Self-Tuning Control Strategy for Antilock Braking Systems

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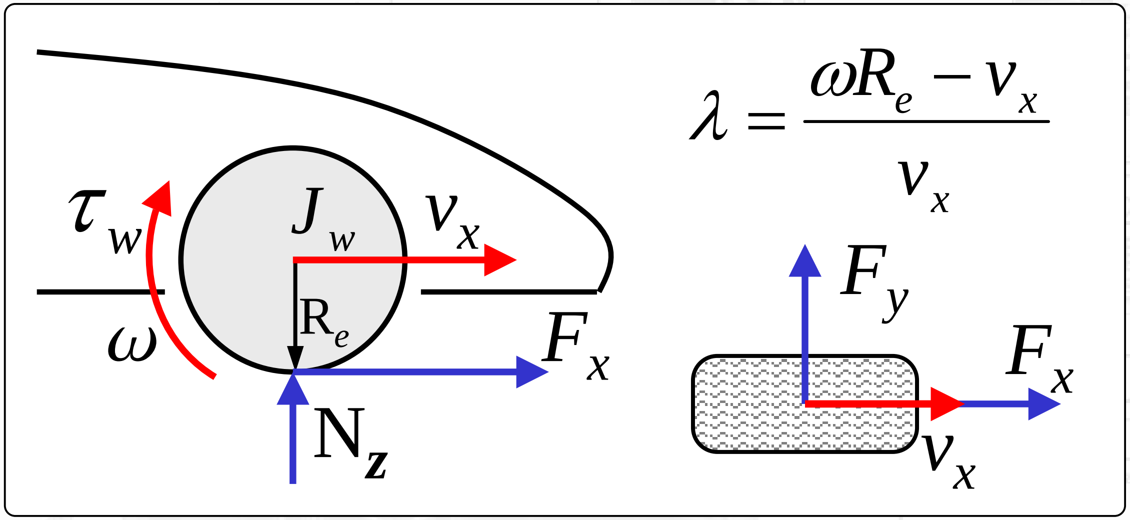
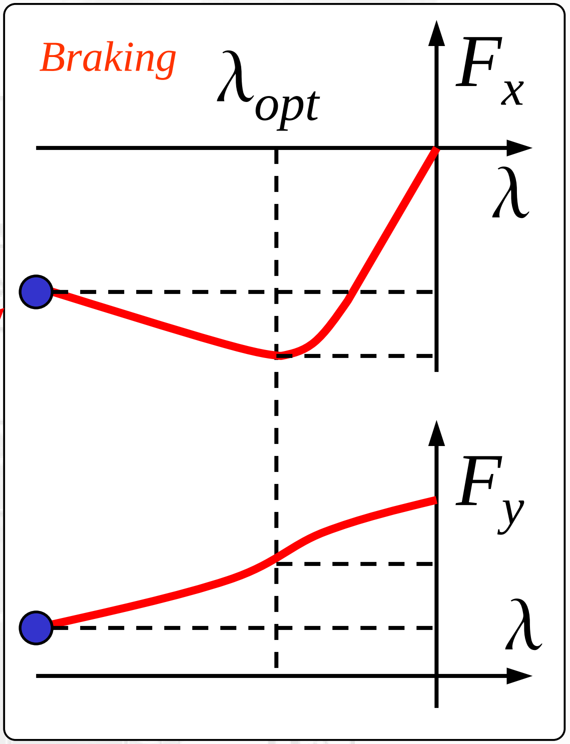
Outline

- Introduction on ABS and emergency braking
- Assumptions
- Basic operating principle
- 6-State control algorithm
- Relaxation of some assumptions
- Simulation experiments and Conclusions

Introduction
Tire Behaviour and Emergency Braking



The longitudinal and lateral tire forces F_x and F_y are a function of the "tire slip" λ



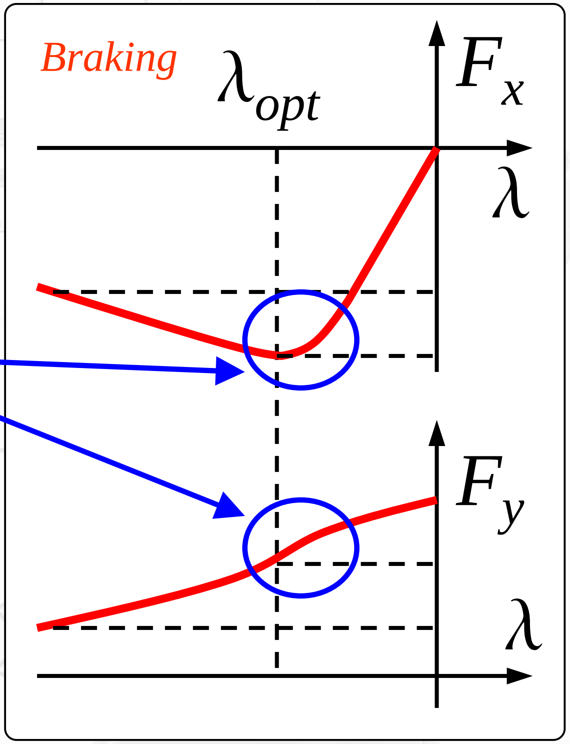
"Panic braking": locked wheels (λ =-1) and suboptimal braking forces, thus

- lengthening of the travelled distance
- reduced steering effectiveness

Introduction
ABS Functioning Principle and Issues

By properly operating the braking system,
during an "emergency braking",
the ABS control should be able to make the tire
to work where the longitudinal and lateral tire
forces F_x and F_y are around their maximum:

- reduced travelled distance
- high steering effectiveness



Main issues:

- high parameters uncertainties
- low cost (low performance) actuators
- low cost and limited sensors
- safe vehicle behaviour when ABS is on
- …

Brief Review of Previous Works About Antilock Braking Systems

There are several papers about ABS (it was first developed in the '70s) and the manufacturers of ABS systems already have a deep experience.

The proposed ABS controls can be roughly classified by evaluating:

1. Sensors (what is supposed to be known or measured?)
2. Actuators (is the actuators dynamics taken into account?)
3. Theory (is the control strategy proved?)

