Bosch Motorsport FSAE – Brakes + ABS

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- 2007-2009 Michigan State University FSAE
  - Suspension Team Leader
- 2011-2014 ADVICS North America
  - ABS and TC calibration
- 2014-2022 Bosch Engineering Group
  - TC Calibration
    - GM production performance projects
    - C7 GS → C8 Z06, 6th Gen 1LE Camaros
- 2022-Present Bosch Motorsport
  - Chassis control calibration
  - ABS and EBS

Bosch Motorsport FSAE – Foundation Brakes

Energy Conversion and Dissipation

Brake Function Objective:

1. **Convert kinetic and potential energy of a moving vehicle into heat**

2. **Transfer heat energy to ambient environment**

Design of FSAE Brake System

- Common pitfalls of racing braking system design:

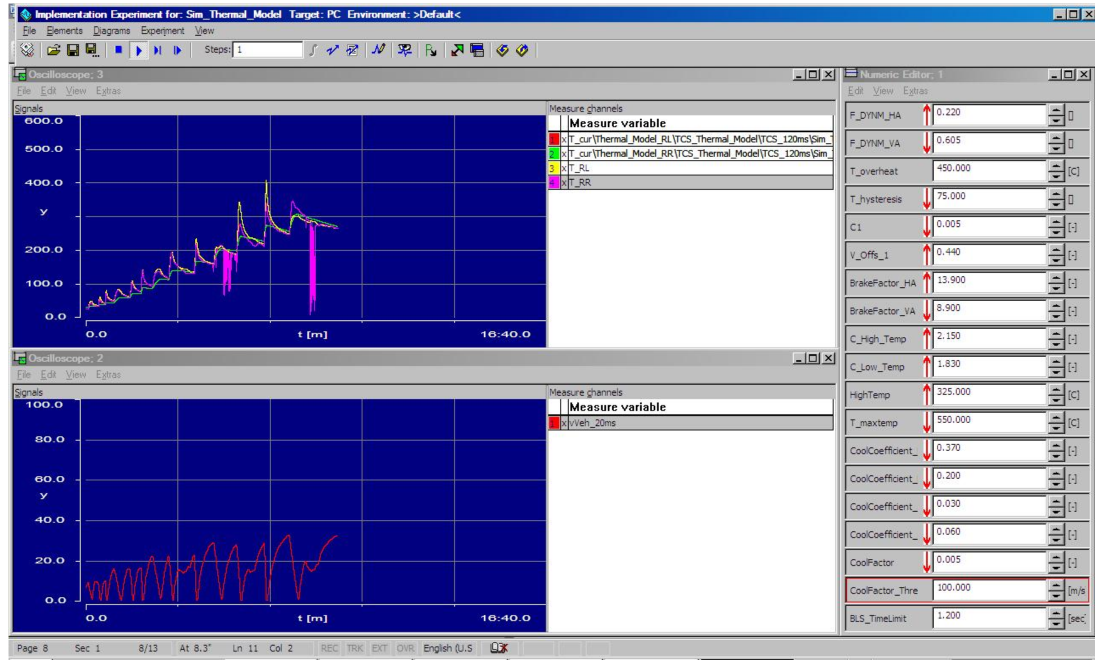
Effect	Cause
Lockup not achievable	Pedal effort is beyond driver’s capability → Improper system sizing Too much system compliance → Master cylinders bottom out
Poor sealing	Improper fitting selection, flaring practices
Poor modulation	Improper pad selection
Poor reliability	High system pressure, poor component design
Poor heat management	Improper component sizing, cooling, and/or pad selection

Design of FSAE Brake System

- Important design considerations:
  - Reliability
    - Brakes are the most important saftey system of a vehicle
  - Heat management
  - Servicabilty
  - Rigidity
  - Know required brake torque to lock wheels at ANY SPEED (lift/downforce)
  - Know your pedal effort
    - What is the maximum force that the driver can apply while seated in the car?
    - What is the desired lock up pedal force?
  - Weight
    - Only important after all other design criteria are met!

