Control Design for X-By-Wire Components

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LABORATOIRE D'AUTOMATIQUE DE GRENOBLE

NeCS

CNRS-INRIA Projet

Class of Systems

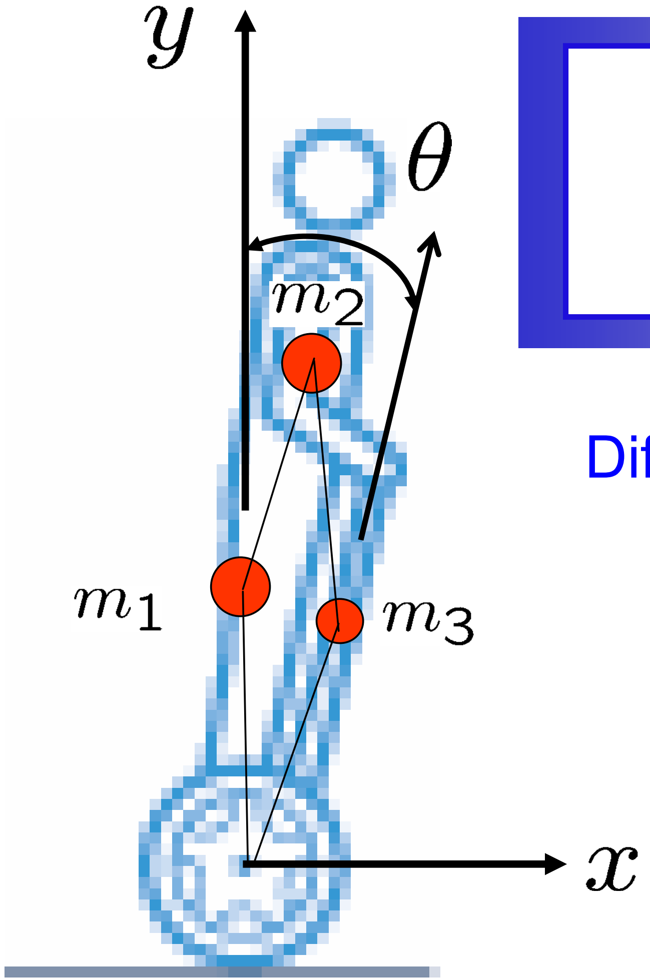
Drive-by-Wire
Systems

Systems with a Driver in the loop

Air-scooters

Balancing
Scooters

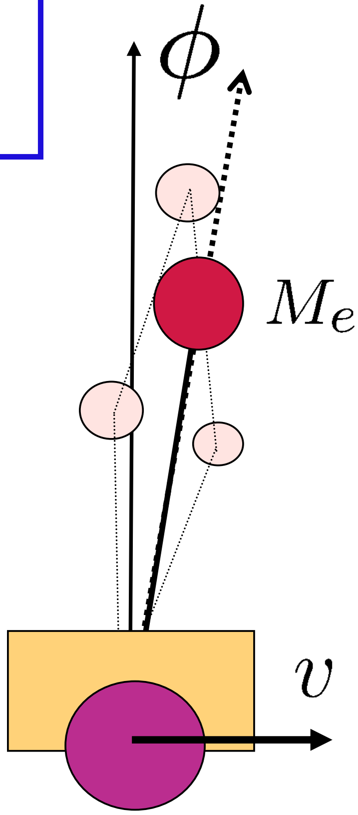
A Motivating Example



Balance Scooter is "similar" to a cart-pendulum

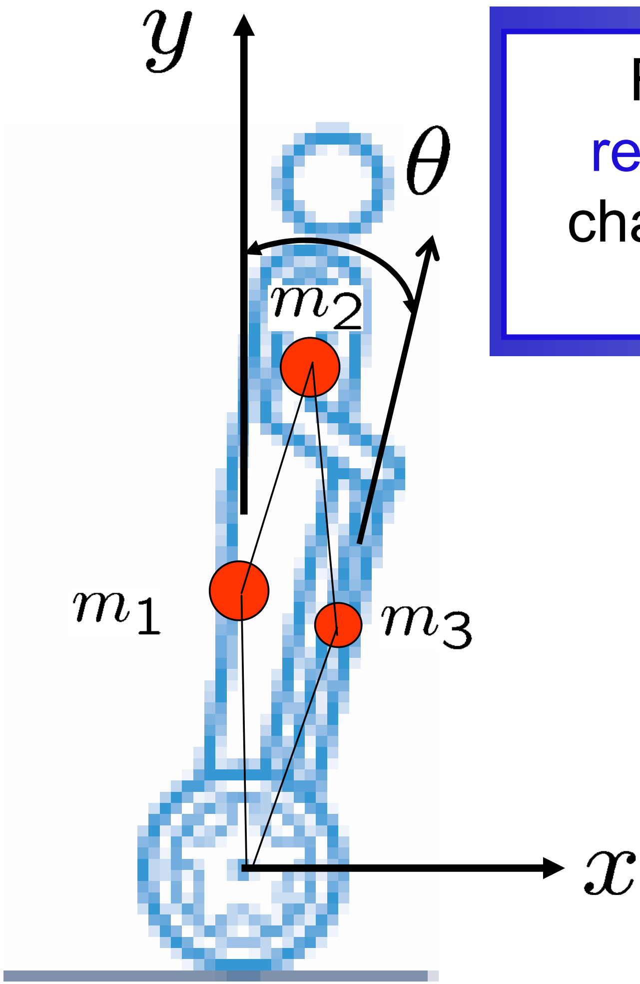
Differences:

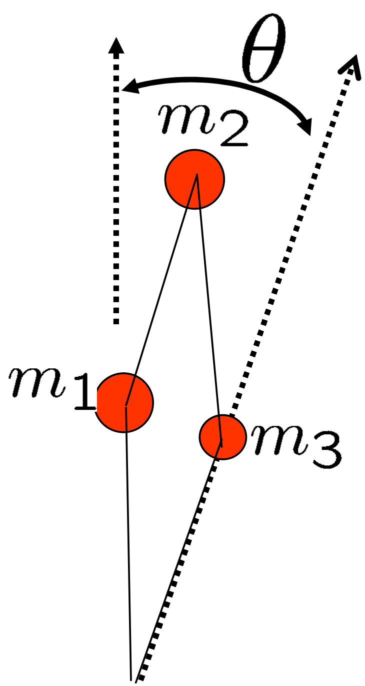
- Stabilization of θ not ϕ
- $v = \dot{x}$ not explicitly regulated

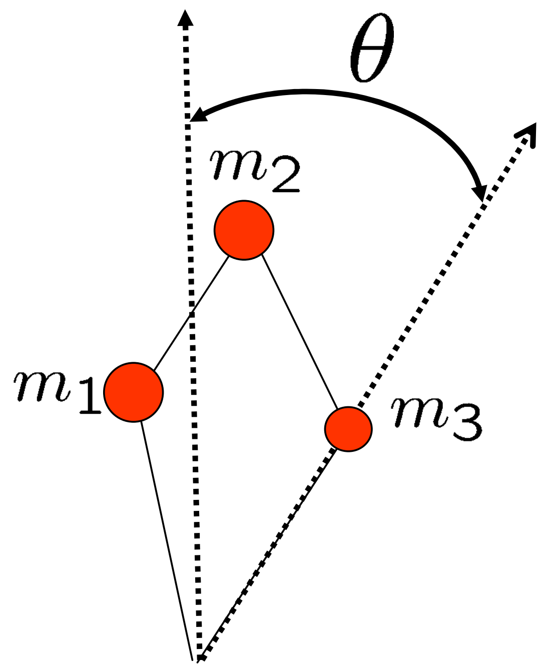


How motion is produced ?

Forward motion is induced as a reaction of the feedback system to changes in the tilt angle arising from forces produced by the rider







Control Paradigm

Seville home made
Balancing scooter

Commercial
Segway© scooter

How to design controllers resulting in:

- Comfortable,
- Safe,
- Pleasant riding

Outline

1. Introduction

- Challenges
- Product Evolution
- Breakthroughs

2. Examples

- Clutch Synchronization
- Steer-by-Wire

3. Conclusions

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Conceptual Challenges

Different driver skills:

- Different levels of: perceptual abilities, physical skills, and technological understanding,

Decision partition between Driver & Automated system:

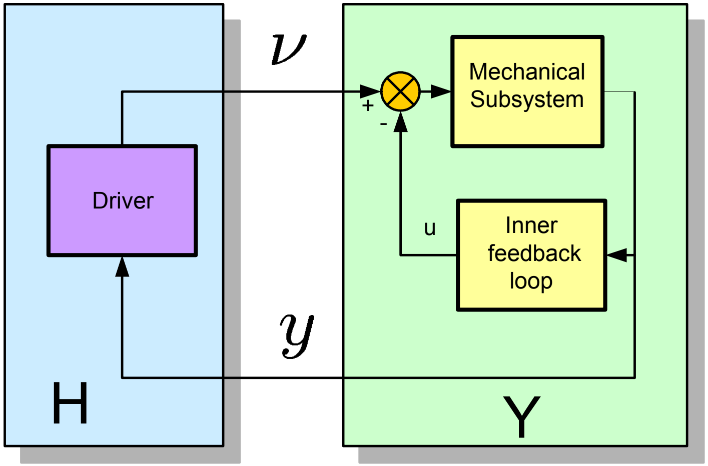
- Little control: Increases workload
  Decreases drivers awareness, comfort & safety
- Too much control Confidence excess: false safety perception

Fun-to-Drive:

"A notion of driving pleasure, whose primary goal is to safely promote comfort"
(Goodrich & Boer 01)

Technical Challenges

$$\boxed{Y : \nu \mapsto y}$$



Lack of well defined metrics

- How to measure comfort ?,
- How to define safety ?

Transfer of “standard” control notions is not always straightforward

- How to integrate in the control specs the comfort metrics (if any) ?
- Are all stable systems safe ?
- How to select/define a few tuning parameters with subjective meaning (pleasant, hard, nice, tiring, etc.) ?

Problem

Main difficulty:

- How to translate subjective vehicle specs into control specs?

Subjective
Vehicle Specs:

- Maneuverability,
- Perceived quality, & security,
- Brio,
- Etc.

→

Control Specs:

- Precision,
- Damping,
- Stability,
- Passivity,
- Etc.

Examples of Vehicle Control Problems Implying Jointly Comfort & Safety Specs

Automatic Clutch

- Smooth synchronization (C),
- Engine stall (S).

Steer-by-wire & Electric Power Steering Systems

- Steering wheel vibrations, Tire/road sensations (C),
- Driver interaction with an active system (S).

Chassis Control

- Reject road vibrations (C),
- Vehicle stability (S).

Adaptive Cruise Control (ACC)

- Smooth distance/velocity regulation (C),
- Vehicle front collisions (S).

Etc…

Car Product Design Evolution

By base functions:

- Suspension,
- Lighting, etc.

By field of expertise:

- Acoustics,
- Passive safety, etc

By customer-perceived performance:

- Drivability,
- Quality, etc.

Distinctive features
Fun-to-Drive
(something more)

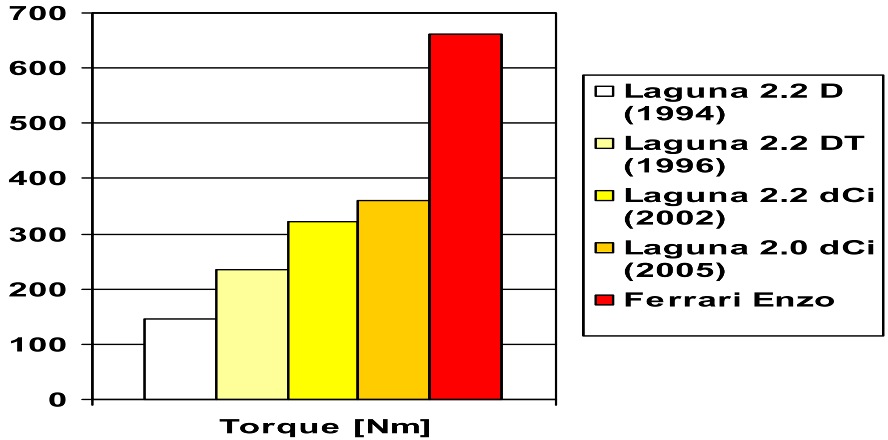
→

Basic features
Perceived as a due

ESP, ABS, TC,
Airbags, etc.

Trade-offs due to the Introduction of Distinctive Features

Example: High torque diesel engines



Clutch torque = 1.2 Peak Engine Torque

Solutions to increase torque clutch capacity:

- Higher pre-constraint forces
- Larger friction plates
- Multi clutch plates

Trade-offs due to the introduction of Distinctive Features

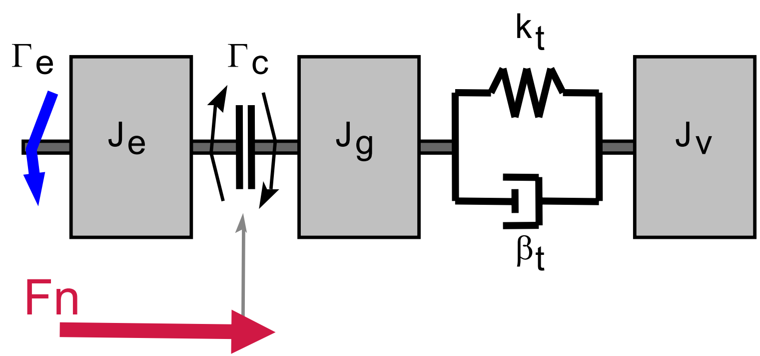
Solution 1: Higher pre-constraint spring force Fn

Side effects:

- Increase of pedal effort
- Lengthening of pedal travel

Constraints:

- Driving ergonomy (for passenger comfort)
- Passenger space (for passenger comfort)
- Crash test foot injuries



Trade-offs due to the introduction of Distinctive Features

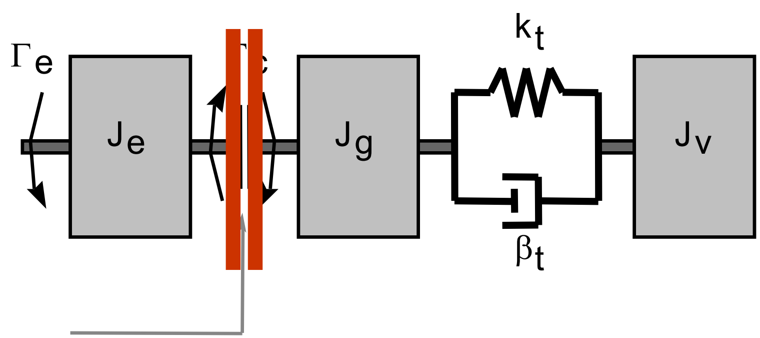
Solution 2: Larger plate disks

Side effects:

- Increase of effective volume
- Increase moment of inertia

Constraints:

- Constraint on power-train packaging
- Under hood dead volume (~20cm) (Thatcham & Danner crash tests)
- Gear shifting quality



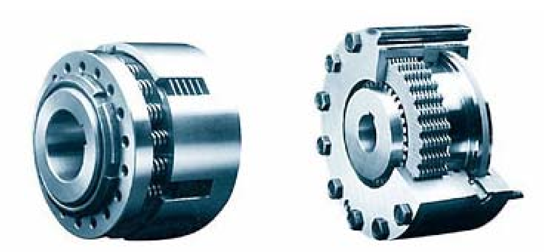
Solution 3: Multi disk clutch

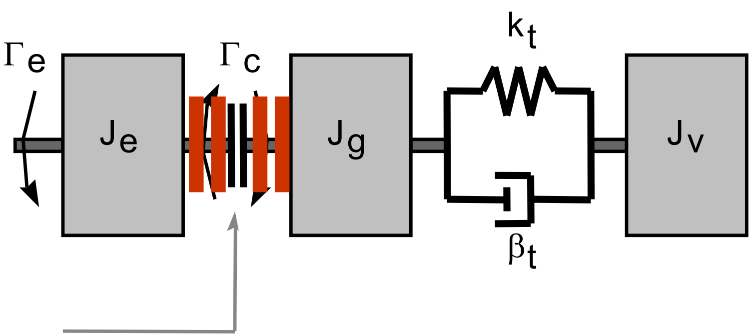
Side effects:

- Increase of lateral vehicle volume → Constraint on power-train packaging
- Increase momentum of inertia → Gear shifting quality

Constraints:

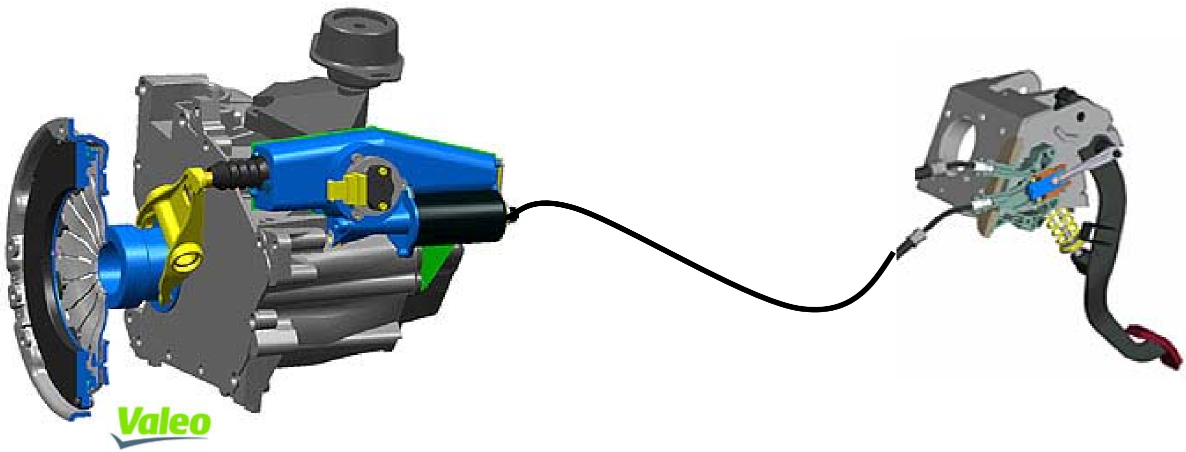
- Constraint on power-train packaging
- Gear shifting quality





Breakthrough Solutions

- Integrate a force assistance device
- Clutch-by-wire System



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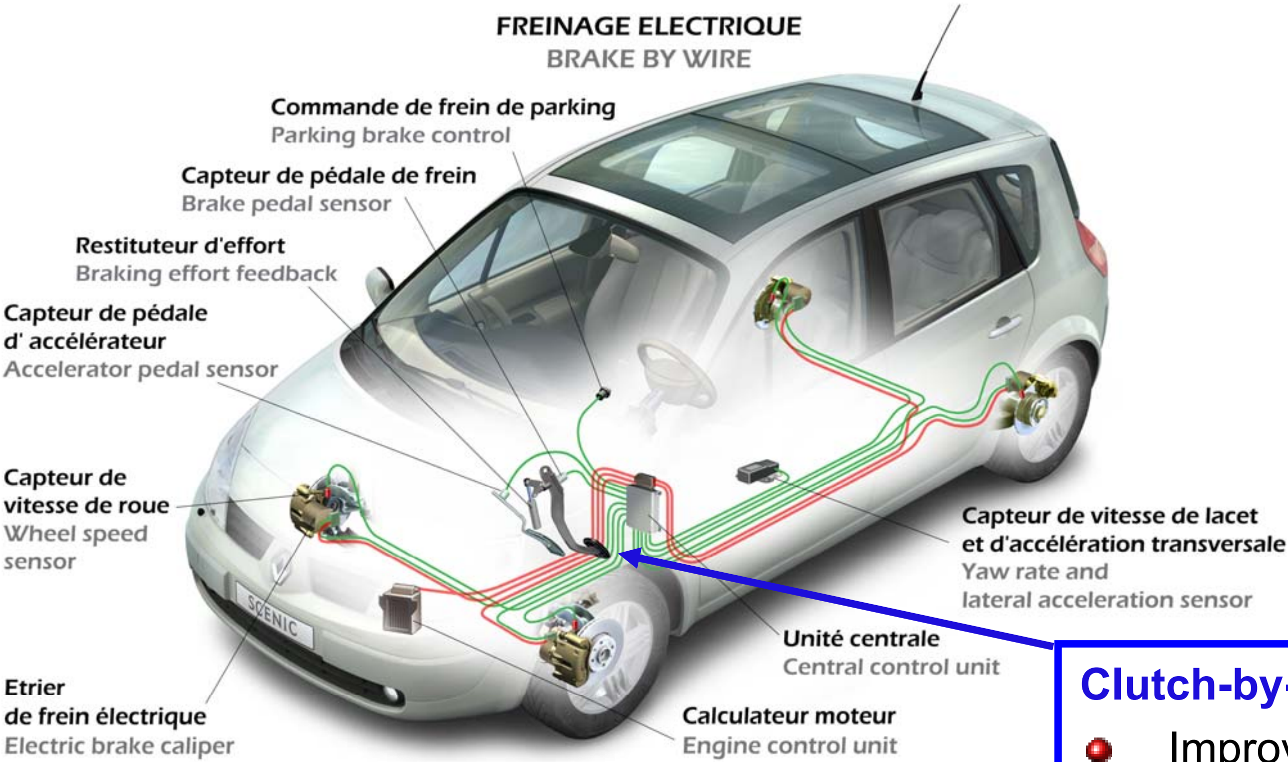
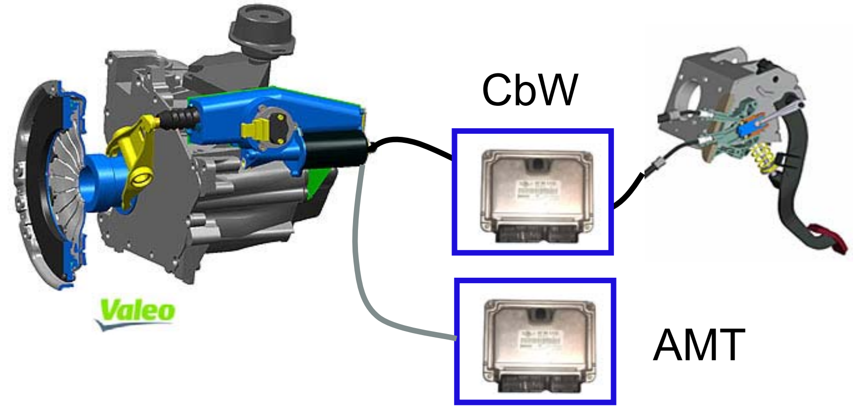
Clutch-by-Wire Benefits



Clutch-by-Wire:

- Improves comfort
- Increase engine duty life
- Avoid motor stall,

Setups



Hardware Setups:

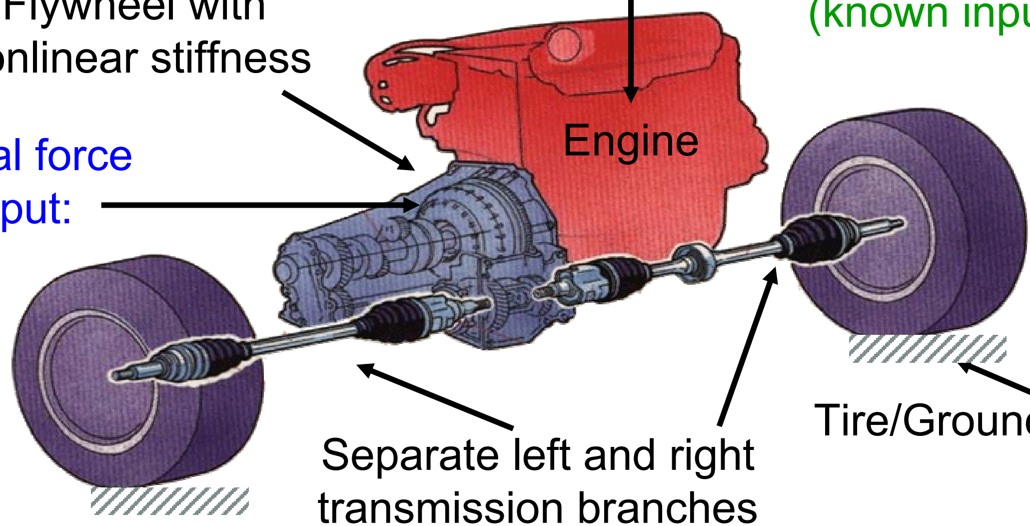
- Clutch-by-Wire (CbW), and
- Automated Manual Transmission (AMT)

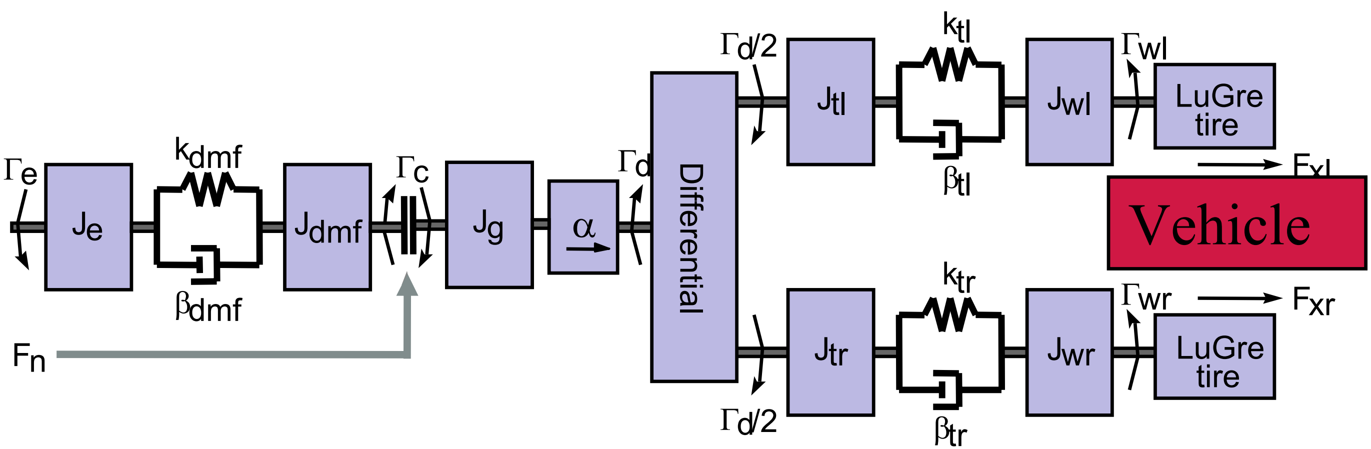
inexpensive and efficient solutions

Control setups:

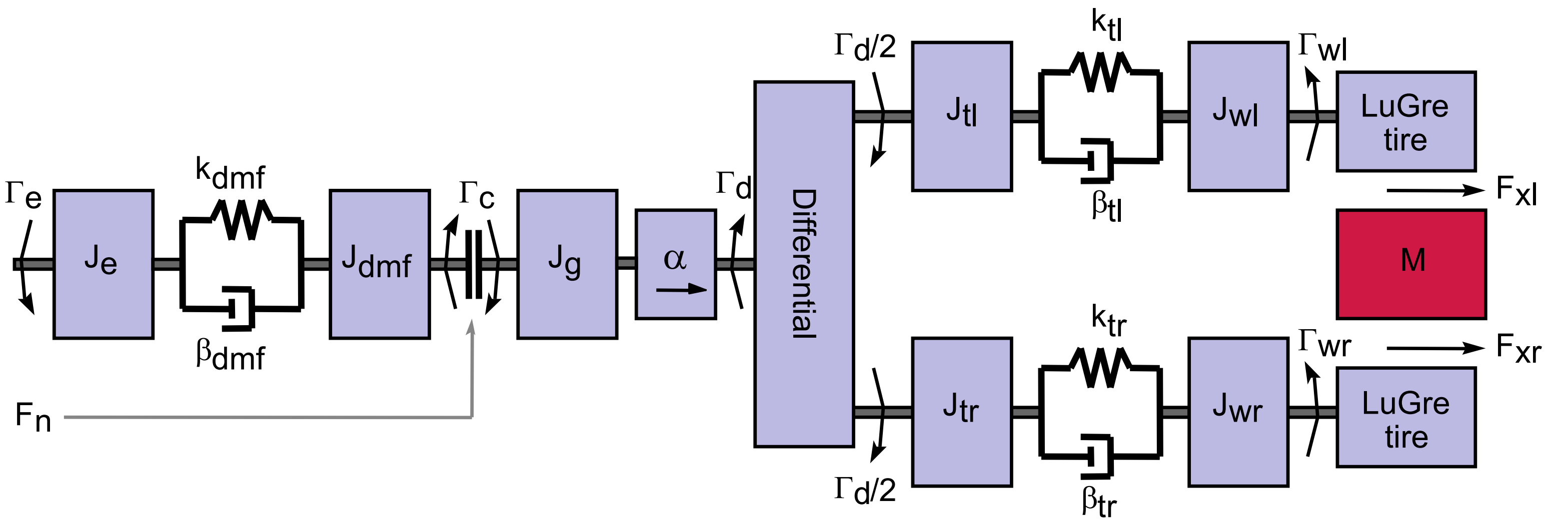
- Both engine and clutch torque as control inputs
- Clutch torque as the only controlled input, considering the engine torque as a known input

Clutch & Driveline Components



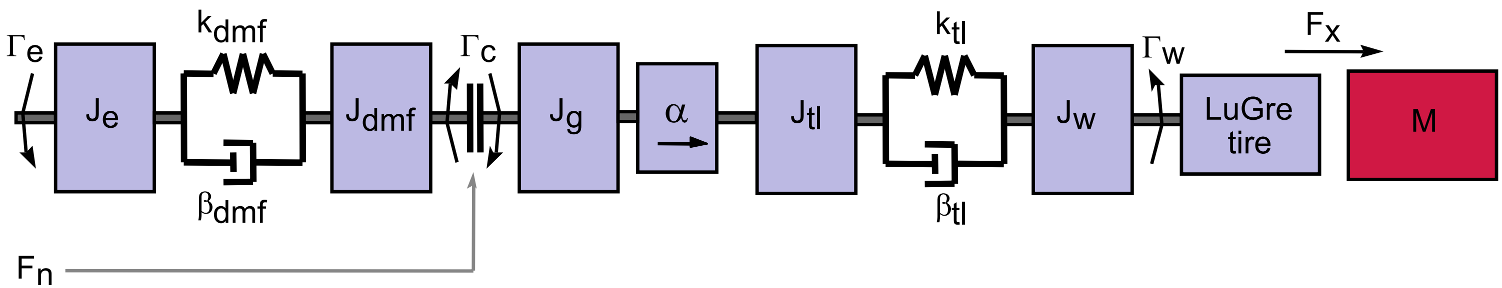


Simple Model for Control



- Assuming right-left symmetry
- Ignoring DMF dynamics
- Ignoring tire dynamics
- Equivalent moment of inertia and stiffness

Simple Model for Control



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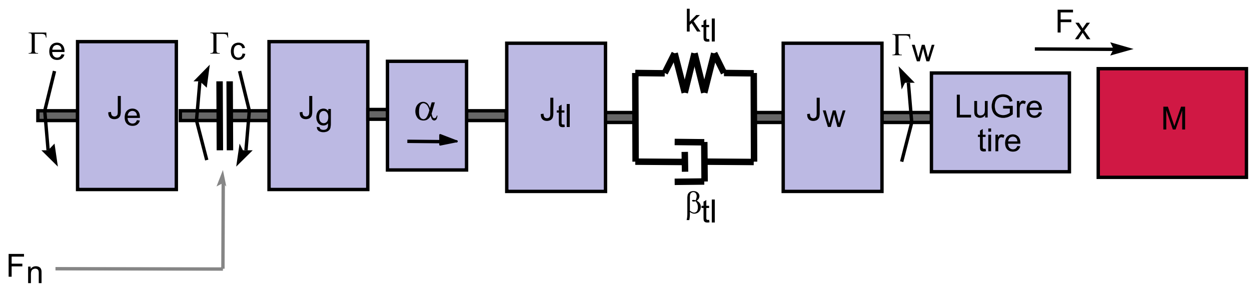

