_s {h_\theta}^2)\int_0^t (\theta - \theta_{des}) d\tau - (-F_{fr} + F_{fl})t_f - (-F_{rr} + F_{rl})t_r - M_s(h_\theta \cos\theta + z)a_y - M_s(h_\theta \sin\theta + z).g \\ &+ (I_x + M_s {h_\theta}^2)\ddot{\theta}_{des}. \end{aligned}$$

Active Suspensions controller design

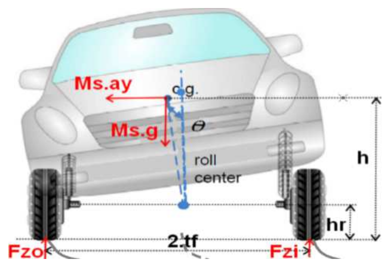
$$\mathcal{M}_\theta = (-U_{fr} + U_{fl})t_f + (-U_{rr} + U_{rl})t_r,$$

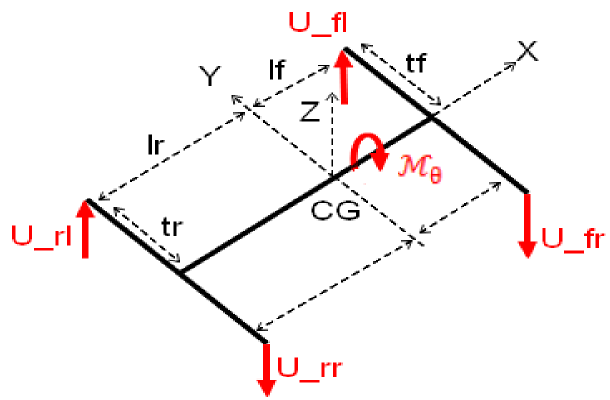
$$U_{fl} = 0.5\frac{\mathcal{M}_\theta}{t_f}\cdot\frac{l_r}{l_f + l_r},$$

$$U_{fr} = -0.5\frac{\mathcal{M}_\theta}{t_f}\cdot\frac{l_r}{l_f + l_r},$$

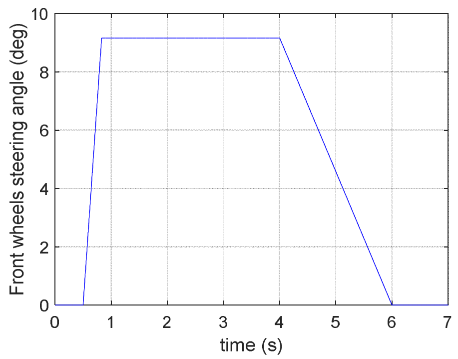
$$U_{rl} = 0.5\frac{\mathcal{M}_\theta}{t_r}\cdot\frac{l_f}{l_f + l_r},$$

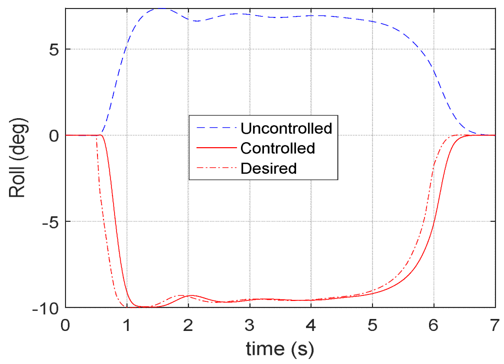
$$U_{rr} = -0.5\frac{\mathcal{M}_\theta}{t_r}\cdot\frac{l_f}{l_f + l_r}.$$