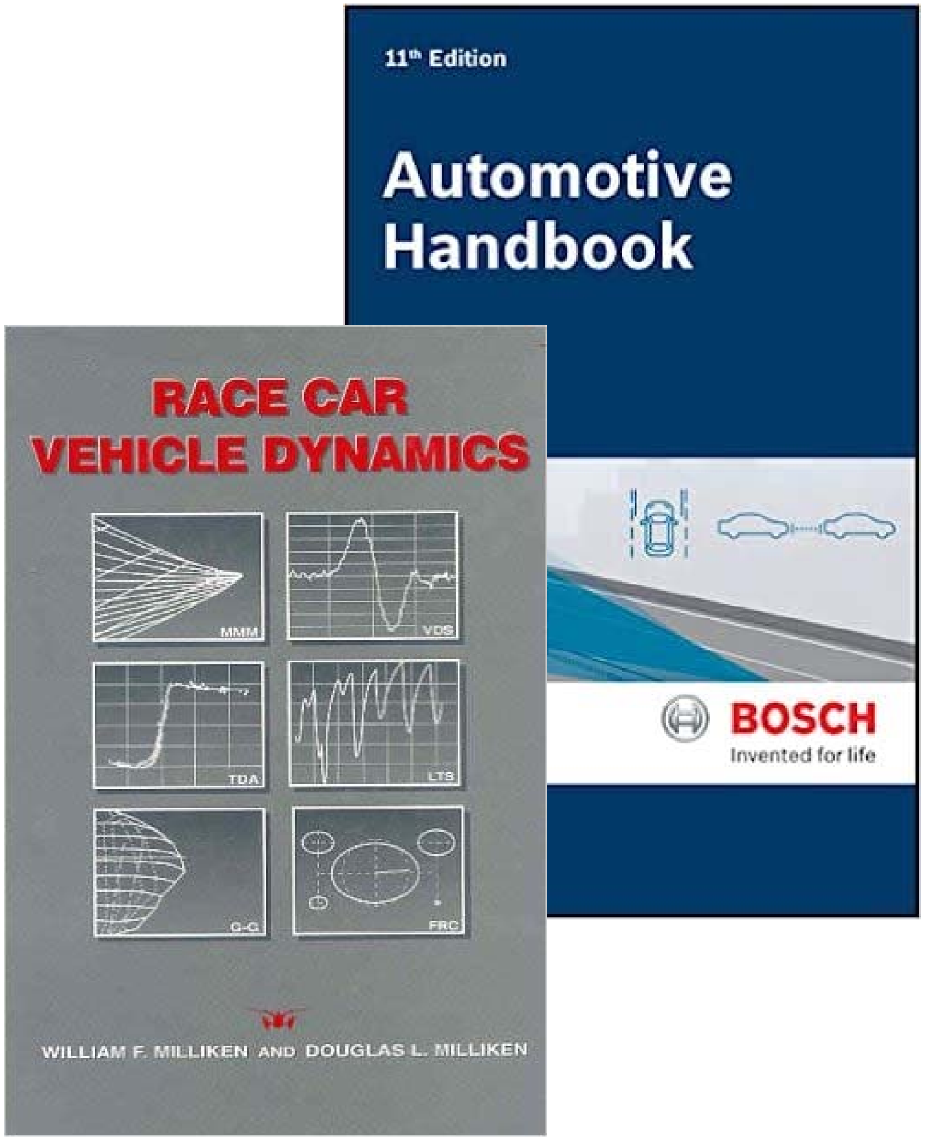
Design of FSAE Brake System

- Design and Simulation
  - Before choosing components, braking system must be understood via simulation
  - Developing an Excel sheet or Matlab model to simulate brake system sizing and heat generation/rejection can speed development

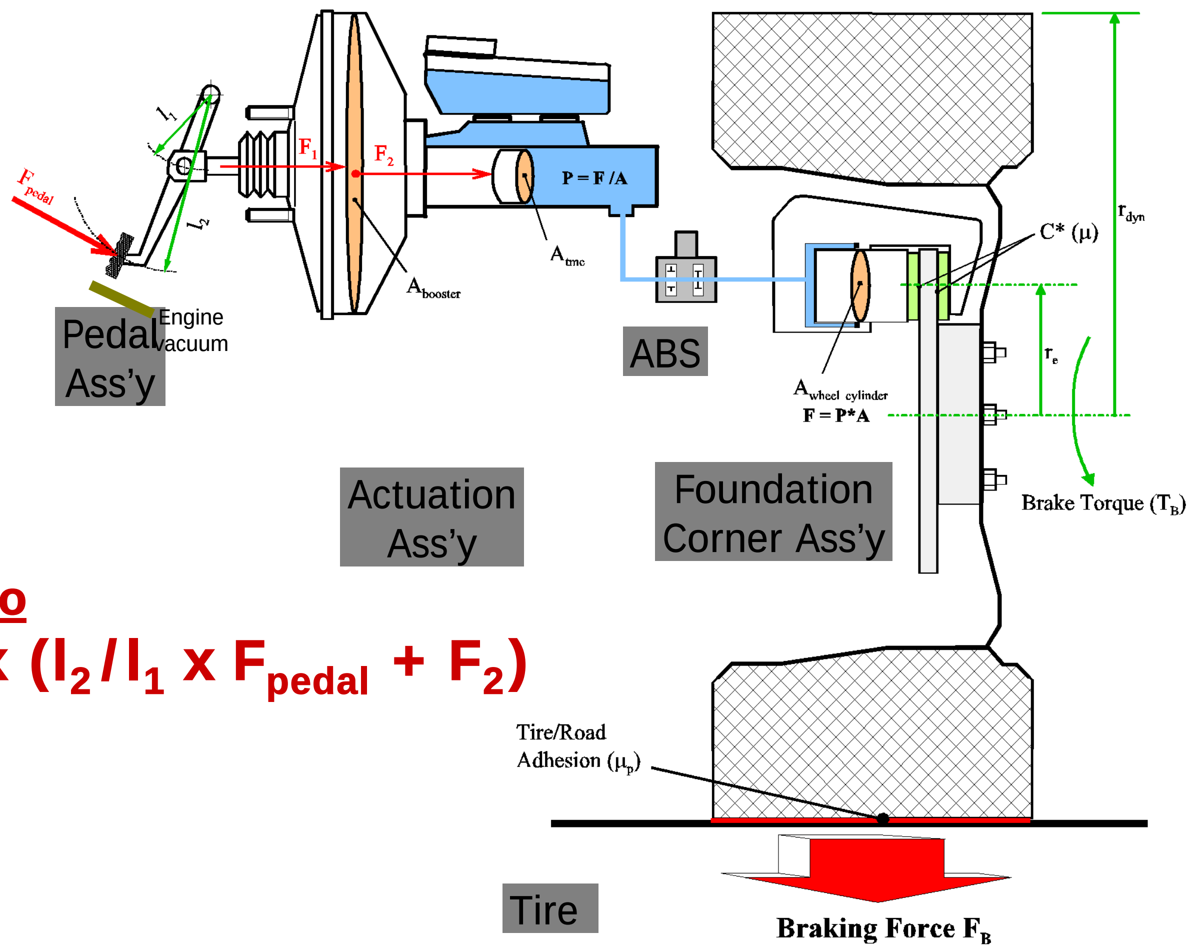


Design of FSAE Brake Packages

- Resources:
  - SAE Papers
    - 2007-01-0588
    - 2008-01-0817
    - 2005-01-0790
  - Bosch Automotive Handbook
  - Milliken's Race Car Vehicle Dynamics