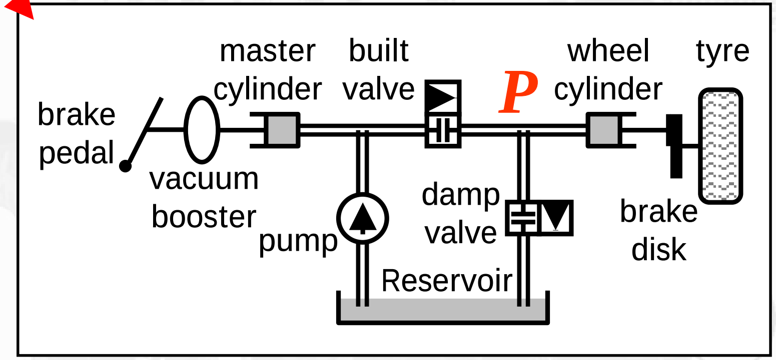
To the best of our knowledge there are NO papers with:

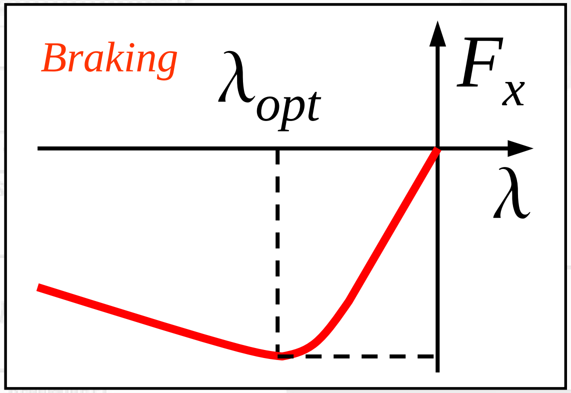
1. "real" and cheap sensors (i.e. wheels speed/acceleration only)
2. dynamics of the hydraulic actuators taken into account
3. proved control strategy (not empirical)

This paper proposes and prove a new ABS control strategy based only on the wheel speed measure and that considers the actuators dynamics.

Assumptions

1. Standard ABS braking system with ON-OFF valves:
   a) few control actions: INCREASE, HOLD, DECREASE pressure P
   b) valve opening/closing time limited above by T_d
   thus any control action is ensured within the time T_d
   c) during the HOLD phases the braking pressure P is constant





2. The curve $F_x(\lambda)$ has a "constant" shape (not time/speed dependent, this assumption is relaxed later) with unique minimum.
3. The wheel angular speed is measured, the wheel angular acceleration is measured or estimated.

Basic Operating Principle

The curve $F_x(\lambda)$ has a unique minimum

⇩

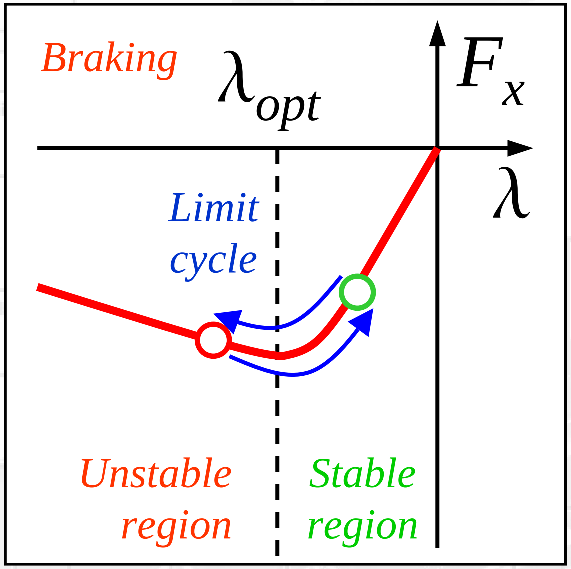
The control strategy is a minimum seek algorithm:

1) Find if the operating point of the tire is in the "stable" or in the "unstable" region.

2) Operate the actuators to switch from one region to the other.

⇩

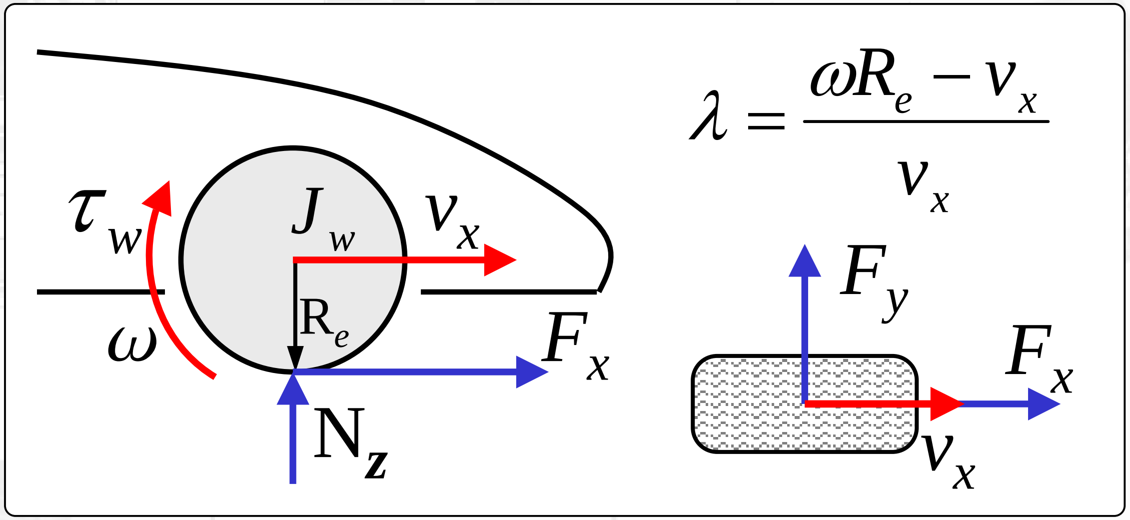
A sort of "limit cycle" arises around the minimum of $F_x(\lambda)$



Where is the operating point of the tire? First 2 Properties

Computing the tire slip time derivative:

$$\dot{\lambda} = R_e \frac{v_x \dot{\omega} - \dot{v}_x \omega}{v_x^2}$$



the following two properties can be proved:

1) if $\dot{\omega} \geq \dot{\omega}_p \geq 0$ then $\dot{\lambda} > 0$

2) if $\dot{\omega} \leq \dot{\omega}_n < 0$ then $\dot{\lambda} < 0$

By measuring the wheel acceleration it is possible to infer the sign of the time derivative of the slip ratio.

$\dot{\omega}_p$, $\dot{\omega}_n$ are known constants.