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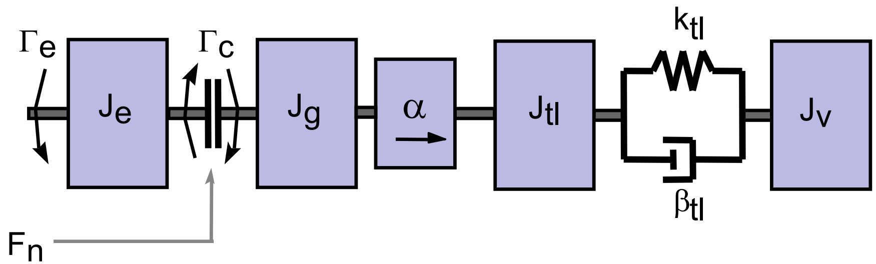

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- **Ignoring tire dynamics**
- Equivalent moment of inertia and stiffness

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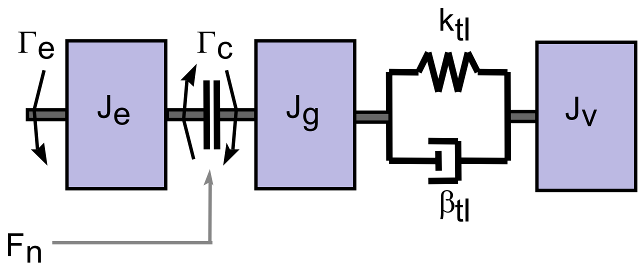

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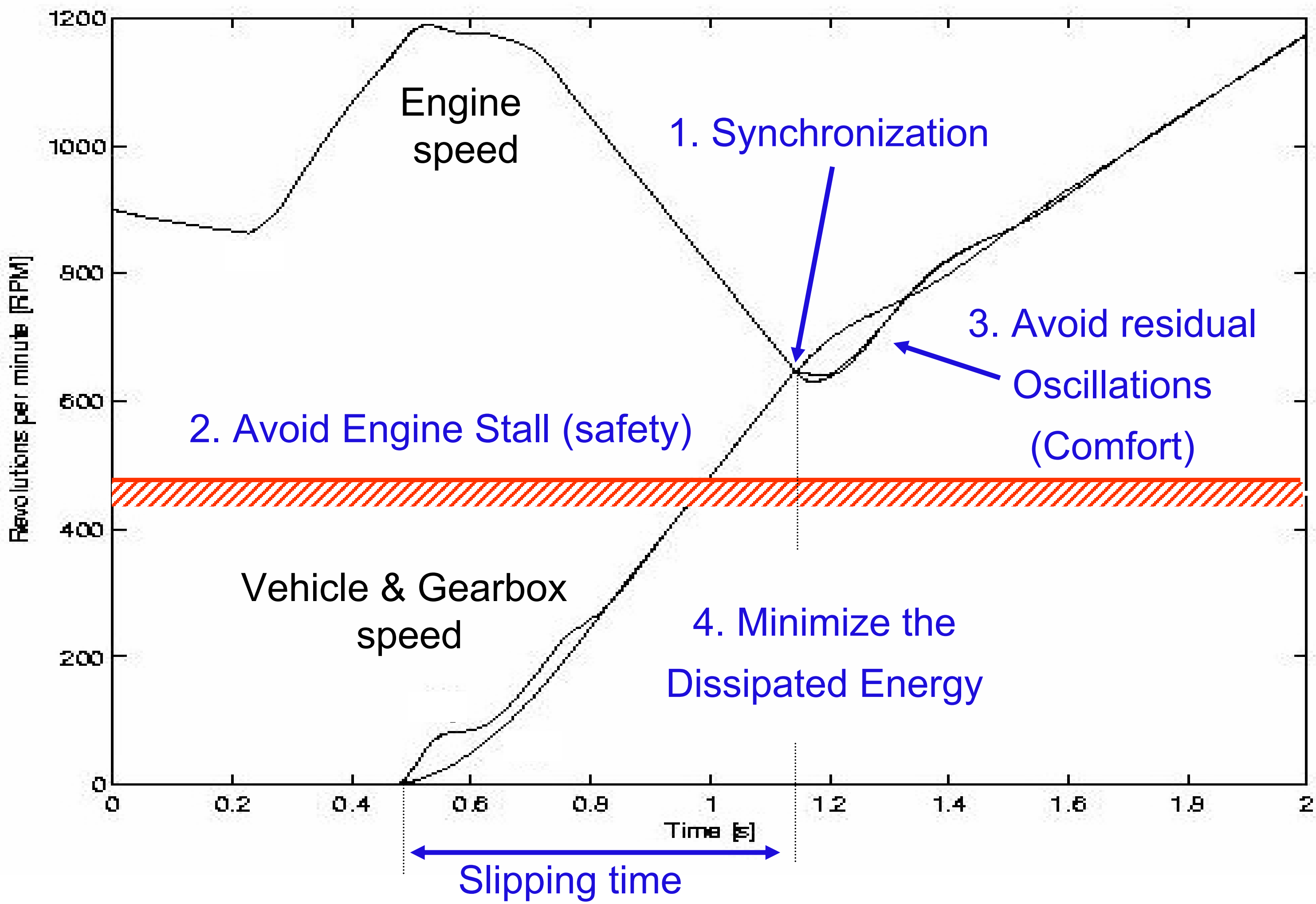
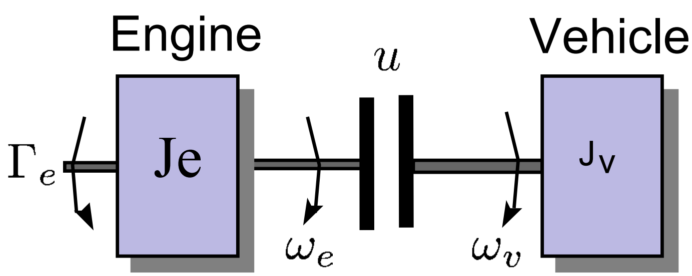
- **Equivalent moment of inertia and stiffness**

Engagement problem



Synchronization & Comfort necessary conditions

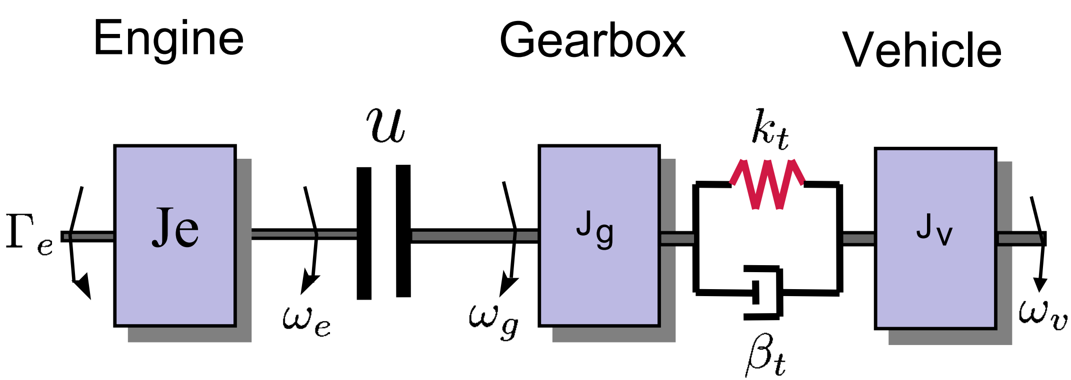
- Clutch Engagement: $\omega_e(t_f) = \omega_v(t_f)$
- No-Lurch condition (Glielmo SAE 2000): $\dot{\omega}_e(t_f) = \dot{\omega}_v(t_f)$



Synchronization & Comfort conditions

- Clutch Engagement: $\omega_e(t_f) = \omega_g(t_f)$
- No-Lurch condition (Glielmo SAE 2000): $\dot{\omega}_e(t_f) = \dot{\omega}_g(t_f)$
- Extended ideal synchronisation & comfort conditions:

$$\begin{array}{l} \omega_e(t_f) = \omega_g(t_f) = \omega_v(t_f) \\ \dot{\omega}_e(t_f) = \dot{\omega}_g(t_f) = \dot{\omega}_v(t_f) \end{array} \Rightarrow \begin{cases} z_1(t_f) = \omega_e - \omega_g = 0 \\ z_2(t_f) = \omega_g - \omega_v = 0 \\ z_3(t_f) = \theta = \frac{1}{k_t} \frac{J_v}{Je + J_g + J_v} \Gamma_e(t_f) \end{cases}$$



Optimal trajectory planning

Problem:

$$J = \frac{1}{2}\int_{t_0}^{t_f} \left[z^T Q z + u^T R u\right] \mathrm{d}t$$

Under:

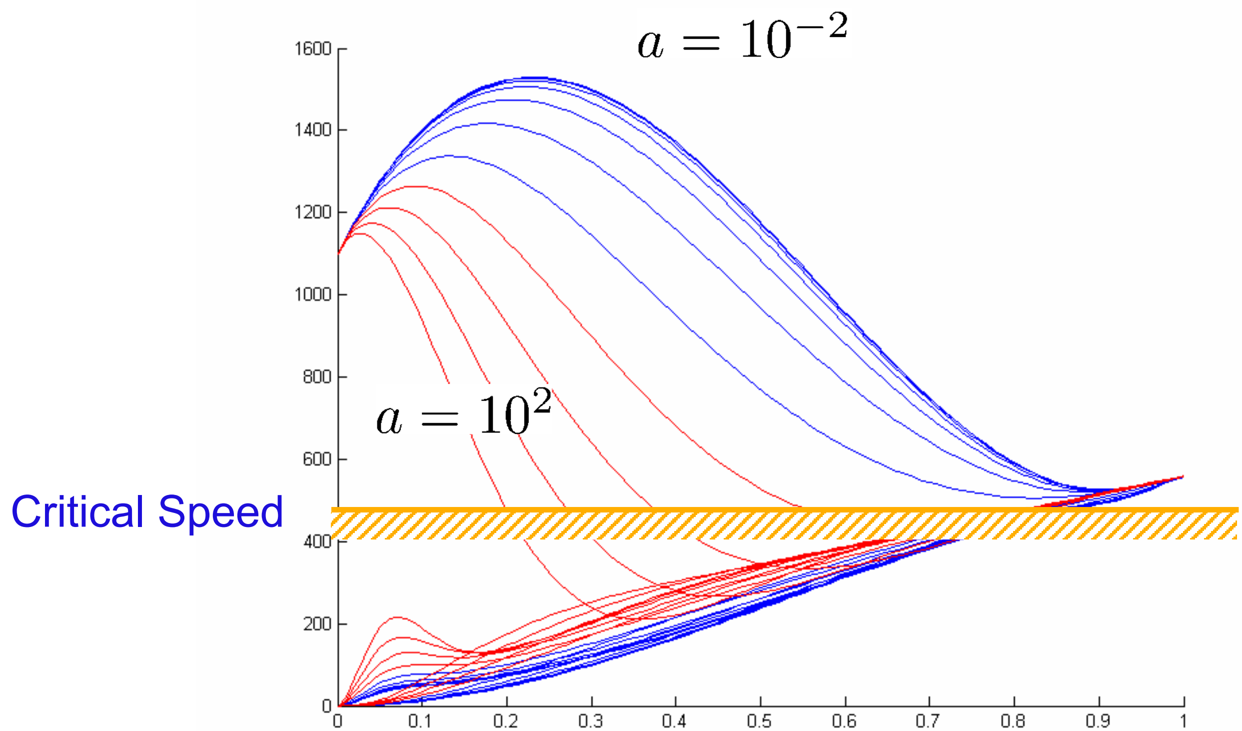
$$\begin{cases} \dot{z} = A_z z + B_{z1}\Gamma_e + B_{z2} u \\ z(0) = z_0 \\ z(t_f) = z_f \end{cases}$$

Analytic Solution: Under the hypothesis of constant Γ_e the TPBVP has an analytic solution $\lambda_0 = f(z_f, z_0, \Gamma_e)$

Energy Minimization: Embedded in the optimization problem via the weighting matrices

Weighting parameters choice ensuring Safety

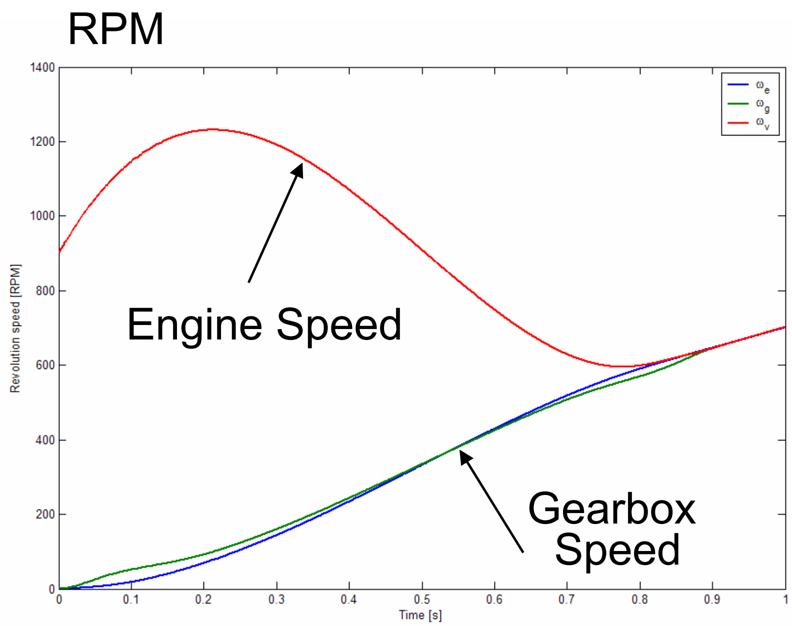
$$J = \int_{t_0}^{t_f} \left[a\left(\omega_e - \omega_g\right)^2 + b\left(\omega_g - \omega_v\right)^2 + u^2 \right] \mathrm{d}t$$



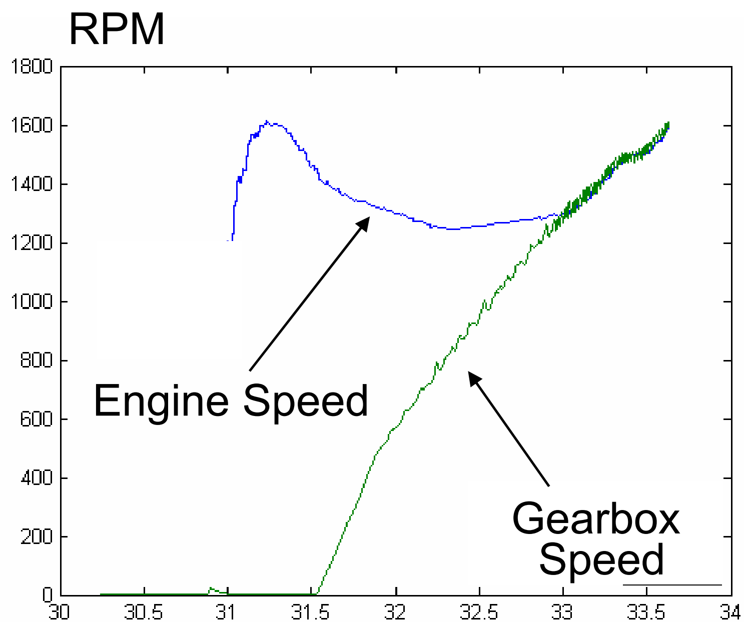
Engine Stall: A posteriori Search of Safe Trajectory as a function of the weighting matrices, i.e. $a \in [10^{-2}, 10^{2}]$