Actual Brake Force



System Ratio

$$F_B \propto r_e / r_{dyn} \times C^* \times A_{wc} / A_{tmc} \times (l_2 / l_1 \times F_{pedal} + F_2)$$

Definitions - System Ratio Equations

- F_B = Braking Force acting against vehicle motion at Tire Road Interface
- r_e = Effective Radius. Center of contact between lining and rotor
- r_{dyn} = Dynamic Rolling Radius of Tire (determined from Revs/ mile)
- C* = Brake Factor, Function of lining friction (2 * Mu for Disc Brake)
- A_{wc}= Area of Wheel Cylinder or Caliper Piston
- A_{tmc}= Area of the Master Cylinder Piston
- l_2= Length of Pedal Arm from pivot to center of foot apply
- l_1= Length of Pedal Arm from Pivot to Booster Actuation Rod
- F_{pedal}= Force applied by driver to Pedal
- F_2= Boosted Force Additional Force Supplied by Booster

Energy Conversion- Fundamentals

$$\partial T(\text{rotors}) = \frac{\partial(\text{Energy})}{c \cdot \text{mass}}$$

c = rotor specific heat constant

m = rotor mass

Energy = vehicle energy generated during braking

Energy Transfer

Conduction Heat transfer occurring on a stationary medium
$q \propto (dT)$

Convection Heat transfer occuring between a surface and a moving fluid (i.e. air) at different temperatures
$q \propto (dT)$

Radiation Heat transfer between two surfaces at different temperature due to energy emission in the form of electromagnetic waves
$q \propto (dT^4)$

q=energy transfer rate
dT=temperature difference between rotor and ambient

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Braking Energy - Single Stop Maximum Vehicle Velocity

V_0 — 0

$$\textbf{Braking Energy } (E_b) = \frac{1}{2} \cdot M \cdot V_0^2$$

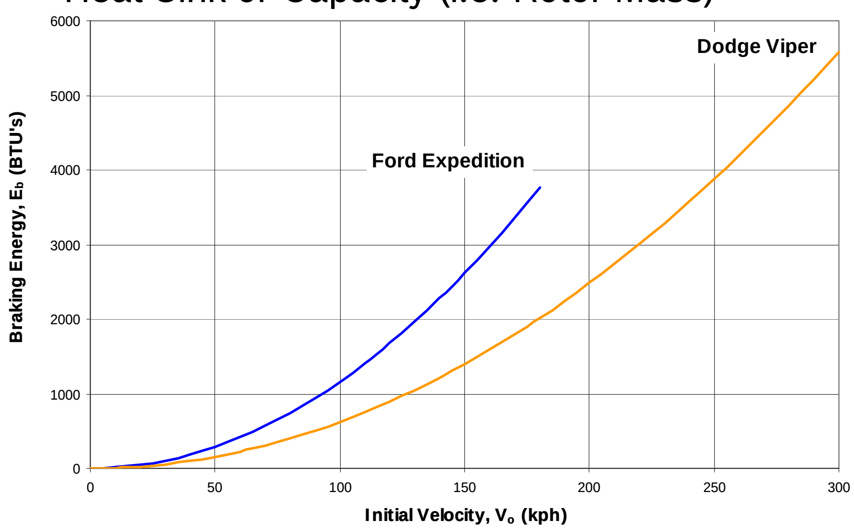
$$\textbf{Braking Power } (P_b) = d\left(\frac{E_b}{\text{time}}\right)$$

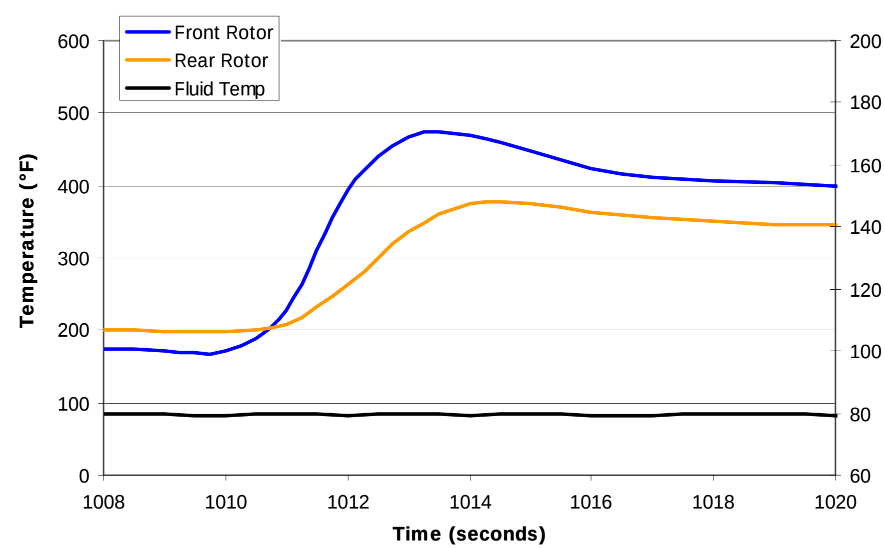
M = vehicle mass

V_0 = initial velocity

Energy is Primary Thermal Considerations

Design Considerations:
Heat Sink or Capacity (i.e. Rotor Mass)