Where is the operating point of the tire?
Last 2 Properties

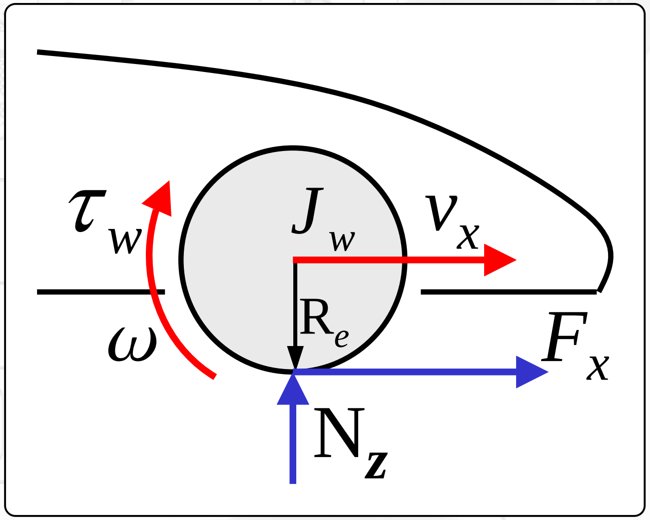
The dynamics of the tire is:

(K_{brk} is the brake coefficient, P is the braking pressure)

$$J_w\dot{\omega} = -K_{brk}P - R_e F_x(\lambda)$$

The time derivative of the above equation is:

$$J_w\ddot{\omega} = -K_{brk}\dot{P} - R_e \frac{dF_x(\lambda)}{d\lambda}\dot{\lambda}$$



(K_{brk} and $F_x(\lambda)$ are not time dependent,
this assumption is removed later)

the following two properties can be proved:

if <u>P is constant</u> and

3) $\dot{\omega} \geq \dot{\omega}_p$ and $\ddot{\omega} < 0$ then $\lambda_{opt} < \lambda < 0$ → The operating point is in the stable region

4) $\dot{\omega} \leq \dot{\omega}_n$ and $\ddot{\omega} < 0$ then $\lambda < \lambda_{opt}$ → The operating point is in the unstable region

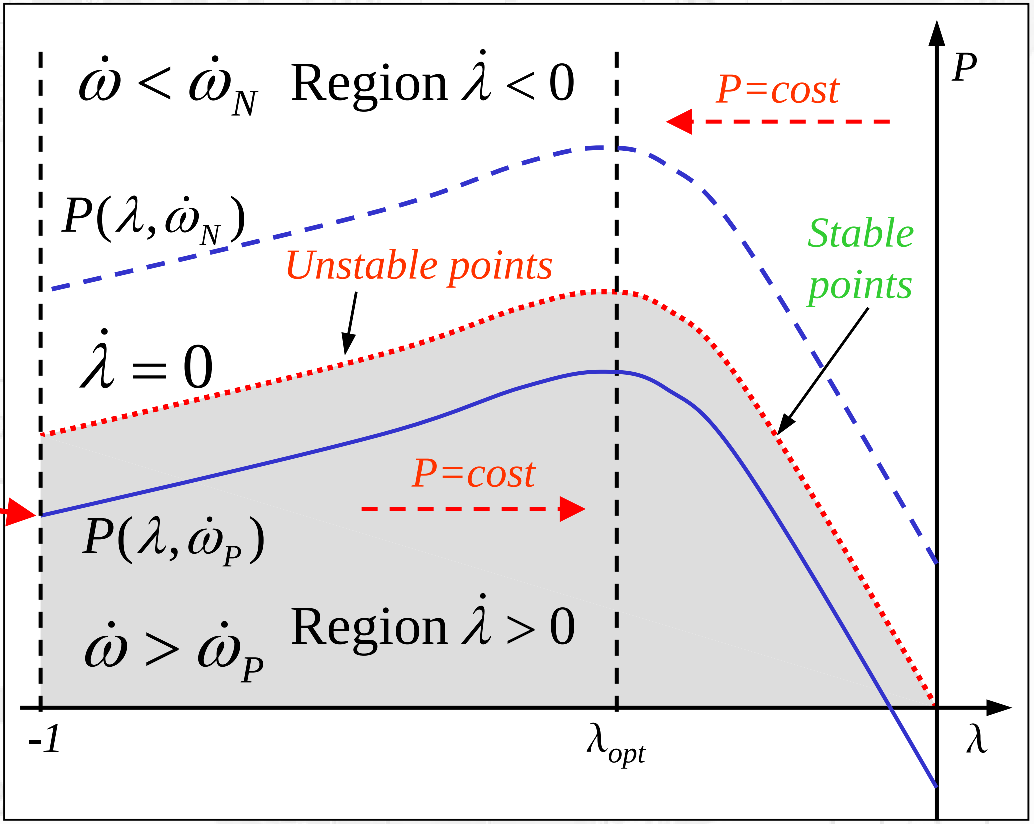
Schematic Representation of the Working Cycle: the "P-λ plot"

From the dynamics of the tire it is possible to compute the pressure P as a function of the slip and of the wheel acceleration:

$$J_w \dot{\omega} = -K_{brk} P - R_e F_x(\lambda)$$

$$P(\lambda, \dot{\omega}) = \frac{-J_w \dot{\omega} - R_e F_x(\lambda)}{K_{brk}}$$

For a fixed value of the wheel acceleration, the shape of the curve $P(\lambda)$ is the same as the shape of $-F_x(\lambda)$ and the 4 properties stated before can be easily represented.



Schematic Representation of the Working Cycle: Properties of the "P-λ plot"

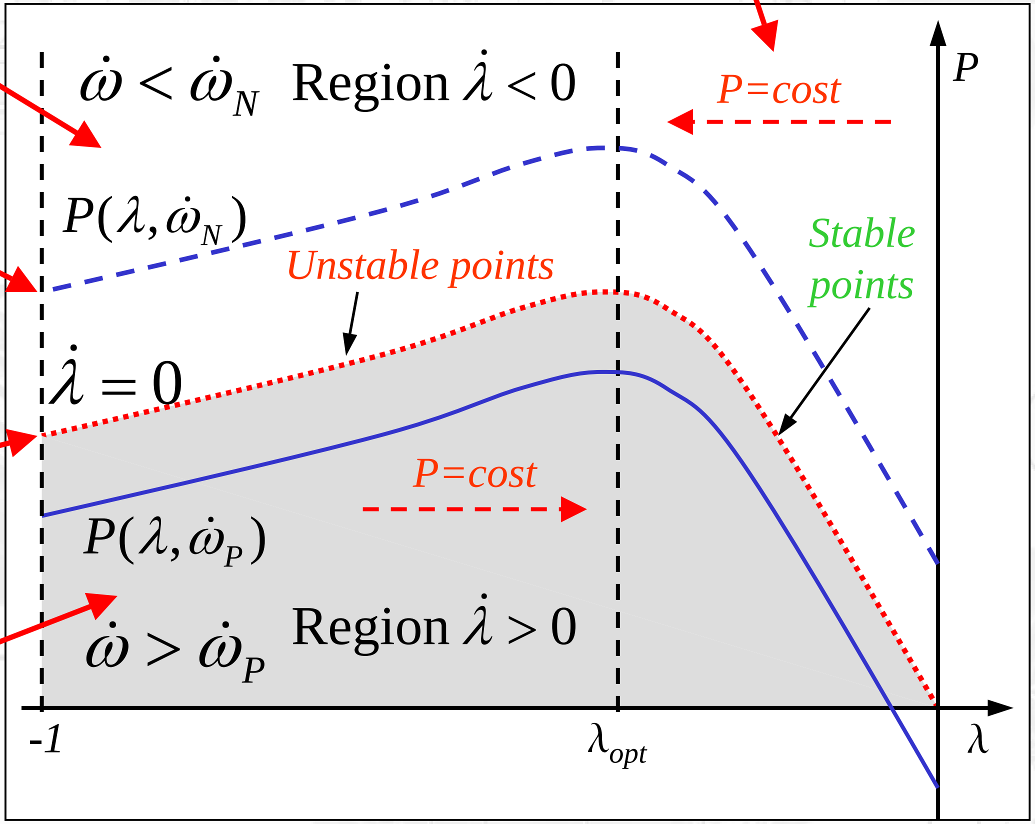
The curves with constant pressure are horizontal lines