Results (Simulation & Experiments)

Standing start on a flat track



Simulations



Experiments

Results (Experimental setup)

Clio II AMT

1.5 dCi 85hp

equipped with dSpace

Tests performed on the track test at Renault Lardy Technical Centre

(South of Paris)

Nov. 2005

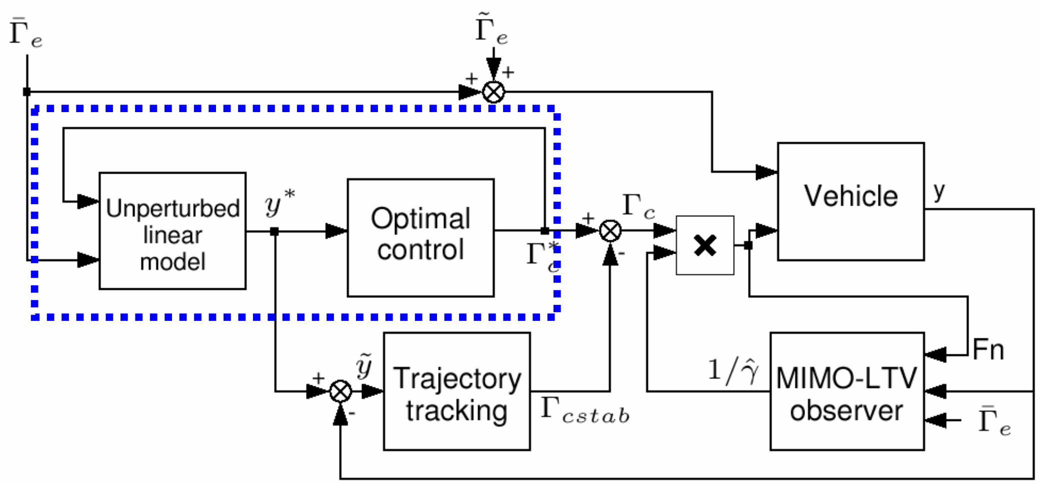
Experiments (Pietro in Action)

Italian Start

Starting with Optimal Control Inside

Issues:

- Oscillation reduction below the human perception threshold, $0.2m/s^2$
- Open-loop trajectories, implemented in closed-loop



- Clutch Friction estimation
- Applied to standing-start, but also useful for gear shifting
- Clutch Synchronization assistance (CbW)

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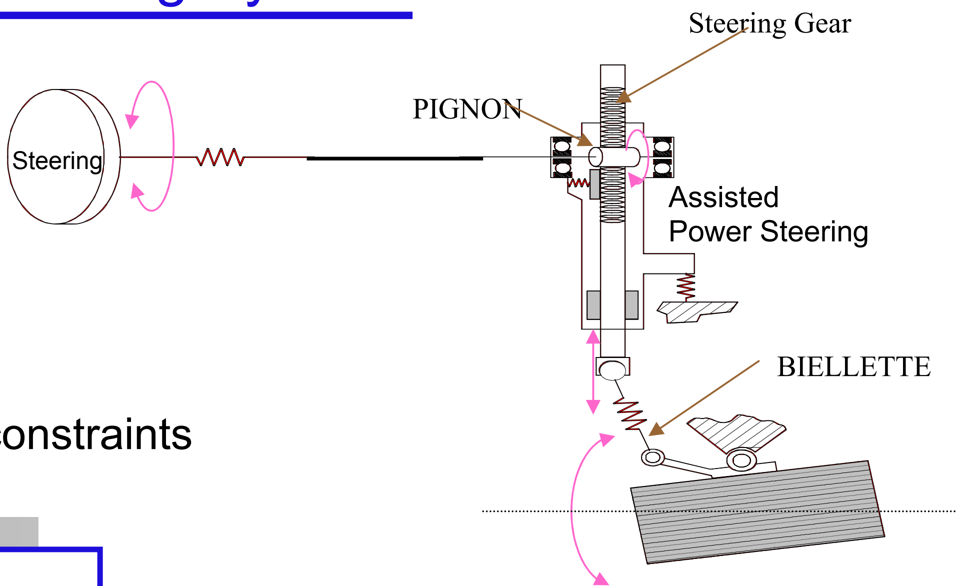
Trade-offs due to the introduction of Distinctive Features

Example: Advanced Power Steering System

- Variable force amplification
- Variable gear ratio
- Active safety systems
- Packaging and Environmental constraints



Electric actuators

Possible solutions :

- Hydraulic Power Steering + Electronic Pomp Assist
- Electric Power Steering
- Active Front Steering

Trade-offs due to the introduction of Distinctive Features

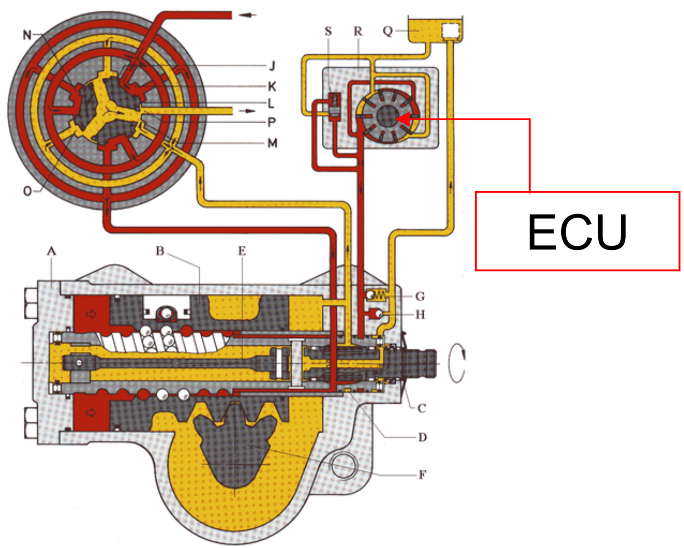
Solution 1: HPS + Electronic Pomp Assist

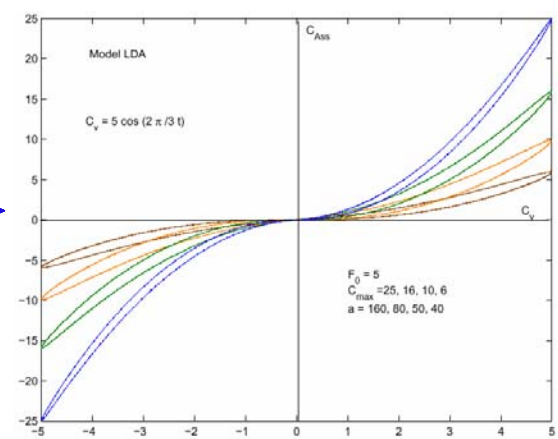
Side effects:

- Pomp assistance dimensioning and control
- Increase of effective volume
- Presence of fluid
- No control of steering angle

Constraints:

- Cost
- Constraint on power-train packaging
- Environmental
- Active safety “not” easy





Trade-offs due to the introduction of Distinctive Features

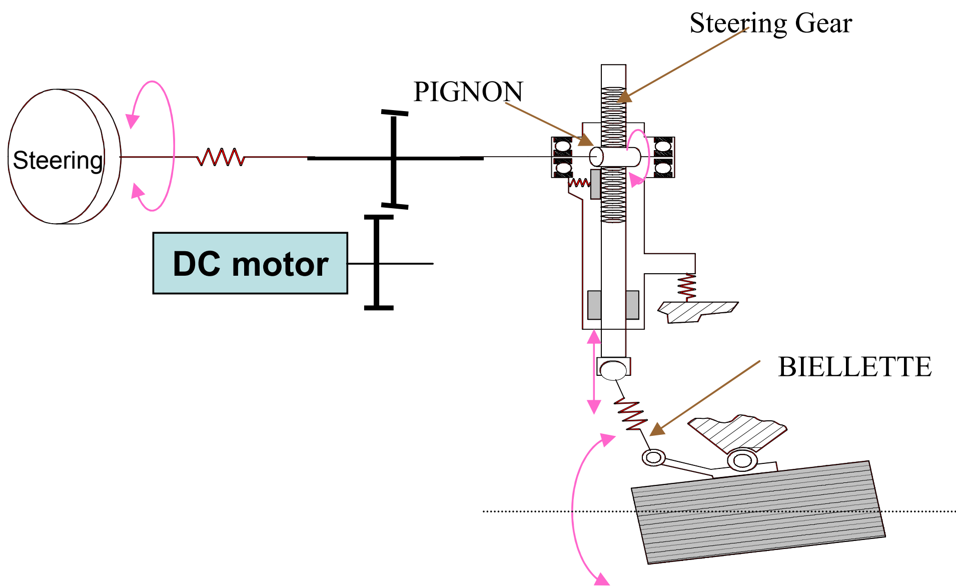
Solution 2: EPS

Side effects:

- Steering column
- Separate Torque Feedback (comfort) or Active Steering (Safety) are not possible

Constraints:

- Constraint on power-train packaging
- No optimal customer benefit



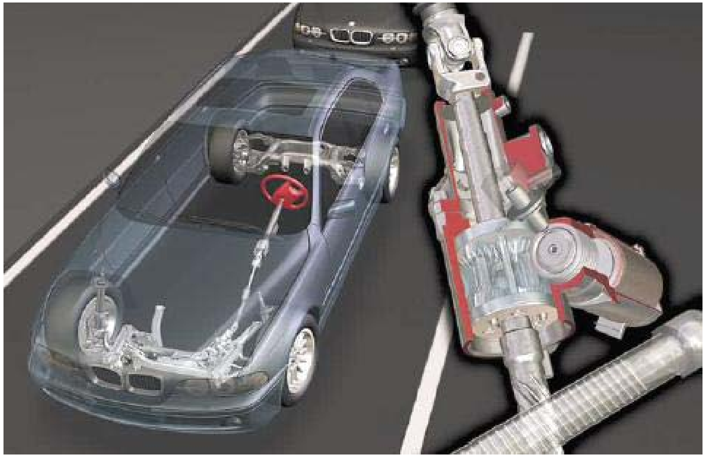
Solution 3: Active Front Steering (AFS)

Side effects:

- Increase of effective volume
- Passive or Active Torque Feedback and Active Safety possible

Constraints:

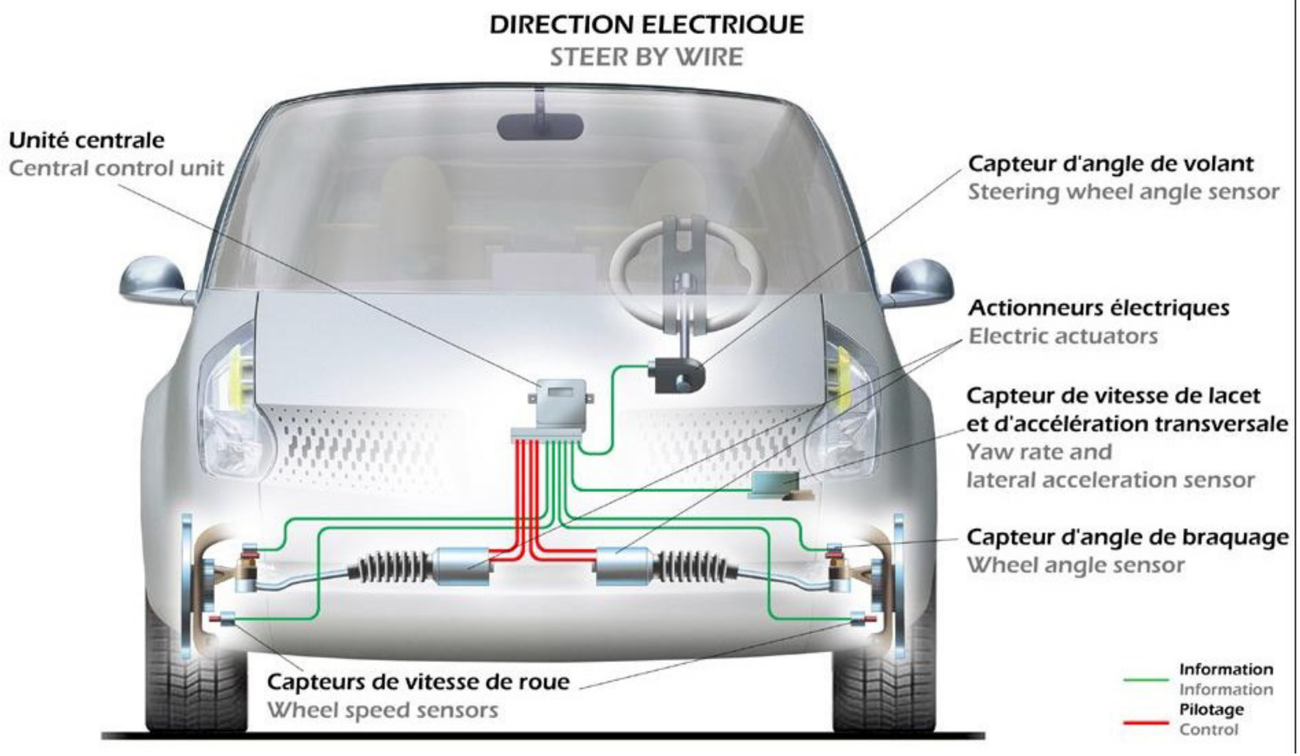
- Constraint on power-train packaging
- Trade off in customer features (comfort and active safety) and Cost