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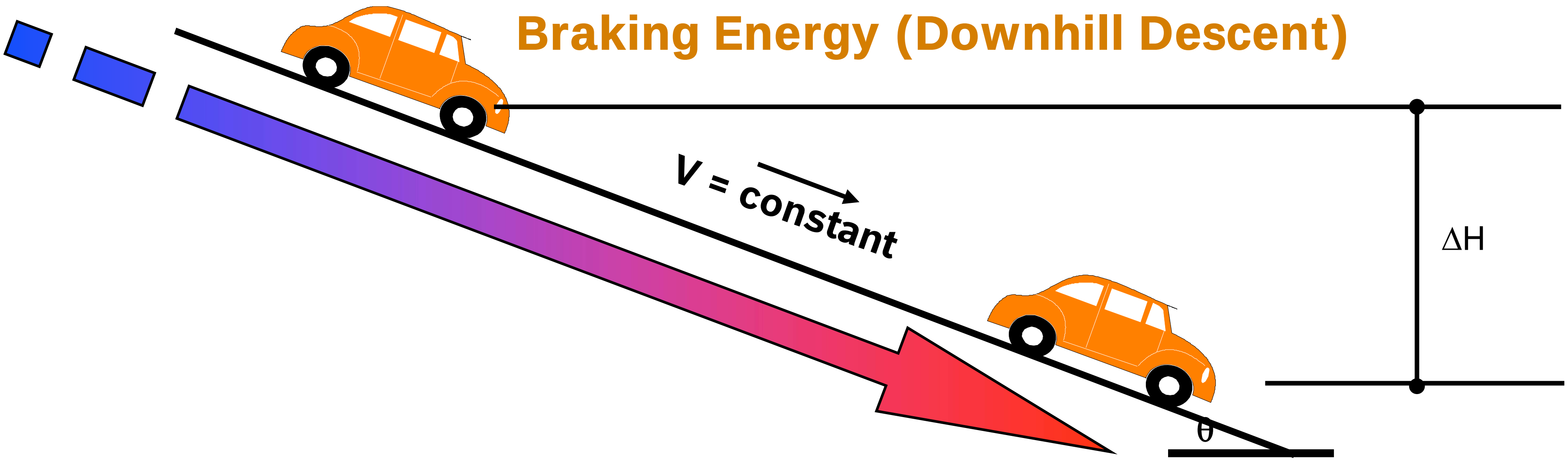
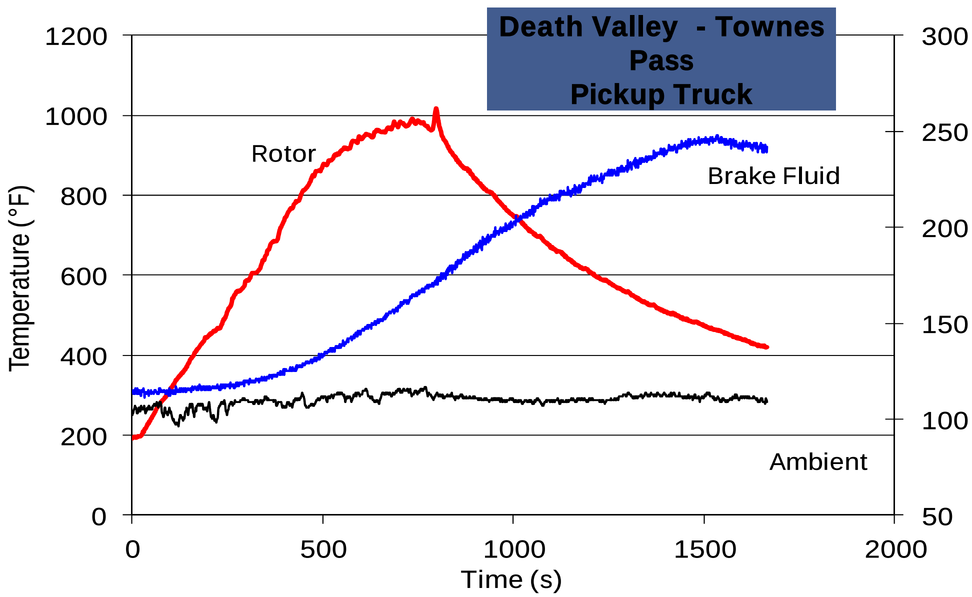
Braking Energy (Downhill Descent)



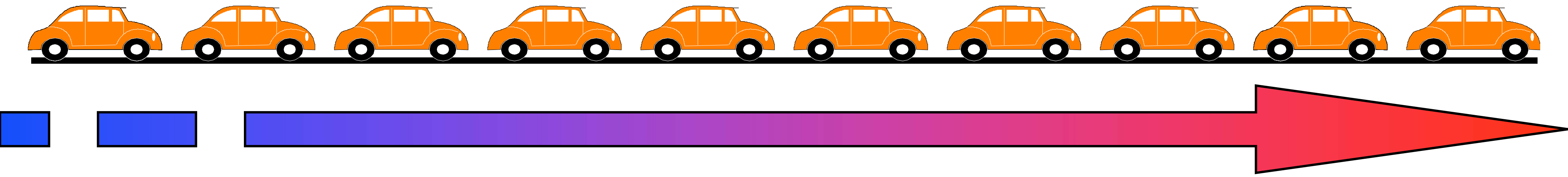
Power is Primary Thermal Considerations

<u>Design Considerations:</u>
Heat Transfer (venting, radiation & rotor surface area)