Property 2: region with decreasing slip

curve $P(\lambda)$ with constant wheel acceleration

It exist a value for the wheel acceleration that ensures a constant slip

Property 1: region with increasing slip

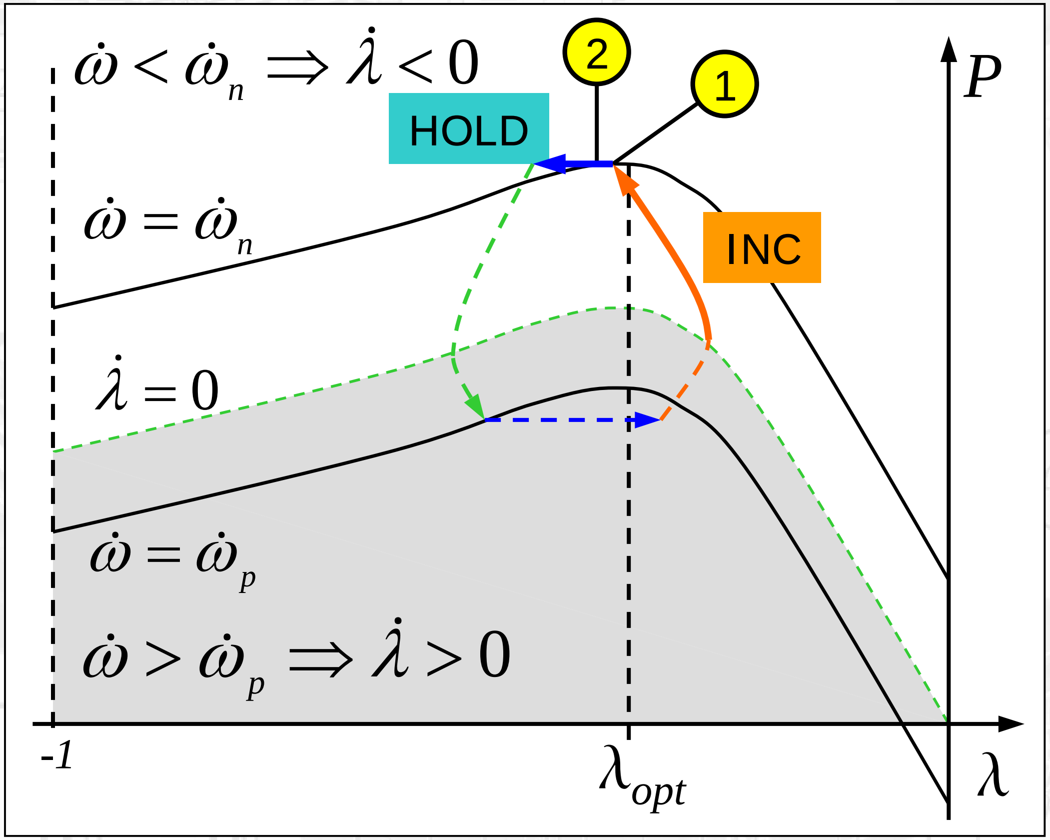


Self-Tuning Control Strategy for Antilock Braking Systems: States 1-2

The proposed control strategy is based on a 6-state algorithm.

Transition (1): $\dot{\omega} < \dot{\omega}_n$
the wheel acceleration is low enough, the slip is decreasing (prop. 2), the HOLD command is given.

Transition (2):
the time T_d has elapsed
the pressure P can be considered constant.
The HOLD command is maintained

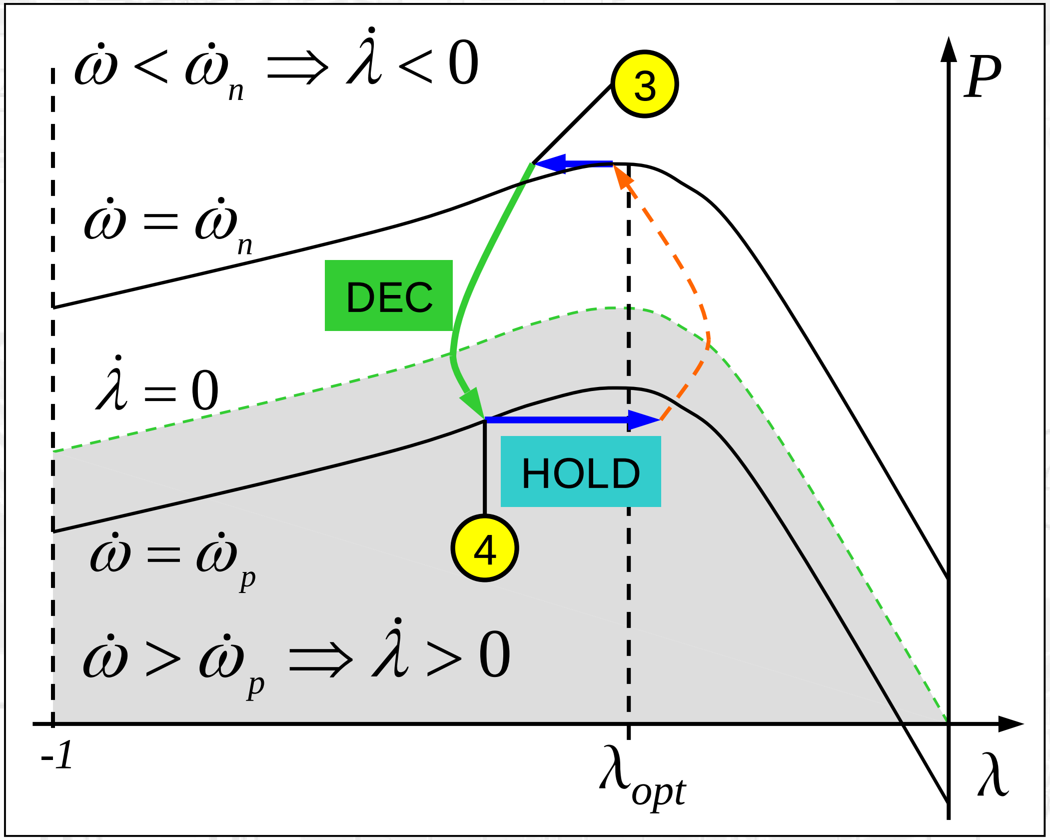


Self-Tuning Control Strategy for Antilock Braking Systems: States 3-4

The proper computation of this condition in a discrete time control system is discussed soon.