Breakthrough Solutions

- Integrate a force assistance and a steering devices
- Steer-by-wire System

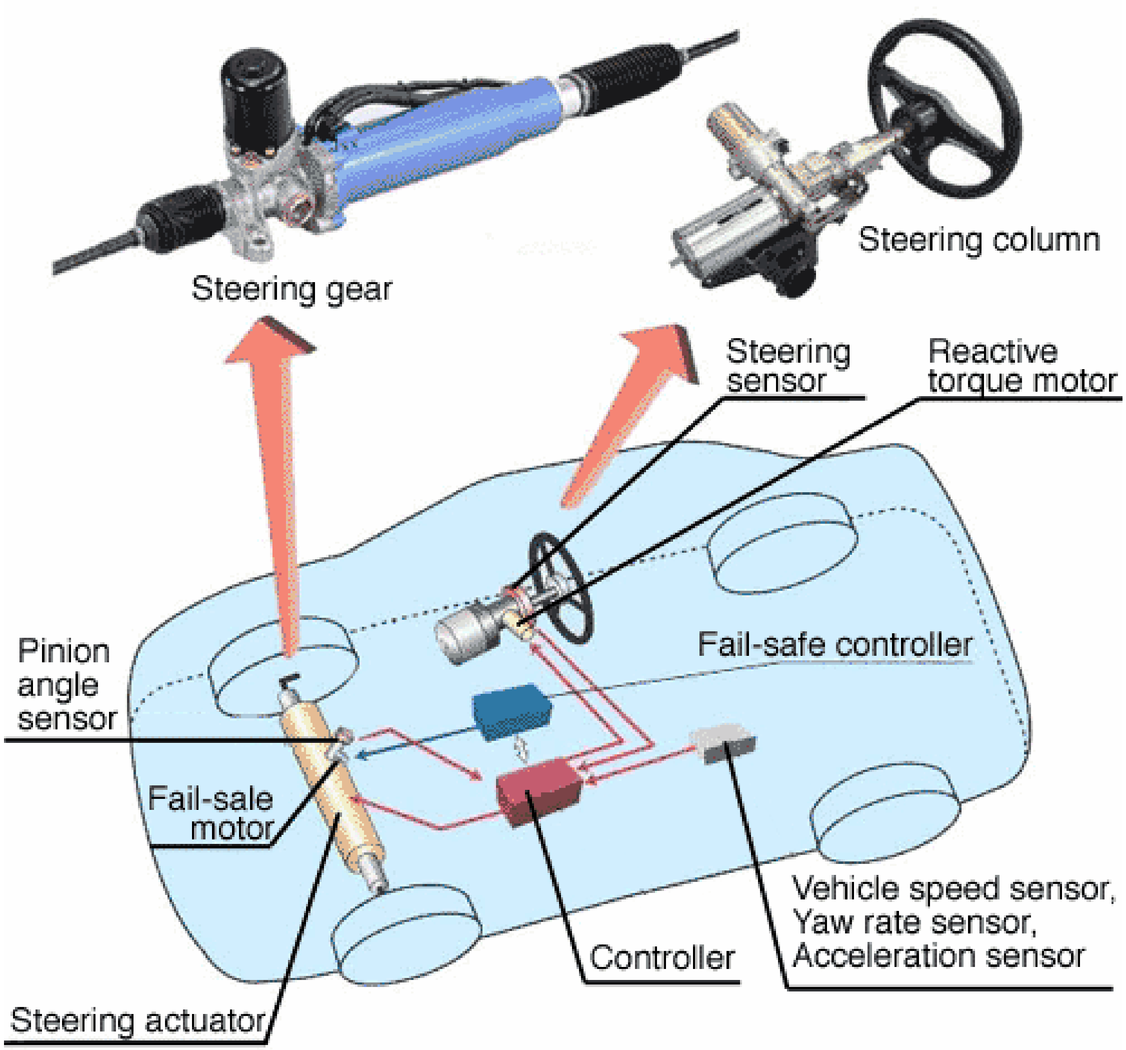
Steer-by-Wire: Benefits



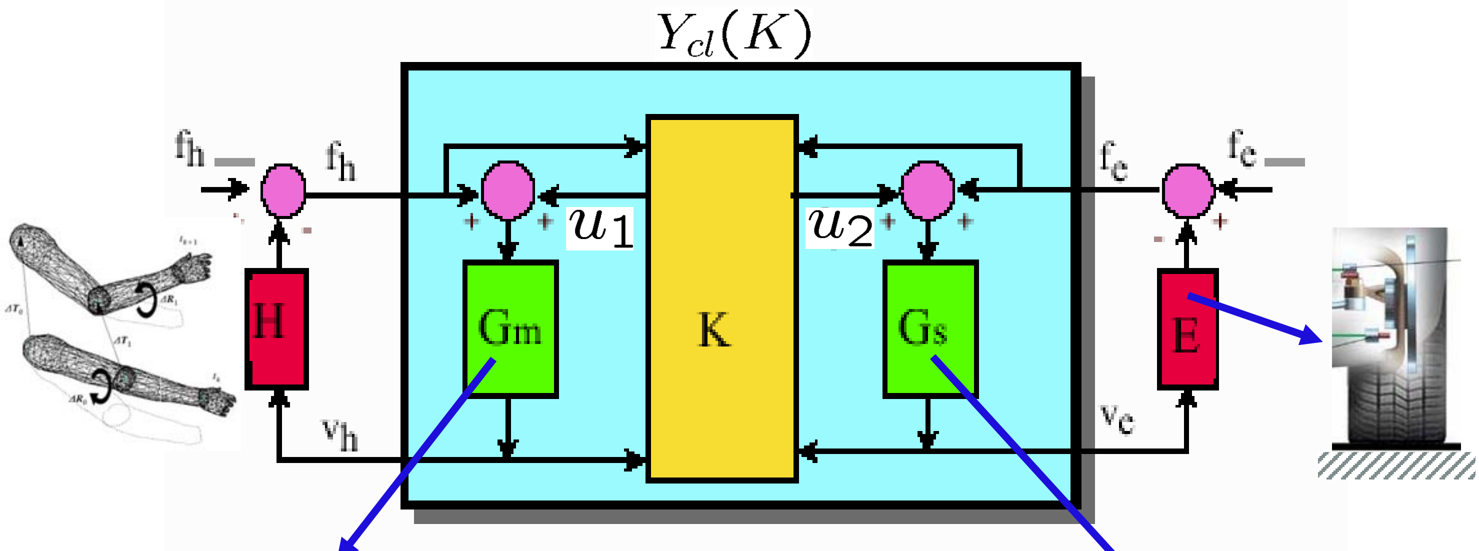
Steer-by-Wire benefits:

- Steering columns disappears
- Easy-to-package (left & right models)
- Improves active vehicle control

Steer-by-Wire: Technology



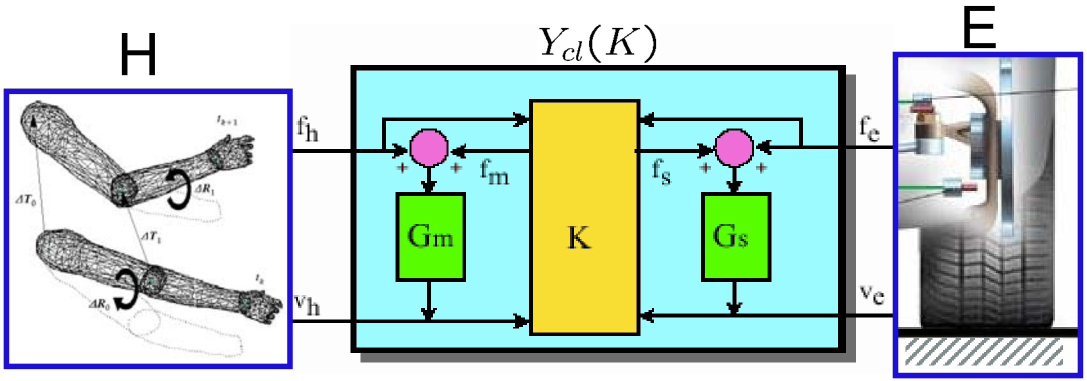
Steer-by-Wire: Control Set-up



Components:

- G_m: Steering column
- G_s: Steering gear
- H: Driver impedance
- E: Tire/road impedance
- K: Controller

Control Specs: Steering Comfort & Safety



- Comfort (Transparency): Ability of minimizing the extent to which the steer-by-wire system alters the sensation felt by the driver,
- Comfort (Steerability): Provide power amplification to the Steering wheel to make it easy to steer,
- Safety (Passivity): A passive system is inherently safer since it does not generate energy, but only stores, dissipates and releases it (Li & Horowitz 99).

Control Specs: Alternatives

Comfort (Transparence, Steerability):

- Separate Force/position scaling,
- Hybrid formulation: impedance/admittance shaping
  - Impedance $Z : v \mapsto F$
  - Admittance $Y : F \mapsto v$

$$\boxed{Z = Y^{-1}}$$

- Nonlinear maps

Safety (Passivity):

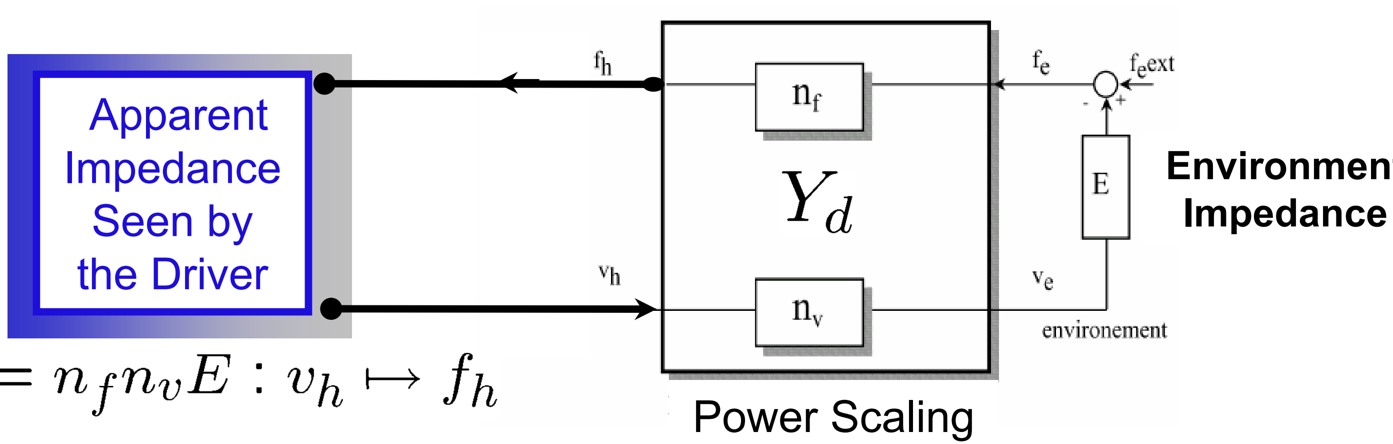
- Bilateral/Unilateral
- Coupled/Uncoupled

Control alternatives:

- Exact Matching
- Approximate matching (Multi-criteria optimization)

Idealizing Comfort: Power Scaling

Separate Force/Position Scaling



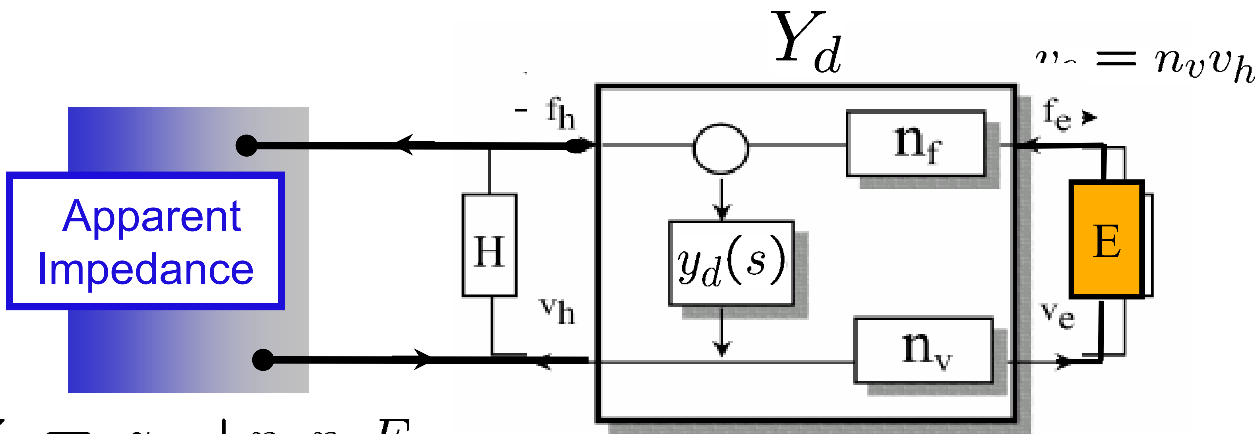
$$Z_a = n_f n_v E : v_h \mapsto f_h$$

$$\boxed{\underbrace{v_e f_e}_{P_e} = \left(\frac{n_v}{n_f}\right) \underbrace{v_h f_h}_{P_h}}$$

$$\begin{bmatrix} v_h \\ f_e \end{bmatrix} = \begin{bmatrix} 0 & n_v \\ n_f & 0 \end{bmatrix} \begin{bmatrix} f_h \\ v_e \end{bmatrix}$$

Power Scaling

Hybrid Force/Position Specs



$$Z_a = \underbrace{z_d}_{y_d^{-1}} + n_f n_v E$$

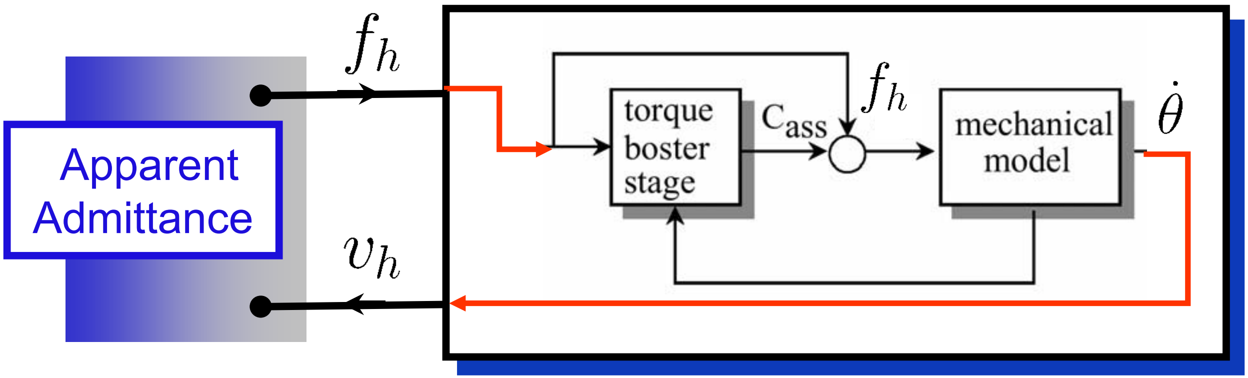
Equivalent Admittance model
Impedance model

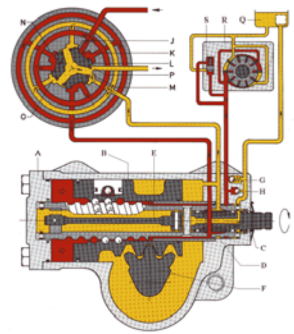
Admittance Representation

$$\begin{bmatrix} v_h \\ v_e \end{bmatrix} = \underbrace{y_d(s) \begin{bmatrix} 1 & n_f \\ n_f & n_f n_v \end{bmatrix}}_{Y_d(s)} \begin{bmatrix} f_h \\ f_e \end{bmatrix}$$

$$P_e = \frac{n_v}{n_f} \left[P_h - v_h^2 z_d \right]$$

Two-Stage model from physics laws (structure)





Driver-perceived performance:

- Auto-alignment torque, (virtual, or true)
- Steering wheel friction
- Torque amplification (booster stage)
- Hydraulic-like behavior
- Speed vehicle dependency

$$J(v)\ddot{\theta} + K_v(v)\dot{\theta} = -C_r(v,\theta,f_e) - C_f(v,\dot{\theta}) + f_h + C_{ass}$$

Mechanics

$$\chi(C_{ass}) = -aC_{ass} - b\sqrt{|C_{ass}|}\dot{\theta} + c(\sqrt{|C_{ass}|+\epsilon})f_h$$

$$\dot{C}_{ass} = \begin{cases} \chi(C_{ass}) & \text{if} \quad |C_{ass}| \le C_{max} \\ 0 & \text{else} \end{cases}$$

Torque booster

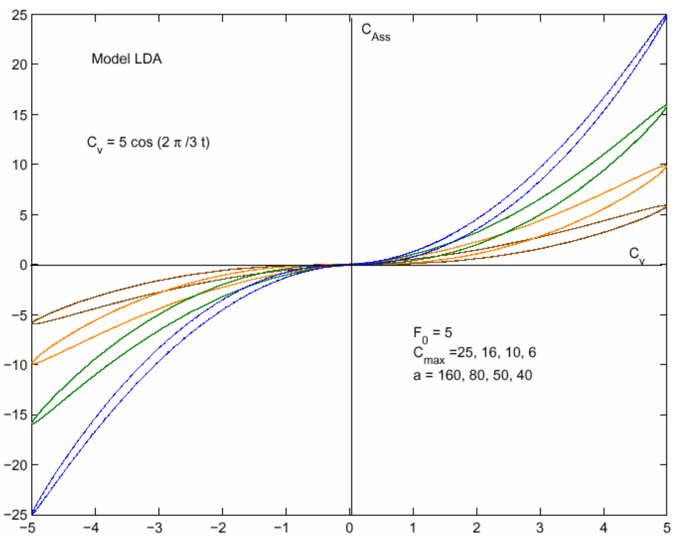
Subjective Parameters Assessment

Torque booster stage

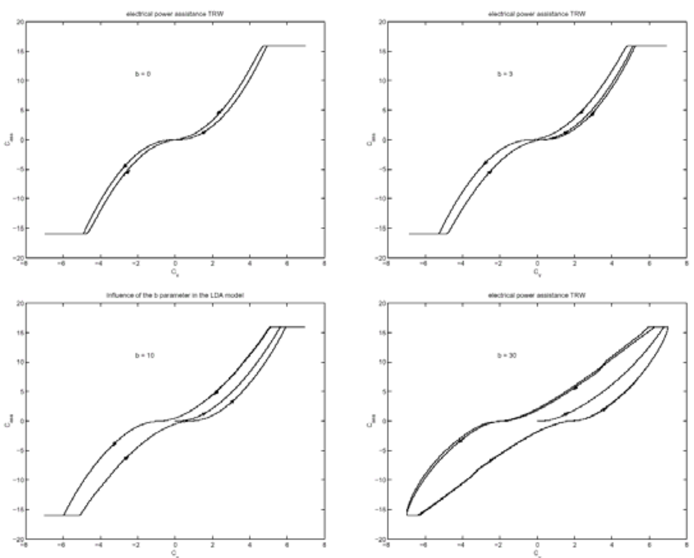
$$\dot{C}_{ass} = \begin{cases} \chi(C_{ass}) & \text{if} \quad |C_{ass}| \leq C_{max} \\ 0 & \text{else} \end{cases}$$

$$\chi(C_{ass}) = -aC_{ass} - b\sqrt{|C_{ass}|}\dot{\theta} + c(\sqrt{|C_{ass}| + \epsilon}) f_h$$