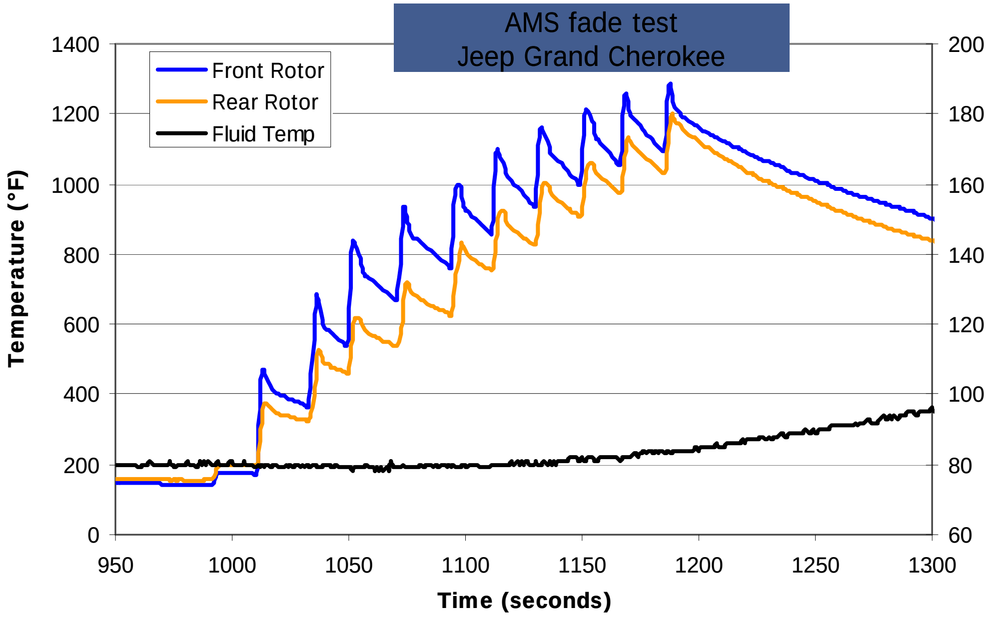
$$\textbf{Braking Energy } (\mathbf{E_b}) = m \cdot g \cdot H$$
$$\textbf{Braking Power } (\mathbf{P_b}) = \mathrm{m} \cdot \mathrm{g} \cdot \mathrm{V} \cdot \sin(\theta)$$
$$\mathrm{M} = \text{vehicle mass}$$
$$\mathrm{V} = \text{Velocity (constant)}$$



Braking Energy - Repeat Braking - Thermal Capacity



Energy and Power are both Thermal Considerations



<u>Design Considerations:</u>

- **Heat Sink and Capacity (Rotor mass)**
- **Heat Transfer (Venting, radiation & rotor surface area)**

$$\text{Braking Energy} = \sum_{1}^{\#stops} \frac{1}{2} \cdot \text{Vehicle Mass} \cdot \Delta V^2 \text{ - cooling behavior of brake rotor}$$

$$\text{Braking Power } (P_b) = d\left(\frac{E_b}{\text{time}}\right)$$

Key Point to Remember

ABS will <u>not</u> fix a bad braking system...

Bosch Motorsport ABS – Why have ABS?

Why ABS?

•ABS is often viewed as a driver‘s aid that can only help an inexperienced driver – ABS can make all drivers faster

•ABS is capable of matching threshold braking deceleration forces in a straight line

•A good driver can modulate the brake in threshold braking but he will never have the ability to change braking based on normal load or surface changes

•Decreased laptimes come with consistently high G stops, driver confidence, and distribution of brake pressure with normal load changes

Fig 1 – ABS off (red) and ABS on (green) showing deceleration gains over rough surfaces.

Why ABS?

•Bosch fitted an ABS M4 system to an Ariel Atom with a good foundation brake system and pro driver

•Driver feedback:

“ABS made it possible to do things in the car that were previously impossible”

“On a perfectly flat surface, it’s possible that a driver could threshold brake equally to ABS, however, if there are any undulations, curves, elevation changes, or surface changes then there is no comparison”

Final Results, VIR Patroit Course:

Best lap – no ABS: 50.7s

Best lap – ABS on: 49.3s

Why Bosch ABS?

Back-to-back testing was performed on two sets of identical cars with the exception of the ABS system