Transition ③: if $\ddot{\omega} < 0$ the operating point is in the unstable region (property 4), the DECREASE command is given to switch to the stable region.

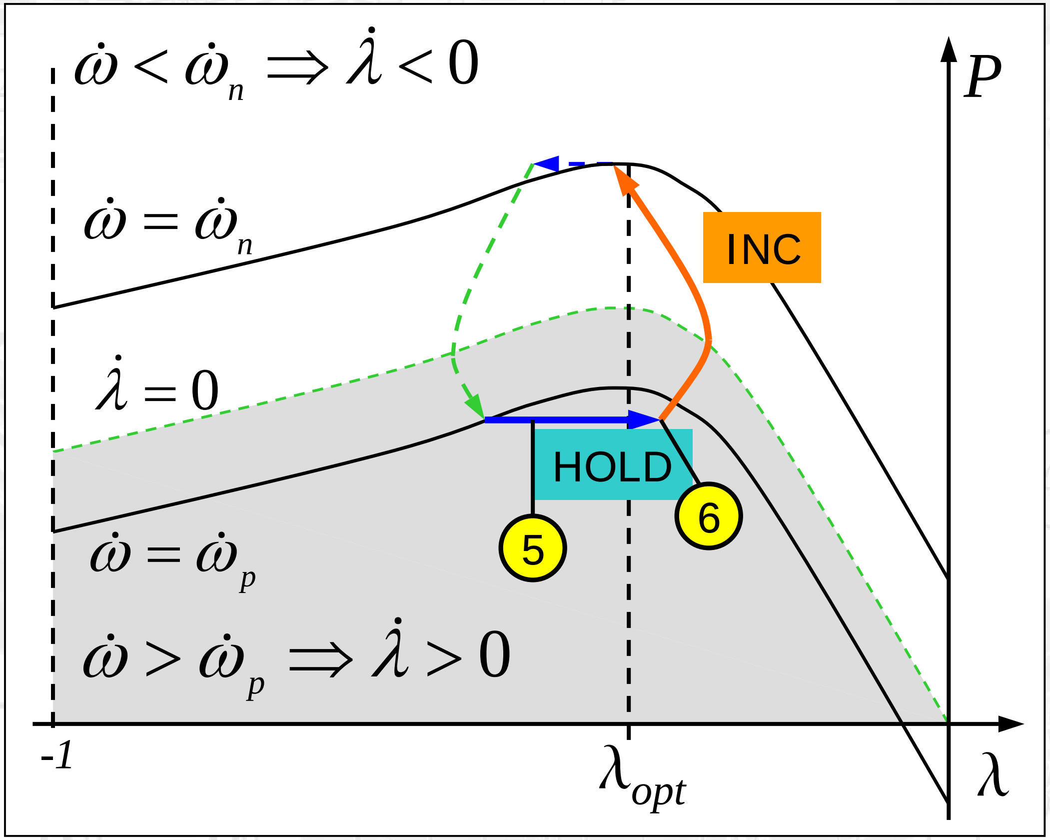
Transition ④: $\dot{\omega} > \dot{\omega}_p$ the wheel acceleration is high enough, the slip is increasing (prop. 1) the HOLD command is given.



Self-Tuning Control Strategy for Antilock Braking Systems: States 5-6

Transition (5):
the time T_d has elapsed
the pressure P can be considered constant.
The HOLD command is maintained

Transition (6): if $\ddot{\omega} < 0$
the operating point is in the stable region (property 3), the INCREASE command is given to switch to the unstable region.



Self-Tuning Control Strategy and Wheel Acceleration Time Derivative

Properties 3 and 4 involve the sign of the time derivative of the wheel acceleration:

if P is constant and

3) $\dot{\omega} \geq \dot{\omega}_p$ and $\ddot{\omega} < 0$ then $\lambda_{opt} < \lambda < 0$ → The operating point is in the stable region

4) $\dot{\omega} \leq \dot{\omega}_n$ and $\ddot{\omega} < 0$ then $\lambda < \lambda_{opt}$ → The operating point is in the unstable region

Since a discrete time control unit is supposed to be used, the acceleration variation $\Delta\dot{\omega}(k)$ is used in place of the acceleration time derivative $\ddot{\omega}$.

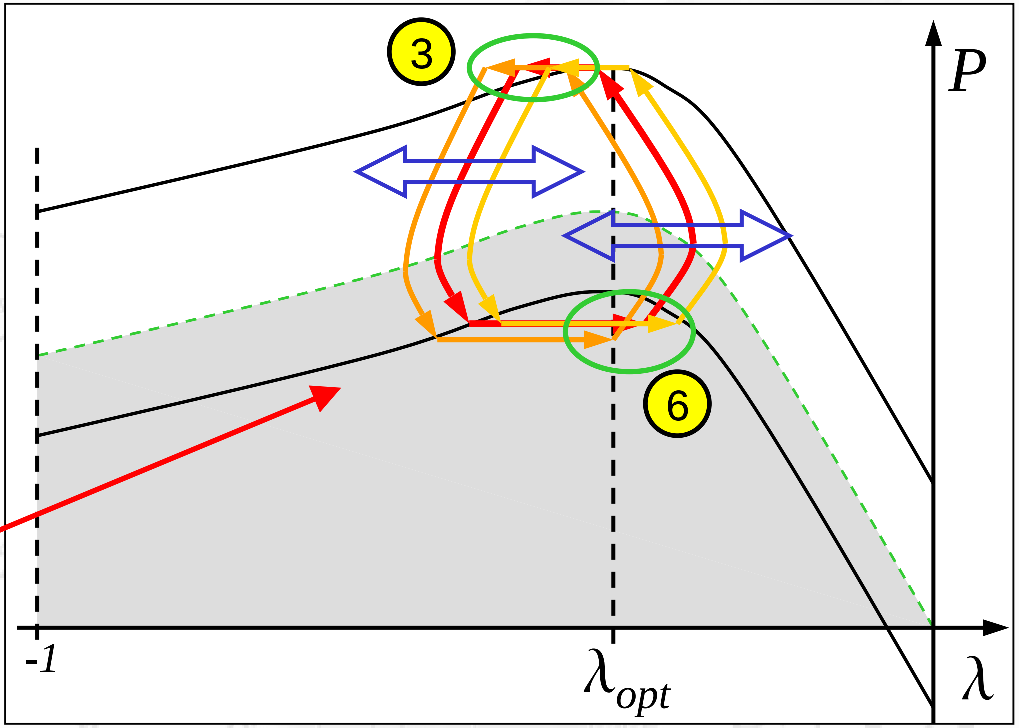
The effects of this approximation are discussed next.