- a-fastness
- b-softness/hardness (flow leakage)
- c-amplification
- C_{max}-Saturation



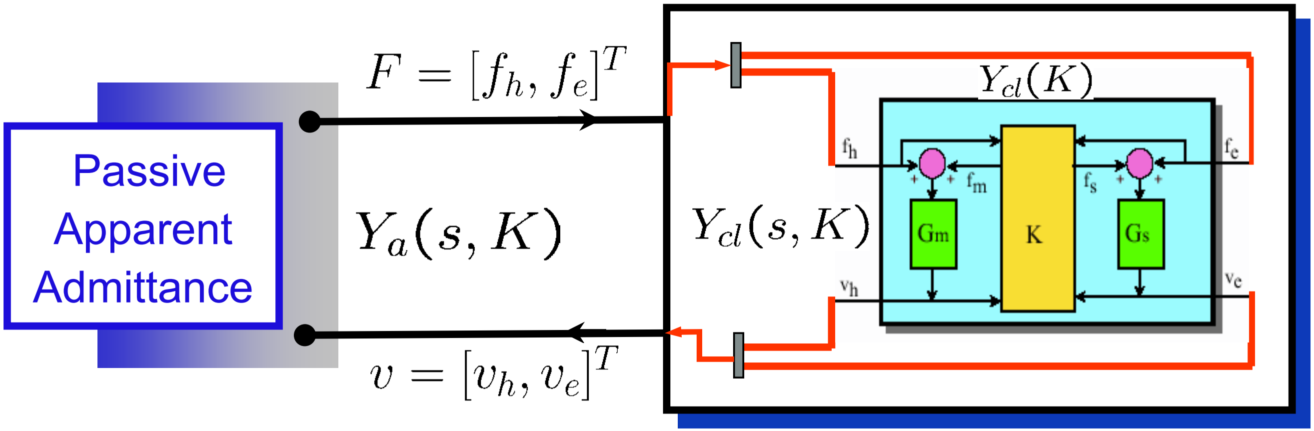
c=f(a, Cmax)-dependency



b-dependency

Uncoupled (Bilateral) Passivity

$$Y_a(s,K) = Y_{cl}(s,K) : F \mapsto v$$



$$\boxed{\int_{t_0}^{t} F(\tau)^T v(\tau) d\tau \geq -\beta}$$

PROs:

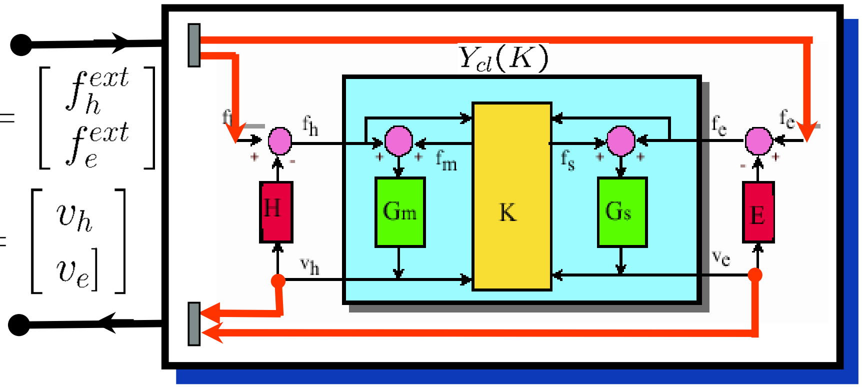
- « very » safe
- Allows connection with non-passive environments

CONs:

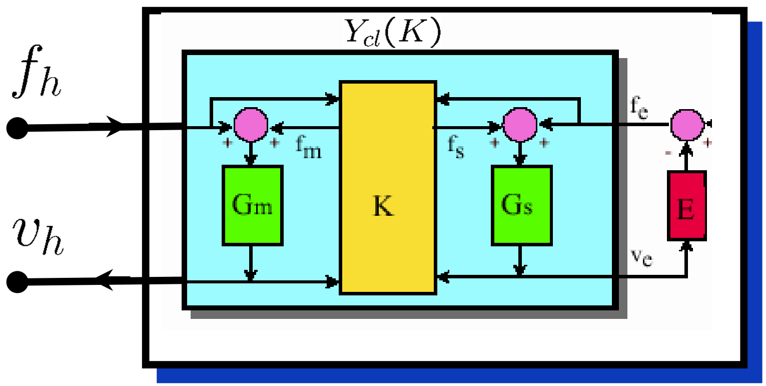
- Conservative design
- Power amplification forbidden

Coupled Bilateral Passivity $Y_a(s, K) : F_{ext} \mapsto v$

$$F_{ext} = \begin{bmatrix} f_h^{ext} \\ f_e^{ext} \end{bmatrix} \qquad v = \begin{bmatrix} v_h \\ v_e \end{bmatrix}$$



Coupled Unilateral Passivity



$Y_a(s, K) : F_h \mapsto v_h$

PROs:
- Less conservative

CONs:
- Knowledge of : E, H

Control Problem: Exact Matching (Linear setting)

PROBLEM: find K(s) such that

- Exact idealized comfort is meet,

$$\boxed{Y_{cl}(s,K) \equiv Y_d(s)}$$

- The closed-loop apparent admittance results in one of the selected passivity constraints:

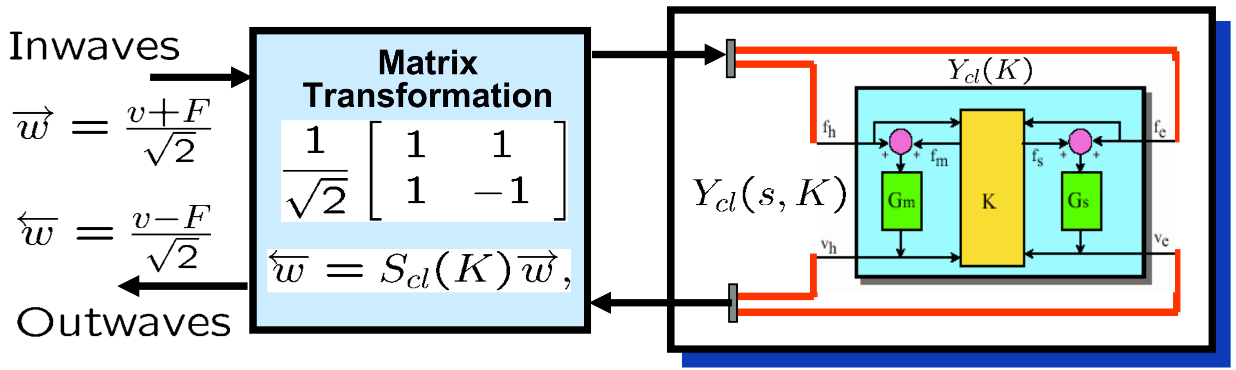
$$\boxed{[Y_a(j\omega,K) + Y_a^*(j\omega,K)] > 0}$$

  - Uncoupled bilateral passivity $Y_a = Y_{cl}$
  - Coupled bilateral passivity $Y_a \neq Y_{cl}$
  - Coupled unilateral passivity $Y_a \neq Y_{cl}$

- Limitations: Solutions may not always exist.
- Relaxation of this problem via optimization

Control Problem: Approximated Matching (Linear setting)

Problem 1: Uncoupled bilateral passivity



$$\min_K \|[Y_{cl}(K) - Y_d\|_\infty$$

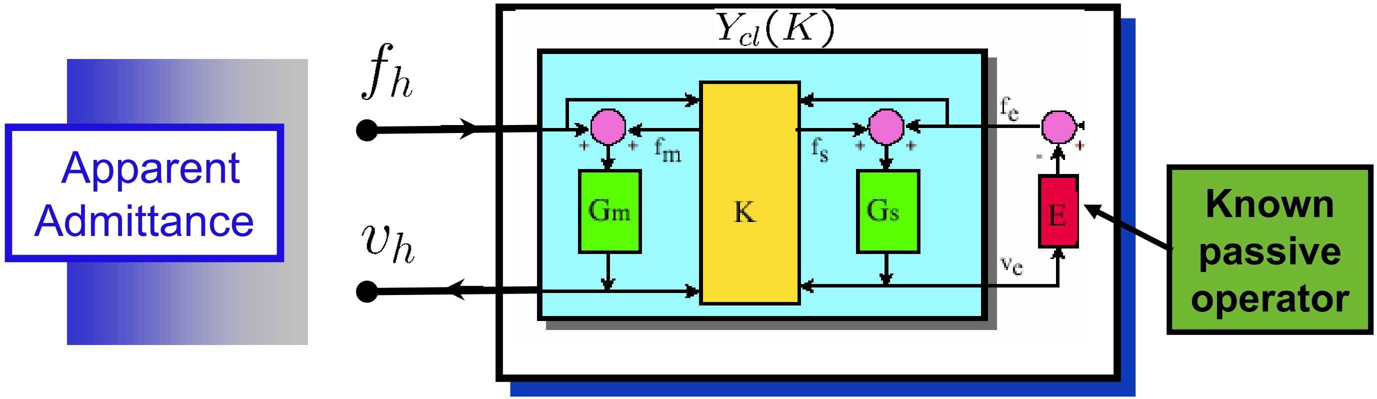
$$under \quad \sup_w \inf_{\beta>0} \sigma_{max}\left(\begin{bmatrix} s_{11} & \beta s_{12} \\ \frac{1}{\beta} s_{21} & s_{22} \end{bmatrix}\right) \leq 1$$

s_{ij} are the elements of $S_{cl}(K) = (Y_{cl}(K) - I)(Y_{cl}(K) + I)^{-1}$

Non Convex Optimization Problem

Control Problem: Approximated Matching (Linear setting)

Problem 2: Coupled unilateral passivity



$$Y_a(s, K) : f_h \mapsto v_h$$

$$Y_{cl}(s, K) : F \mapsto v$$

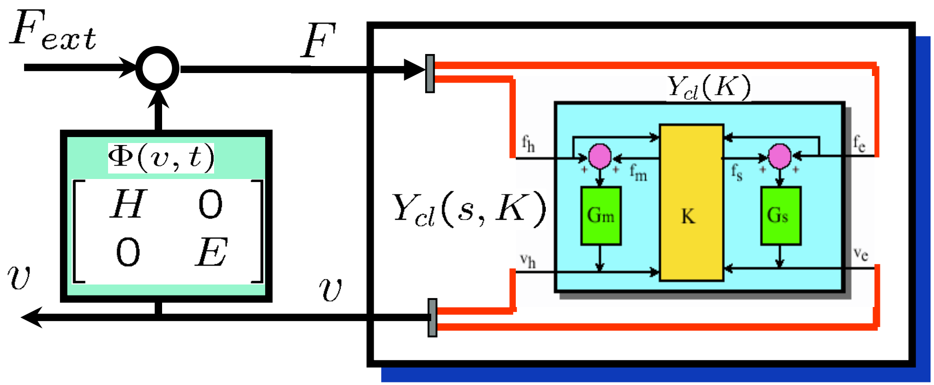
$$\min_K \|Y_{cl}(K) - Y_d\|_\infty$$

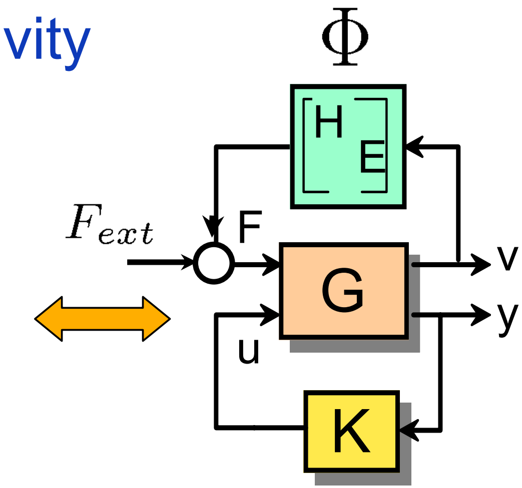
$$under: \quad \inf_w \{\mathrm{Re}\,[Y_a(K)(j\omega)]\} \geq 0$$

Convex Optimization Problem

Control Problem: Approximated Matching (Robustness)

Problem 3: Coupled Bilateral passivity





$\Phi(v,t)$ is a sector bounded nonlinearity,

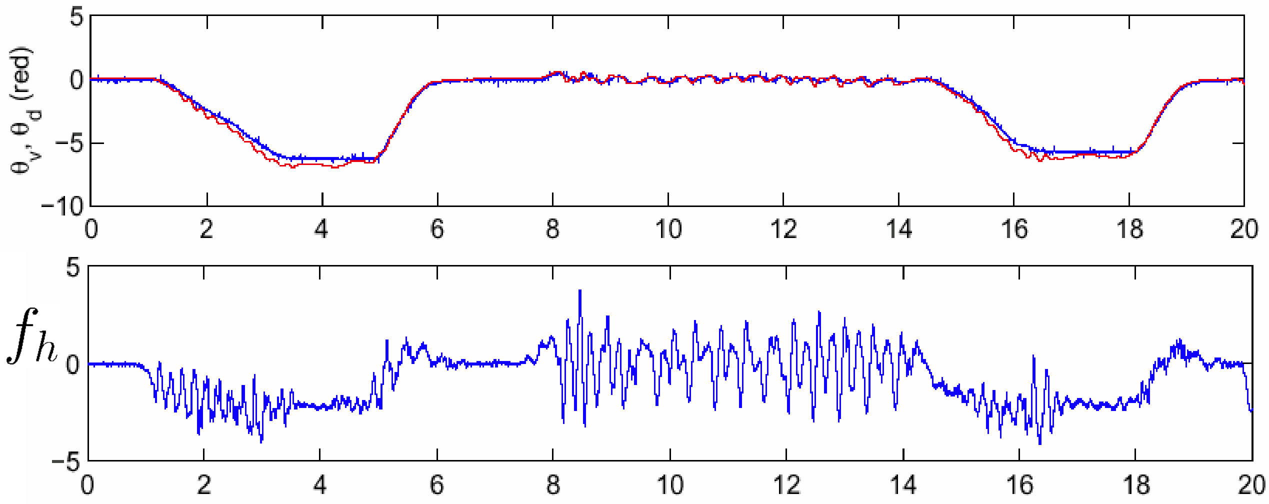
$$(\Phi(v,t) - Q_1 v)^T (\Phi(v,t) - Q_2 v) \leq 0, \qquad Q_2 > Q_1 > 0.$$

$$\min_K \| [Y_{cl}(K) - Y_d \|_\infty$$

$$under: \quad [I + Q_2 Y_{cl}(K, j\omega)] \, [I + Q_1 Y_{cl}(K, j\omega)]^{-1}, SPR$$

Convex Multi-criteria Optimization Problem

Summarizing



Linear setting:

- Model matching (Exact or approximate) is tractable,
- Control Specs are somewhat limited

Nonlinear setting:

- Richest specifications
- Exact Model matching may not be tractable:
  - **Real system dimension higher than model**
- Approximated Model matching (non linear optimization):

Outline

1. Introduction

- Challenges
- Product Evolution
- Breakthroughs

2. Examples

- Clutch Synchronization
- Steer-by-Wire
- **Adaptive Cruise Control**

3. Conclusions

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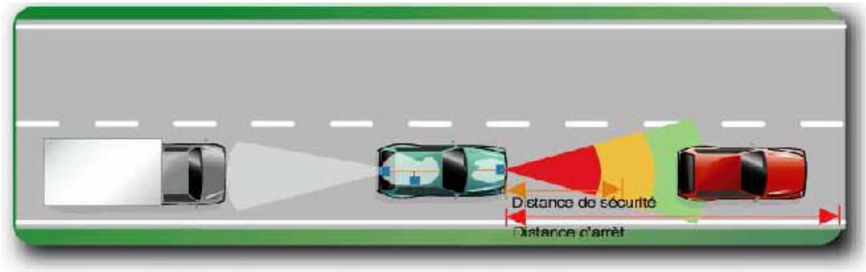
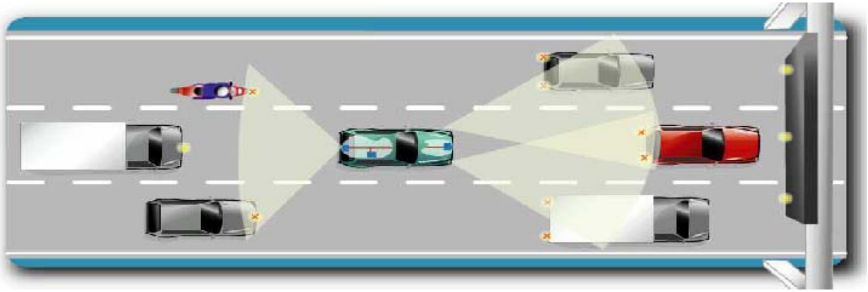
ACC: 3-Levels of Complexity

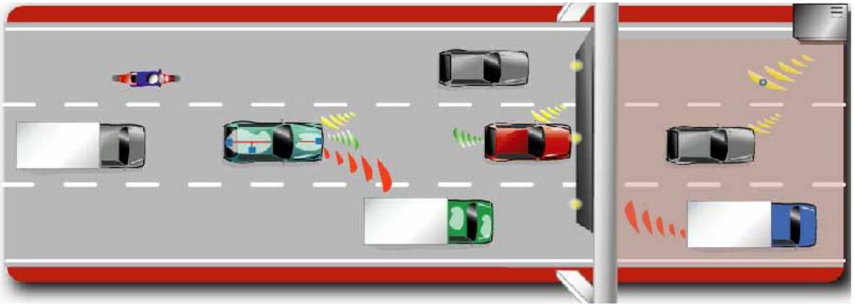
- Front/Rear longitudinal inter-vehicular control



- + Multi-lane control



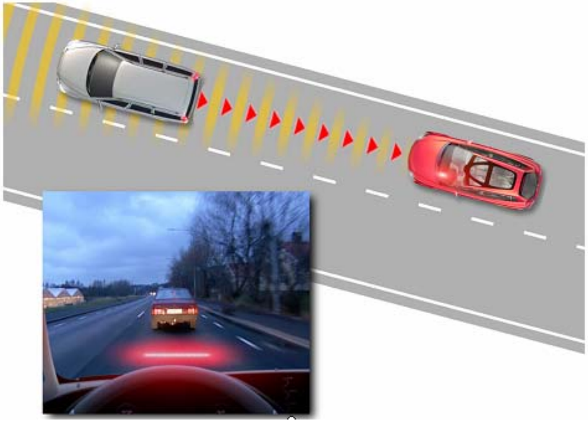
- + infrastructure exchange of information & collaborative control.



Some Data

The French National Observatory of Road Security has reported 90220 car accidents during the year 2003.

28% correspond to accidents resulting in rear-end collisions:



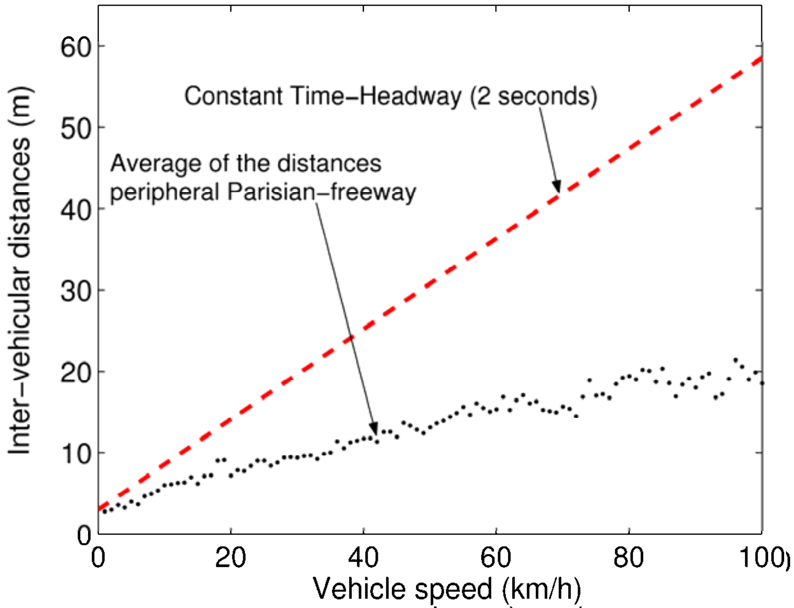
Causes of accidents:

- Misestimated vehicular inter-distance
- Badly adapted or insufficient braking
- Approaching speed too high
- Erroneous estimation of the road conditions

Statistics:

- 55 % Drivers do not respect the minimum 2 sec « safety time »
- 25% Drivers do not respect the minimum 50 m « safety distance »

Example of « safety distance »: Constant Time-Headway rule



- Newtonian motion equation
- Stationary solution

Relative braking distance

Reaction time distance

$$\boxed{d_{safe} = \cancel{\lambda_1({v_f}^2 - {v_l}^2)} + \lambda_2 v_f + \lambda_3}$$

Threshold distance

- *Constant* and *similar* braking capacity for both vehicles
- Does not account for any comfort criteria.

Typical Safety & Comfort Specs

Safety:

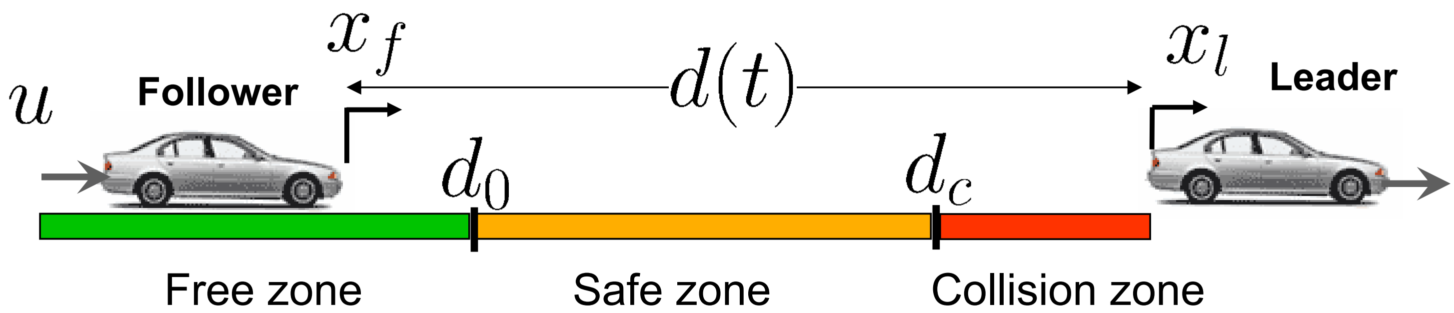
- Constant time headway (Chien and Ioannou, 1992),
- Variable time headway (Yanakiev and Kanellakopoulos, 1995),
- Potential forces (Gerdes et. al., 2001).

Comfort:

- Driver's behavior model (Persson et. al., 1999),
- Human perception-based model (Fancher, et. al. 2001),
- Design of braking and jerk's profiles (Yi & Chung, 2001).

New Specs Combining Safety & Comfort are needed

Inter-distance Vehicle Policy

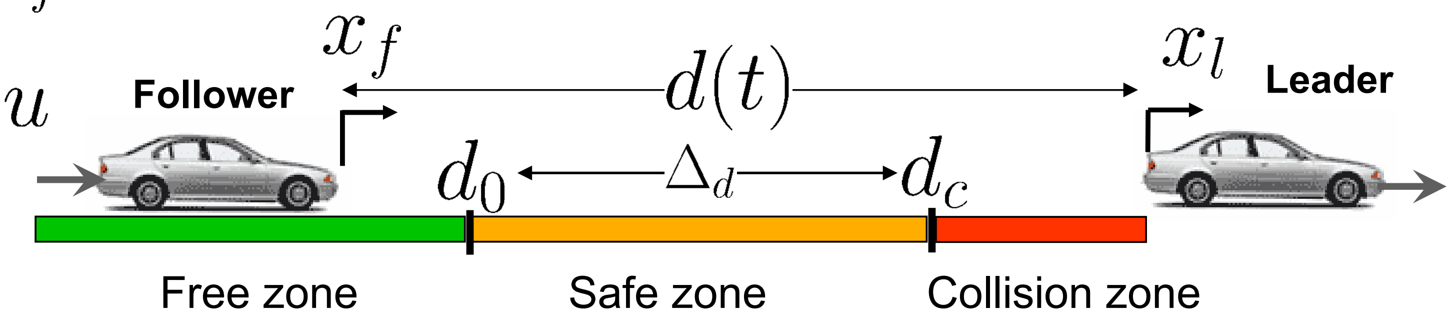


Desired Properties:

- Avoid collisions (safety)
- Limit Jerk (comfort)
- Respect Braking Capabilities

Inter-distance Vehicle Policy—cont.

$$\ddot{x}_f = u$$



Given:

- Maximum velocity, deceleration & Jerk:

$$|v_f| \leq V_{max}$$
$$|\dot{v}_f| \leq B_{max}$$
$$|\ddot{v}_f| \leq J_{max}$$

- Minimum inter-distance d_c

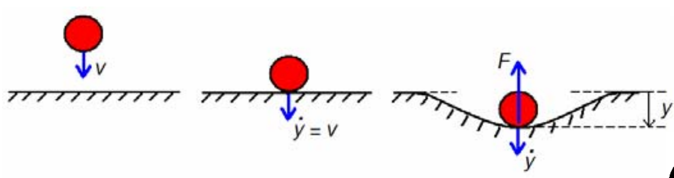
Design goals:

- Define the Safe zone Δ_d
- Made the orange zone invariant
- Respecting the velocity, deceleration & jerk constraints

Inspiration from Compliant Contact Models

Genesis:

- Hertz 1881
- Marhefka & Orin, 1996

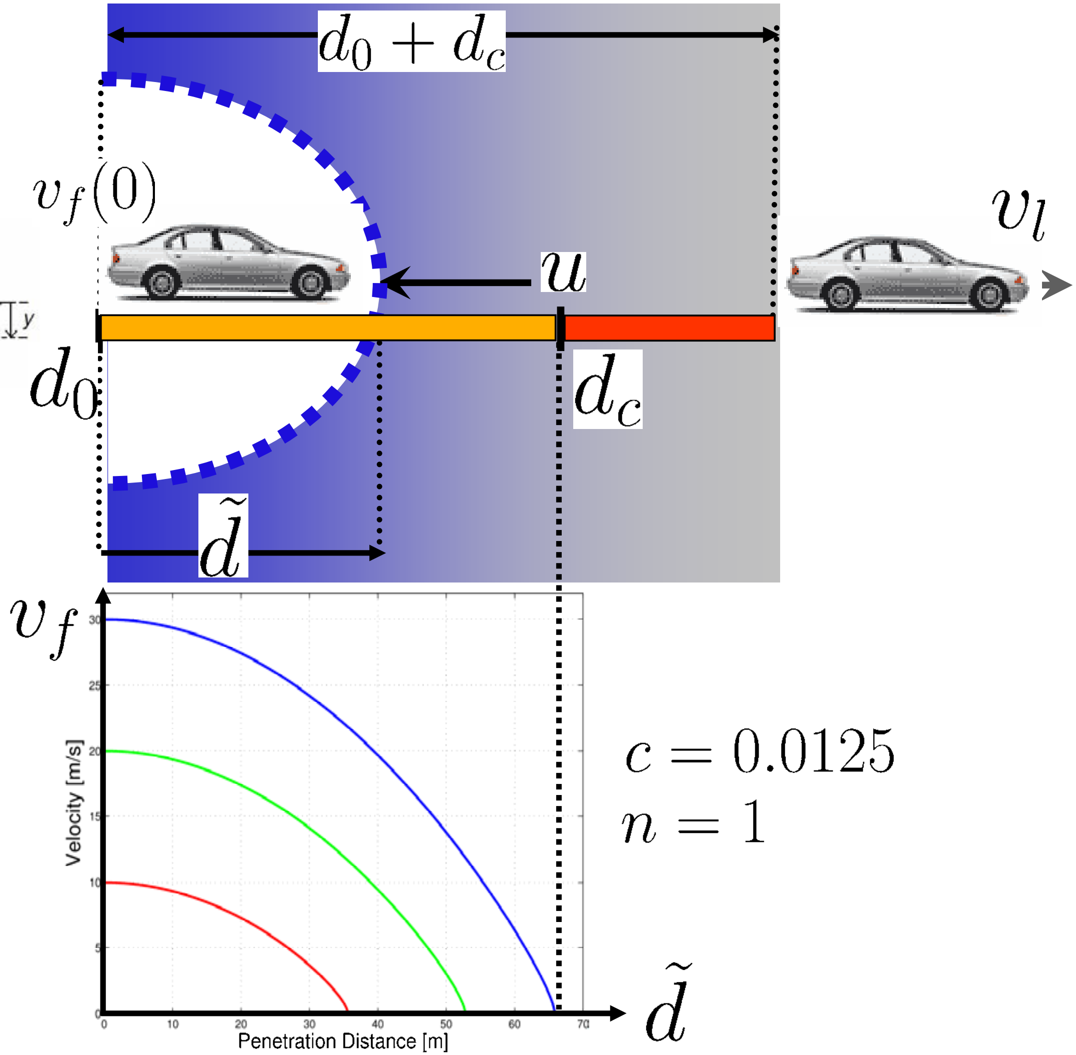


- Nonlinear damping

$$u = -c|\tilde{d}|^n \dot{\tilde{d}}$$

- Integral curves of

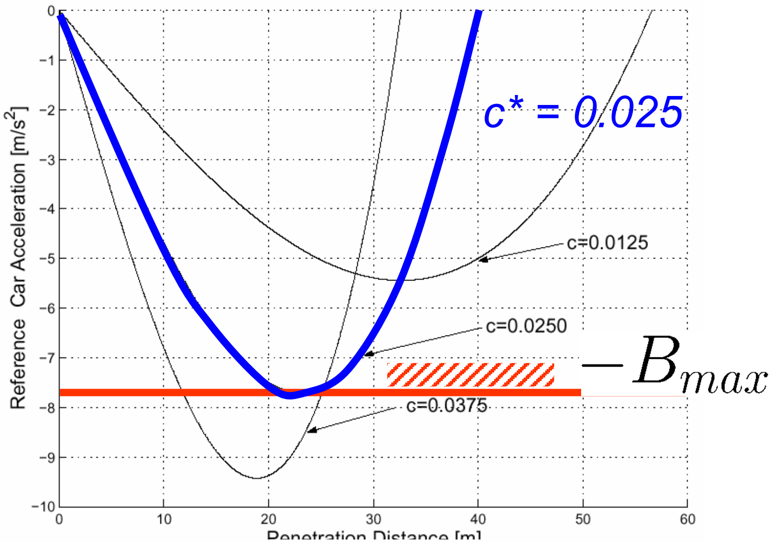
$$\partial v_f = -c|\tilde{d}|^n \partial \tilde{d}$$