Grand Am GS Car - Competitor's system
Best lap: 1:15.76

Grand Am GS Car - ABS M4
Best lap: 1:14.80, -0.96s

➡ ***ABS M4 0.6s faster on average***

SCCA World Challenge GT Car - no ABS
Best lap: 1:04.89

SCCA World Challenge GT Car - ABS M4
Best lap: 1:03.80, -1.09s

➡ ***ABS M4 1.7s faster on average***

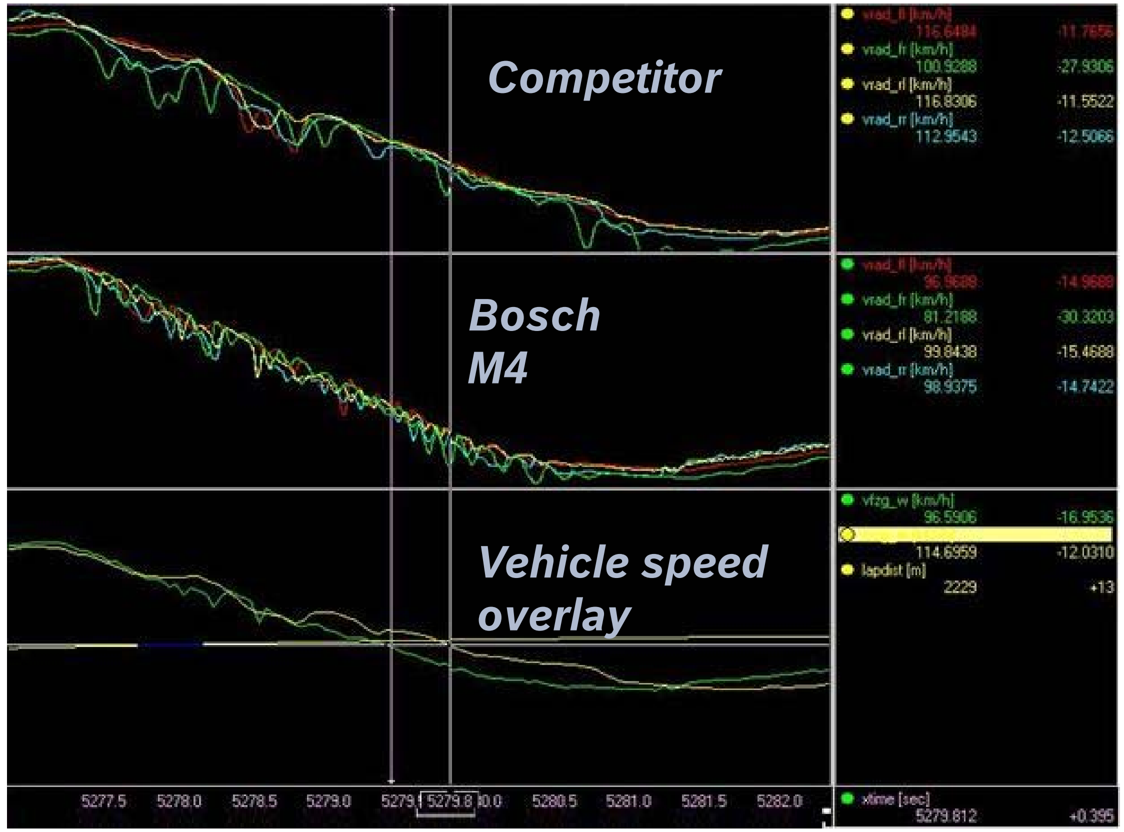
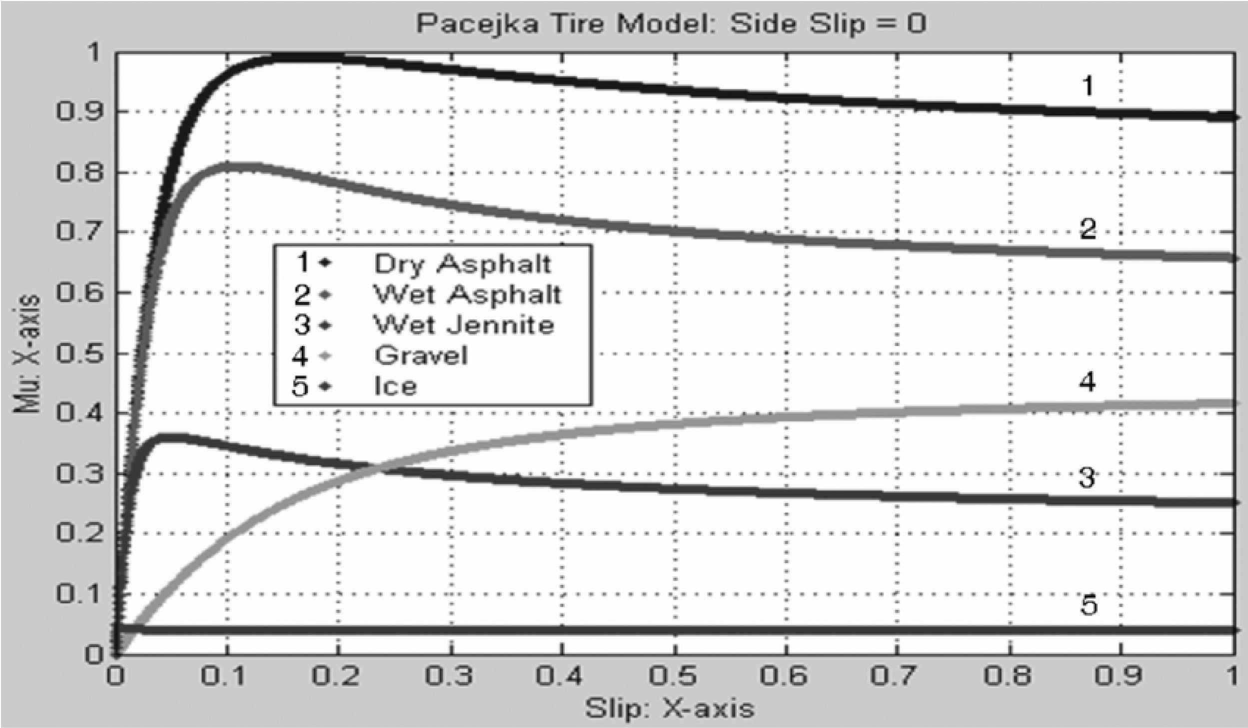


Fig 1. - Benchmarking of ABS M4 vs. Competitor – back to back test

Bosch Motorsport ABS M5 – Principles of Operation

Tire Dynamics

- Tires generate tractive forces when slipped
  - Non-linear relationship
- Peak deceleration happens in a narrow band of tire slip values