Self-Tuning Control Strategy: Parameters Variations and Robustness (1/2)

What does it happen when K_{brk} and $F_x(\lambda)$ are time variant? Two new terms appears in the equation of the time derivative of the wheel acceleration:

$$J_w\ddot{\omega} = -K_{brk}(t)\dot{P} - \frac{dK_{brk}(t)}{dt}P - R_e\frac{dF_x(\lambda,t)}{d\lambda}\dot{\lambda} - R_e\frac{dF_x(\lambda,t)}{dt}$$

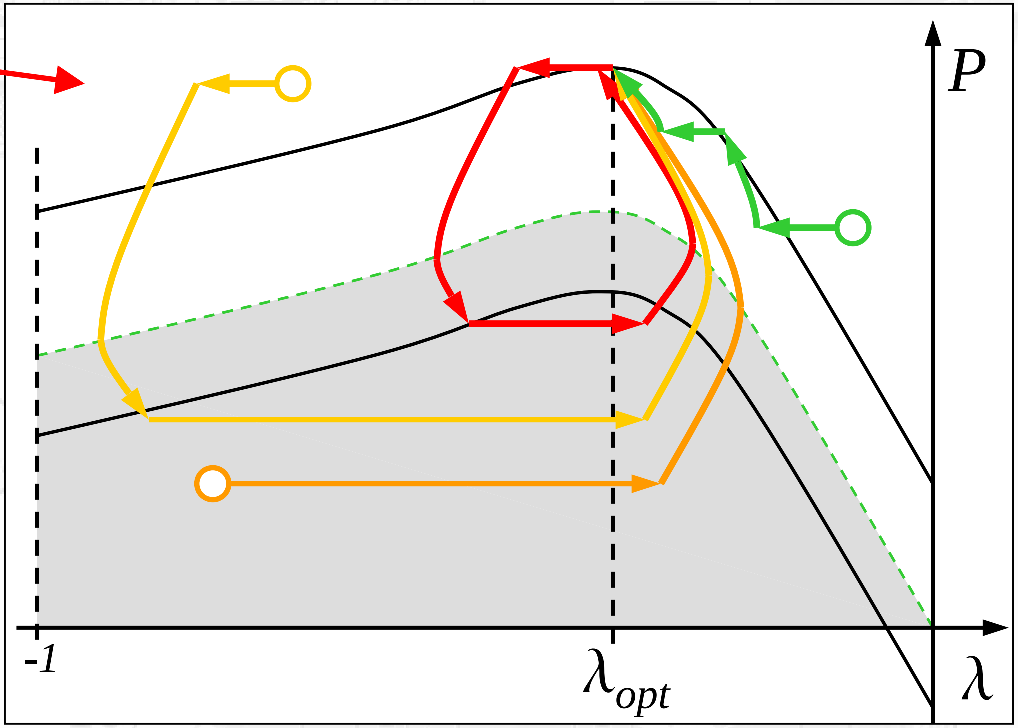
- Prop. 1 and 2 are not affected
- The condition $\ddot{\omega} < 0$ of prop. 3 and 4 does not exactly ensure the switch between the stable/unstable regions.
- However if the two new terms are slowly time varying, their effect on transitions 3 and 6 (based on prop. 3 and 4) is a translation of the "limit cycle".
- The same happens if $\Delta\dot{\omega}(k)$ is different from $\ddot{\omega}(t)$.



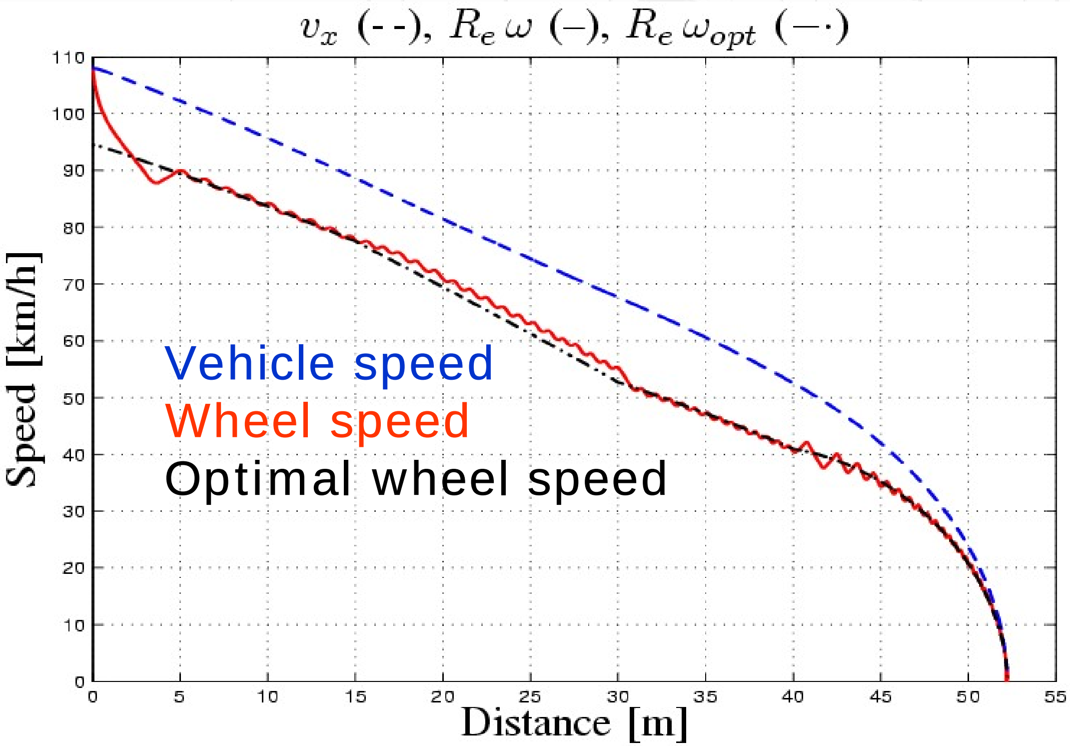
Self-Tuning Control Strategy: Parameters Variations and Robustness (2/2)

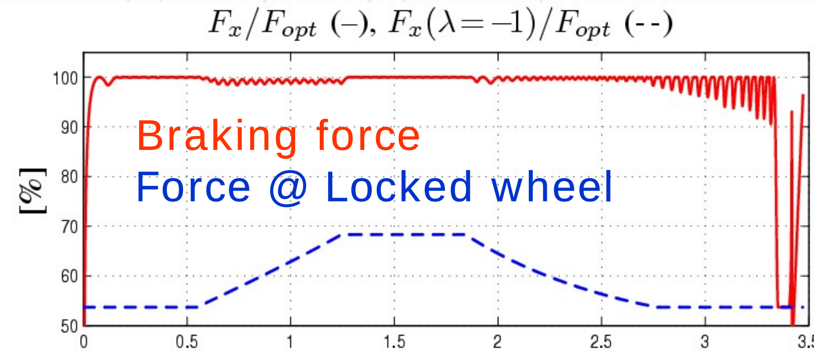
What does it happen in case of sudden parameter variations?