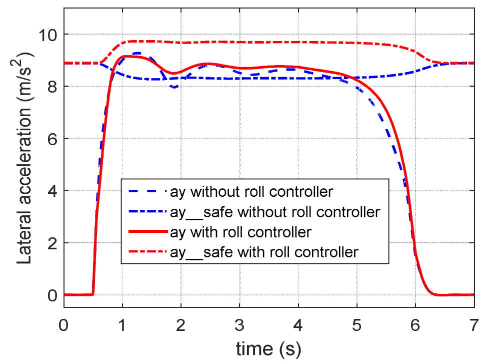


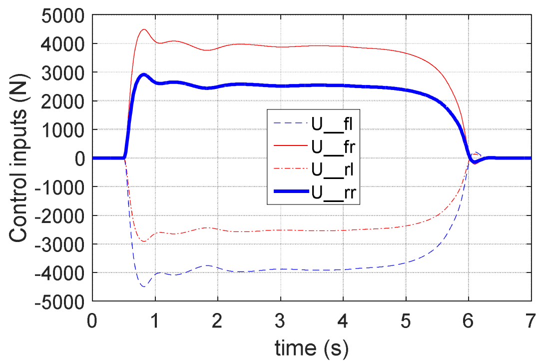


Controller validation V0= 130 Km/h

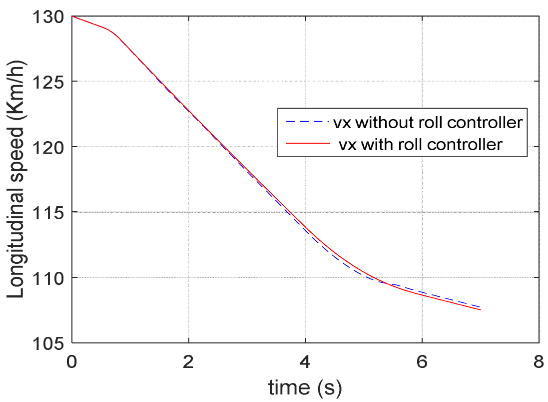


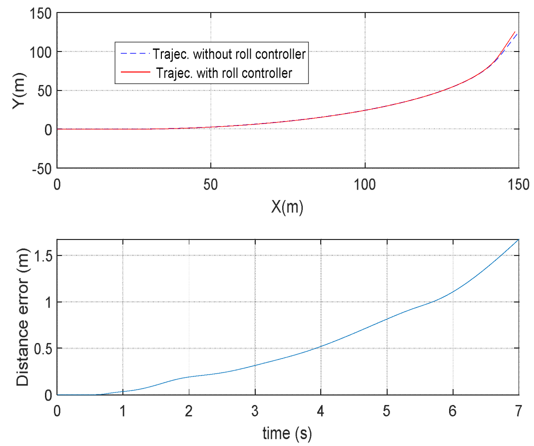


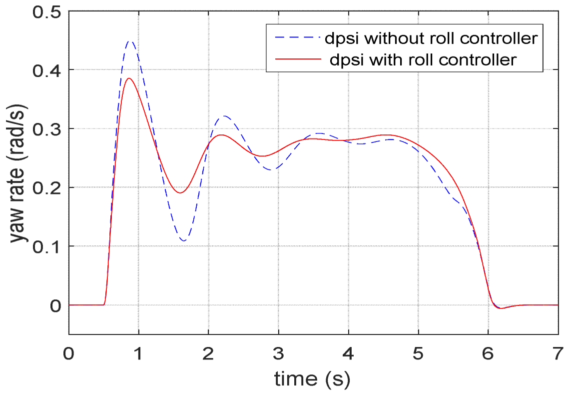


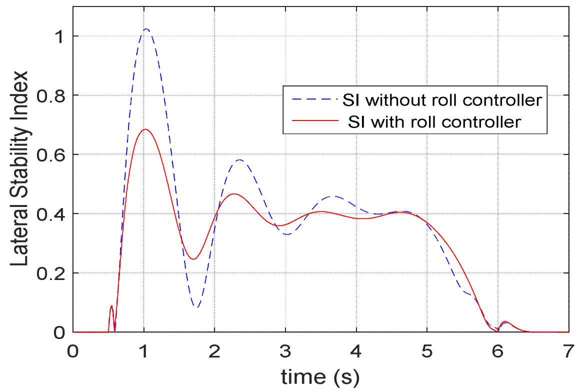


Controller observations – Side Advantages









Conclusion

- Develop and Validate a full-vehicle model on Scaner Studio.
- Study of rollover phenomenon and possible solutions.
- Active suspensions control for rollover avoidance.
- Active suspensions advantages on vehicle lateral dynamics.
- Comfort + perturbation isolation (ITSC 2016).

Perspectives

- Active suspensions for lateral stability
- Active suspensions decision layer (comfort, perturbation isolation, rollover avoidance, lateral stability)
- Global chassis control, a decision layer to coordinate active suspension, differential braking, and active steering.
- Vehicle actuators fault tolerant control.

Thank you for your attention!