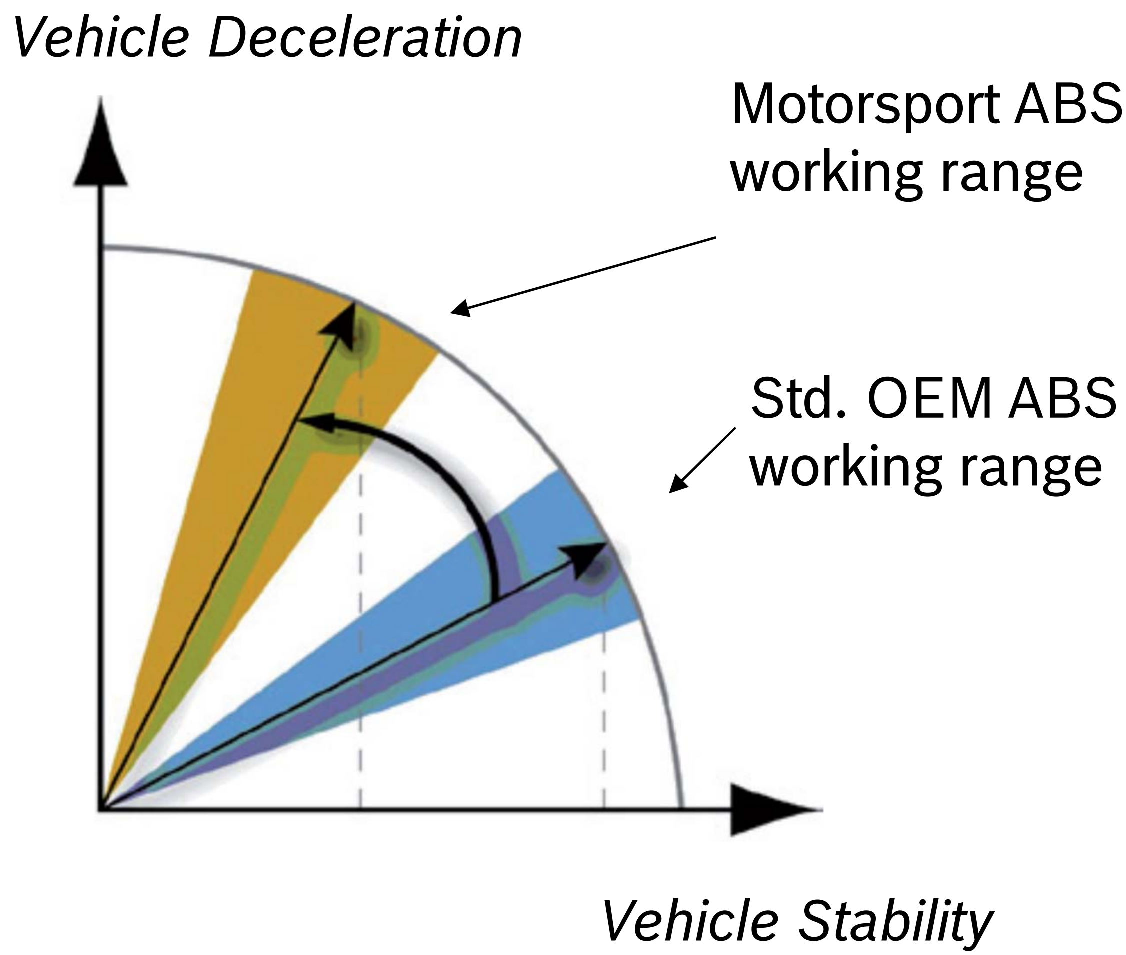


ABS in Motorsport

•The ABS drives a compromise between Stability and Deceleration

•Motorsport → More deceleration, less stability

•The M5 system addresses a unique set of challenges for ABS in racing, including accomodation of large brake system fluid volumes, extreme deceleration rates, and curb detection



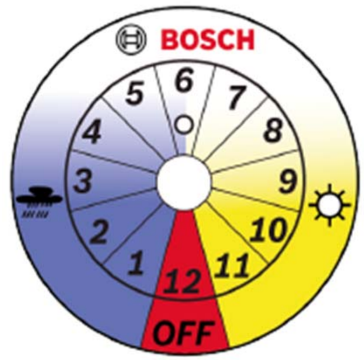
Software features of the ABS M5

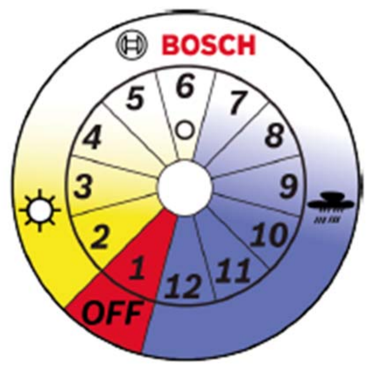
12 control settings:

•All ON positions are pre-calibrated and driver selectable for changes in weather, track condition, and driving style

•All maps can be custom calibrated for individual drivers, tire condition, chassis setups

•OFF disables ABS for base brake tuning. All CAN data remains available.





Measuring vehicle dynamics:

•ABS M5 uses lateral and longitudinal acceleration data as well as yaw rate to calculate control settings and react appropriately.

Communication:

•Data is provided on CAN so that other devices can log and interpret ABS signals. This includes wheel speed, switch position, accelerometer values, brake pressure, and yaw rate.

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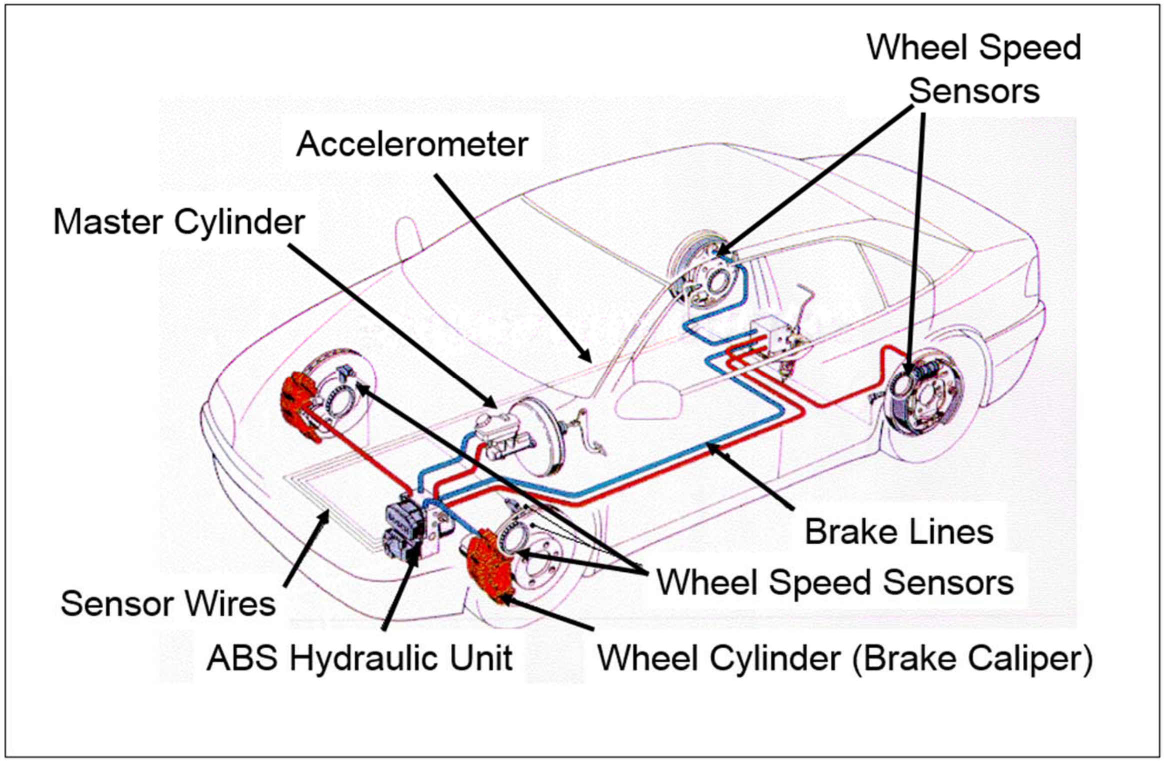
Key differences between road/race ABS