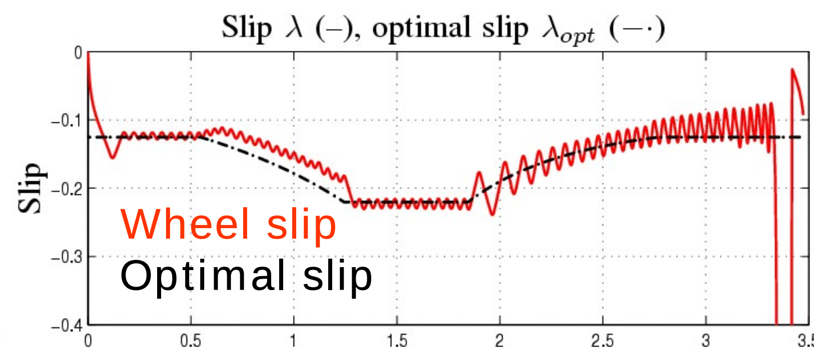
- The operating point is subject to a "jump".
- Independently from the current state of the algorithm, 1 or 2 transitions are enough to "detect" where is the new operating point and "recovery". The detection and the recovery are embedded in the algorithm.
- As soon as the parameters become slowly varying again, the operating points approaches the new "correct limit cycle".

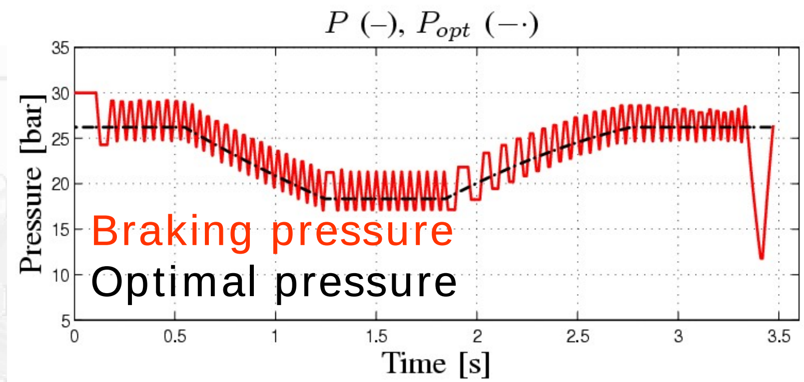


Simulation Results 1/3
High Quality Actuators and Sensors

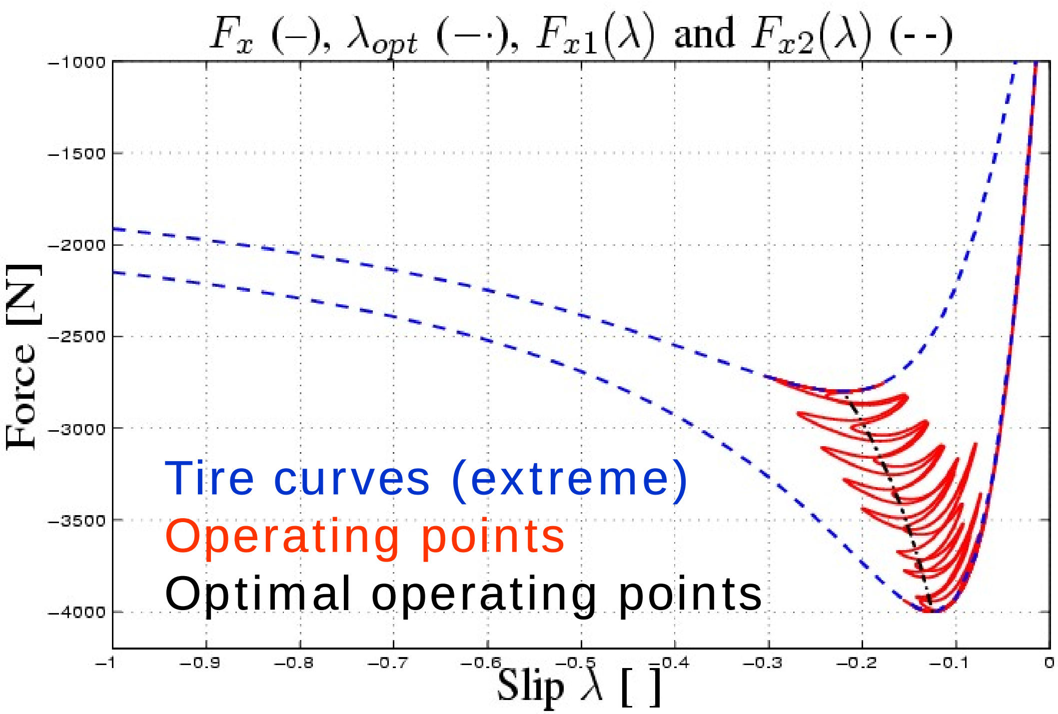


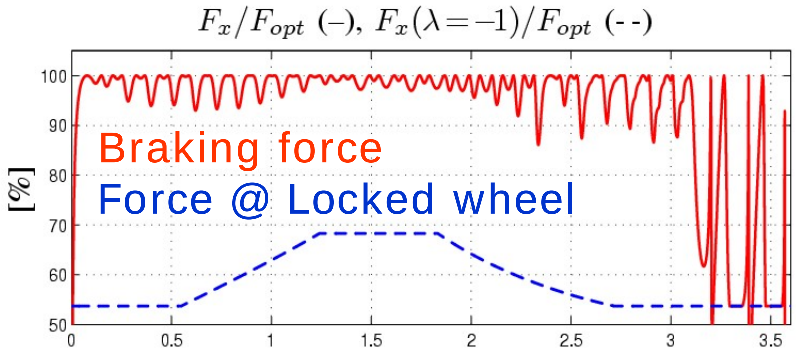


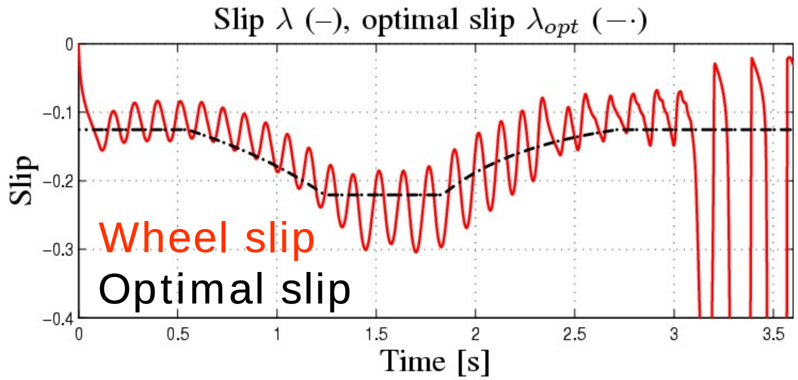