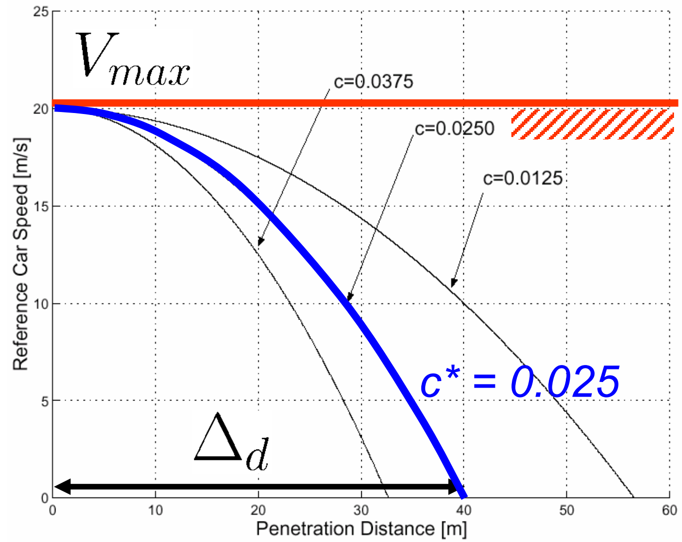


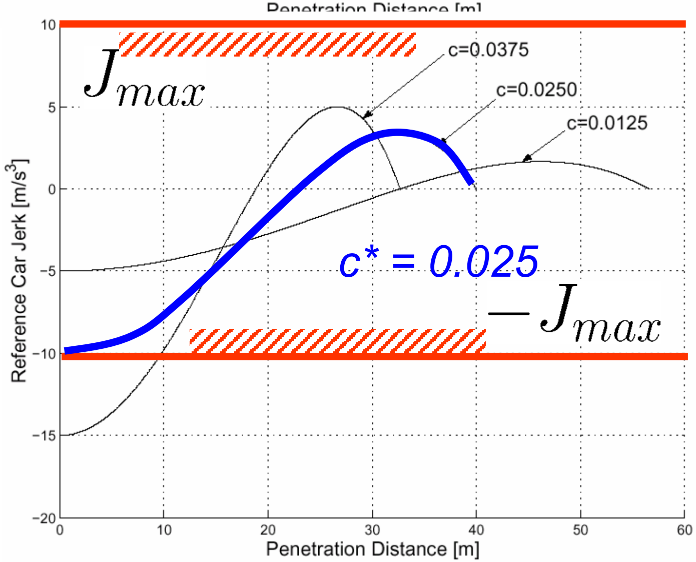
$c = 0.0125$

$n = 1$

Problem Formulation



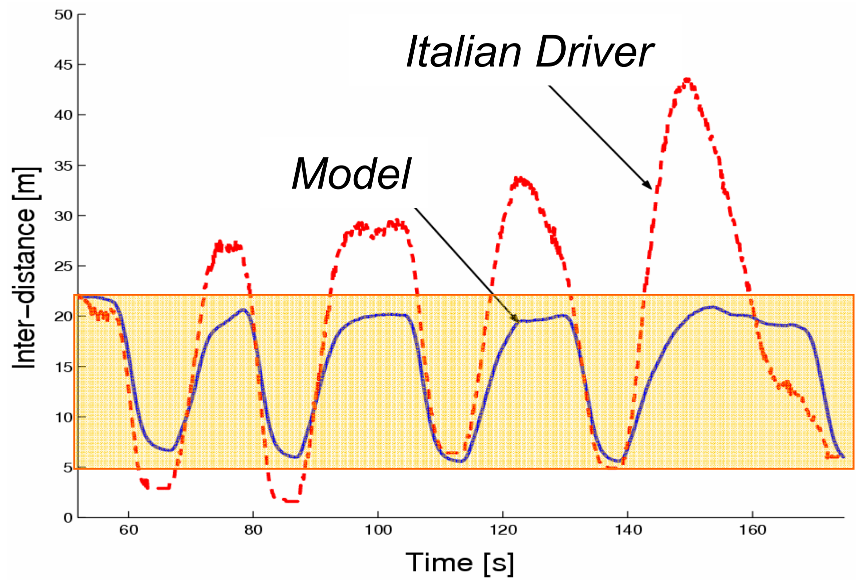


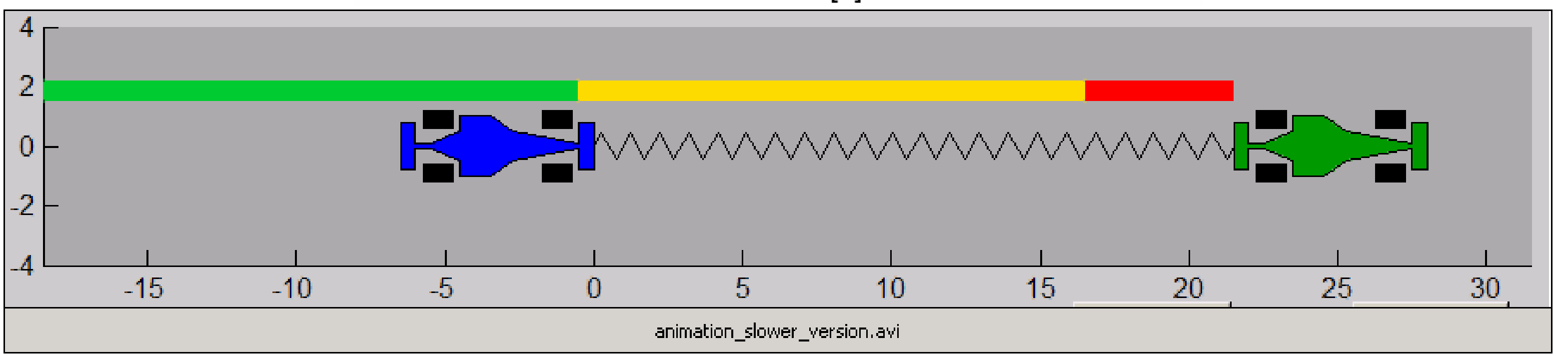


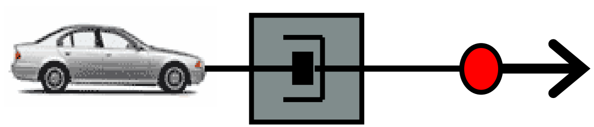
$$c^* = \min_{c>0} |\Delta_d(c)|,$$

$$under: \quad \begin{array}{l} |v_f| \leq V_{max} \\ |\dot{v}_f| \leq B_{max} \\ |\ddot{v}_f| \leq J_{max} \end{array}$$

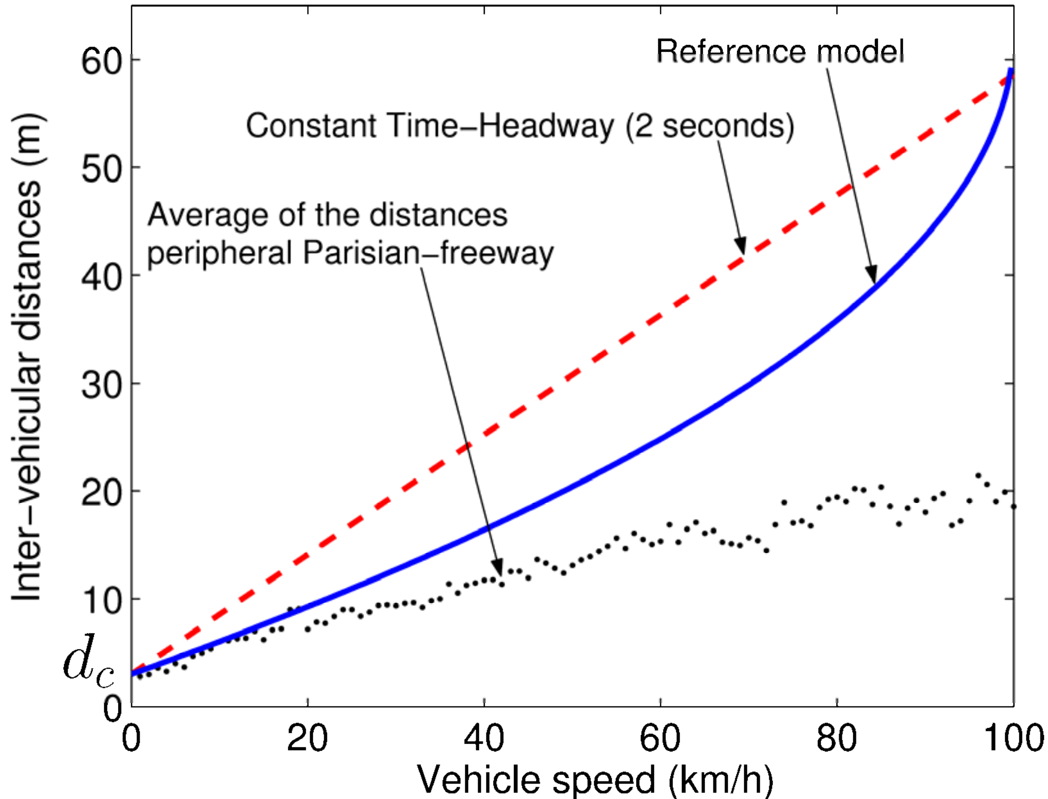
Stop & Go Scenario







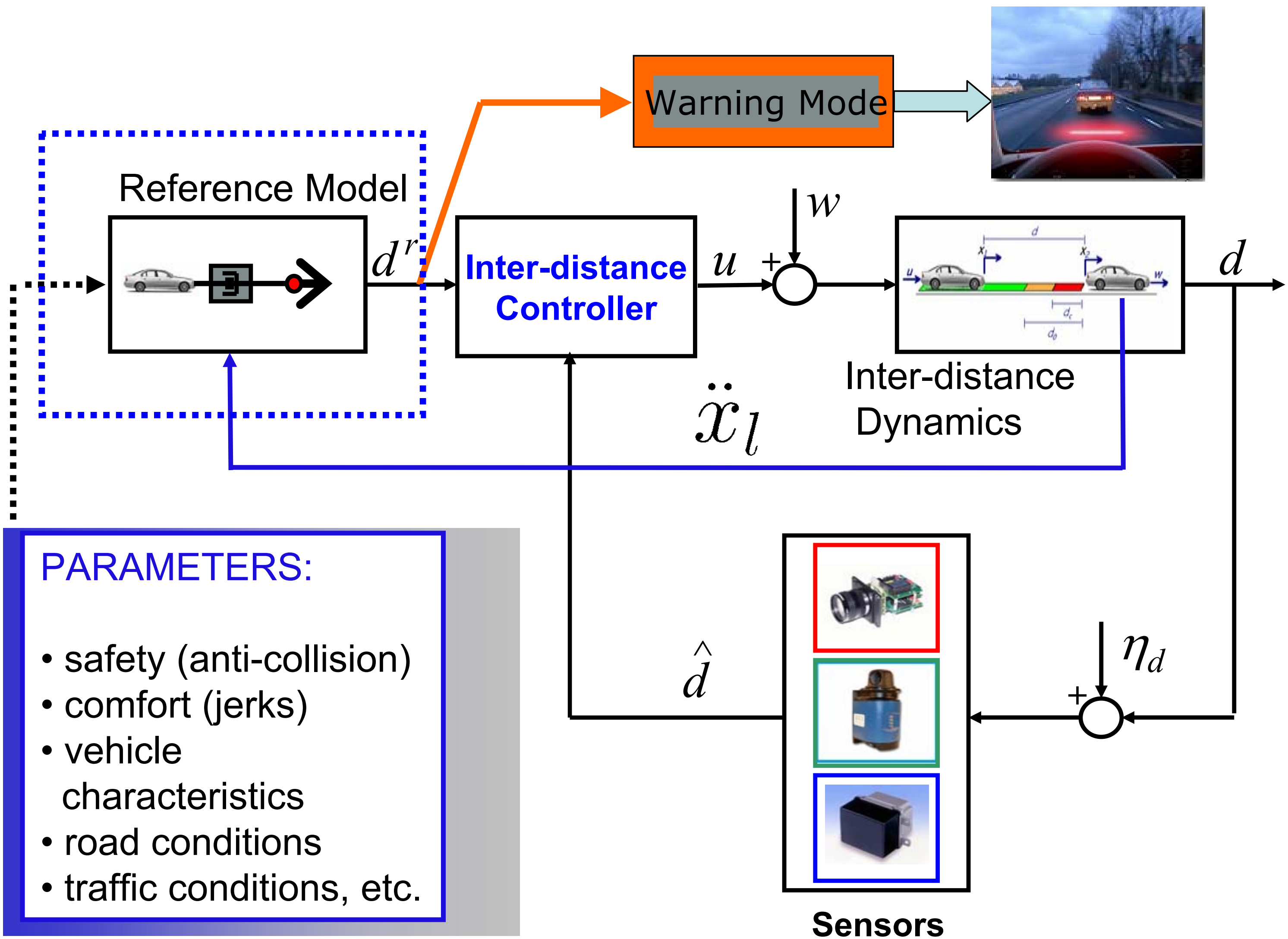
Comparison with the constant time-headway policy



Advantages:

- Less conservative safe distance
- Better matches the drivers' average inter-vehicular distance at low velocities.

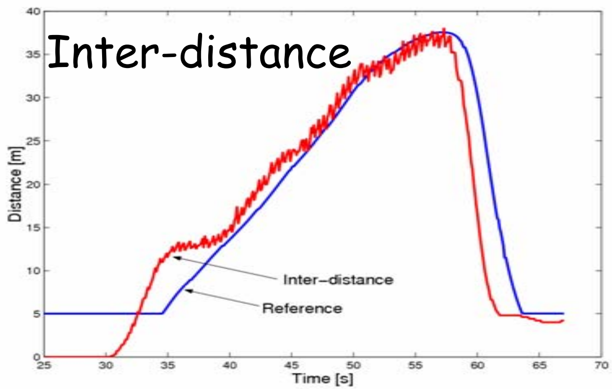
Control Scheme: Model Tracking

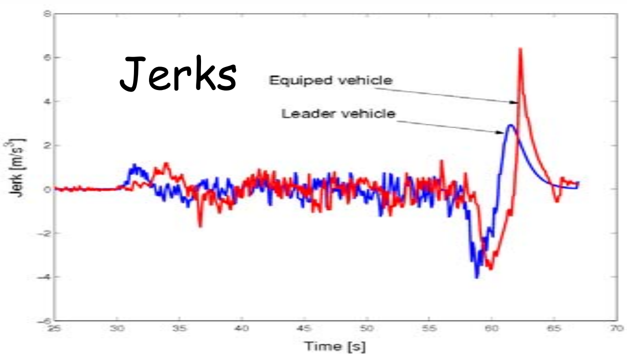


PARAMETERS:

- safety (anti-collision)
- comfort (jerks)
- vehicle characteristics
- road conditions
- traffic conditions, etc.

Experimental Results:
Hard stop (ARCOS-Program)





Test Track : Satory (France).

Vehicle : LOLA (LIVIC-LCPC-INRETS)

Thanks to : Axel Von-arnim (LCPC) & Cyril Royére (LIVIC)

Summarizing

Nonlinear dampers:

- More flexibility (integral curve shapes)
- Continuous acceleration & Jerks (comfort assessment)

On-line adaptability:

- Road & traffic conditions

Model is not a true exosystem:

- Model is driven by leader vehicle acceleration,
- Provides bounded solutions (integral curves)

Warning mode:

- Use the model to provide driver assistance only

Switching Controllers are welcomed:

- Switching between different sensors.

Conclusions

- More and more applications with subjective Specs
- Complexity limits reached.
- Industry needs:
  - *further tools and unified views for relating subjective & control specs*
  - *tools and general views for components integration, i.e. all-by-wire*

Aiming at...

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