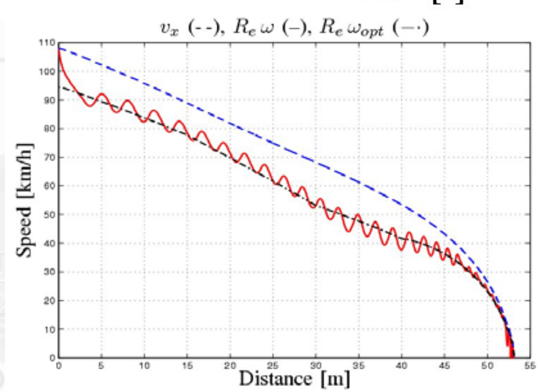


Simulation Results 2/3
Mid Quality Actuators and Sensors

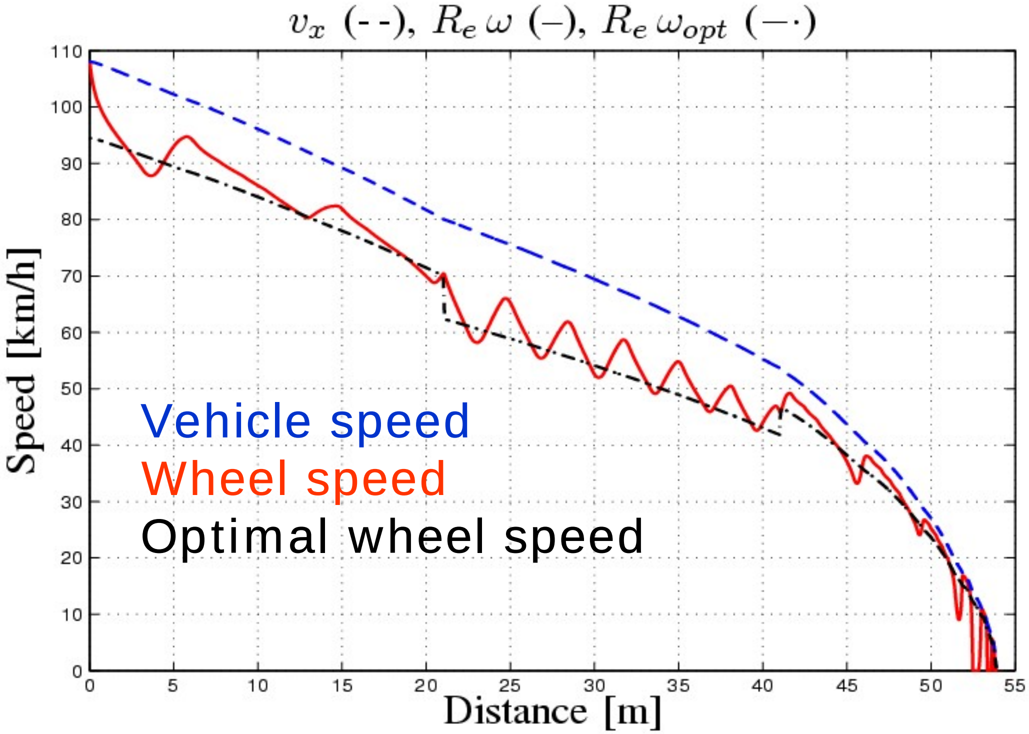


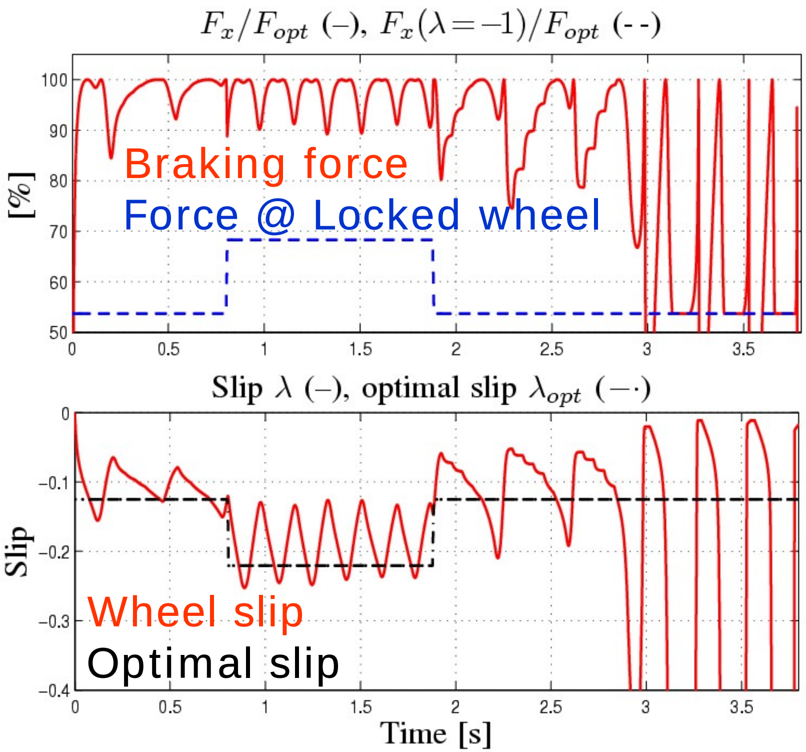






Simulation Results 3/3
Low Quality Actuators and Sensors





Conclusions

- The proposed control strategy is based on some assumptions rather close to the real implementation.
- The algorithm is based on few proved properties.
- The remaining key issue is the computation and the detection of the condition $\ddot{\omega} < 0$.
- Thanks to its simplicity and its adaptability, the proposed control can be used as a benchmark to test different control strategies.