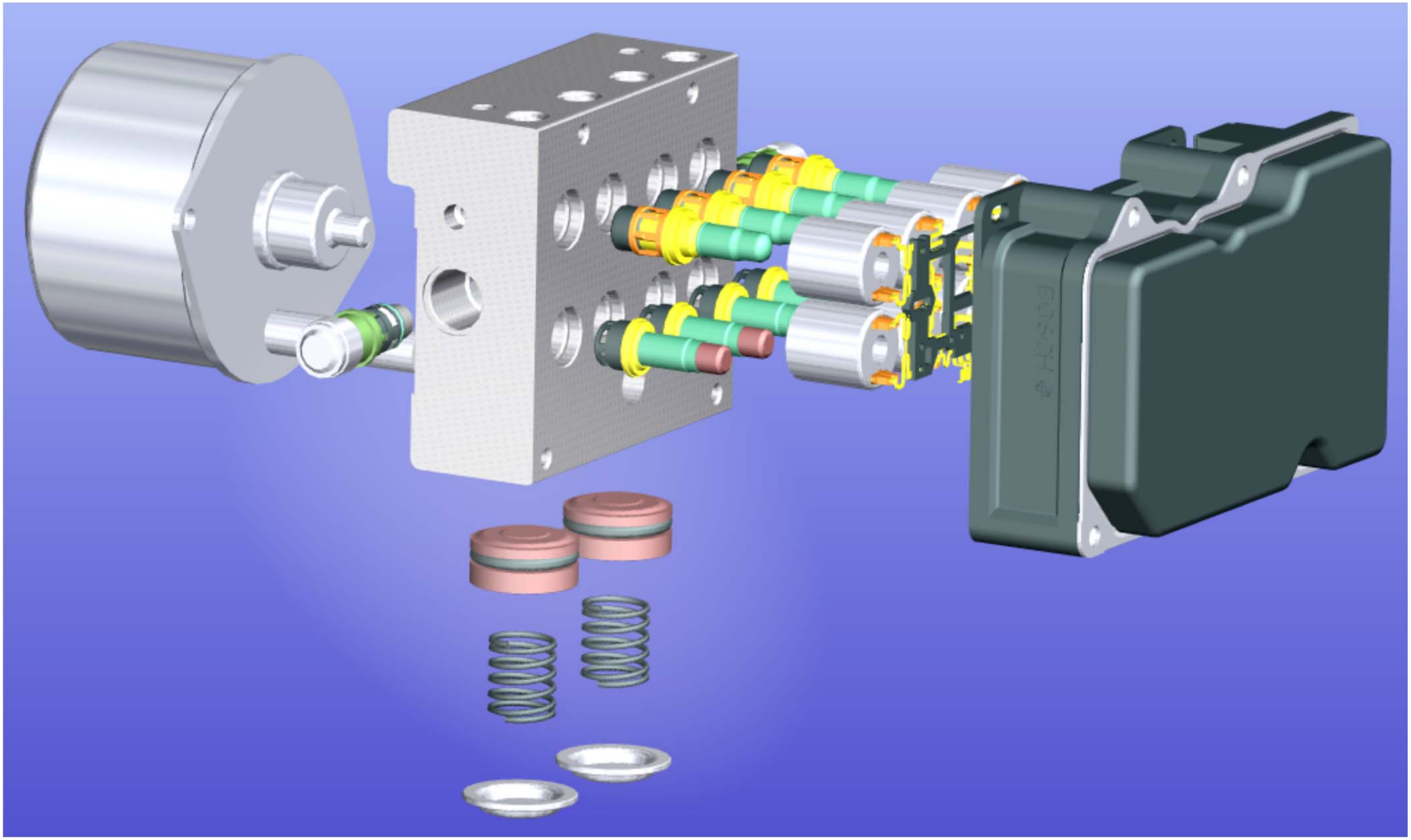
- Software algorithm can handle higher deceleration rates and lateral forces
- Instability controller instead of slip controller for more robust control
- Comfort fuctionalities reduced or removed
- Improved pedal feel to enable the driver to operate on the edge of ABS modulation
- Curb detection to guarantee good performance and pedal feel on curbs
- Vehicle jump detection for fast pressure build up after a jump
- Shift logic (downshift detection)
- Includes front and rear pressure sensors
- Includes acceleration sensor for reference speed support
- 12 position switch
- Possibility to switch ABS off, e.g. for base brake calibration
- CAN speed according to Motorsport requirements

How ABS works?

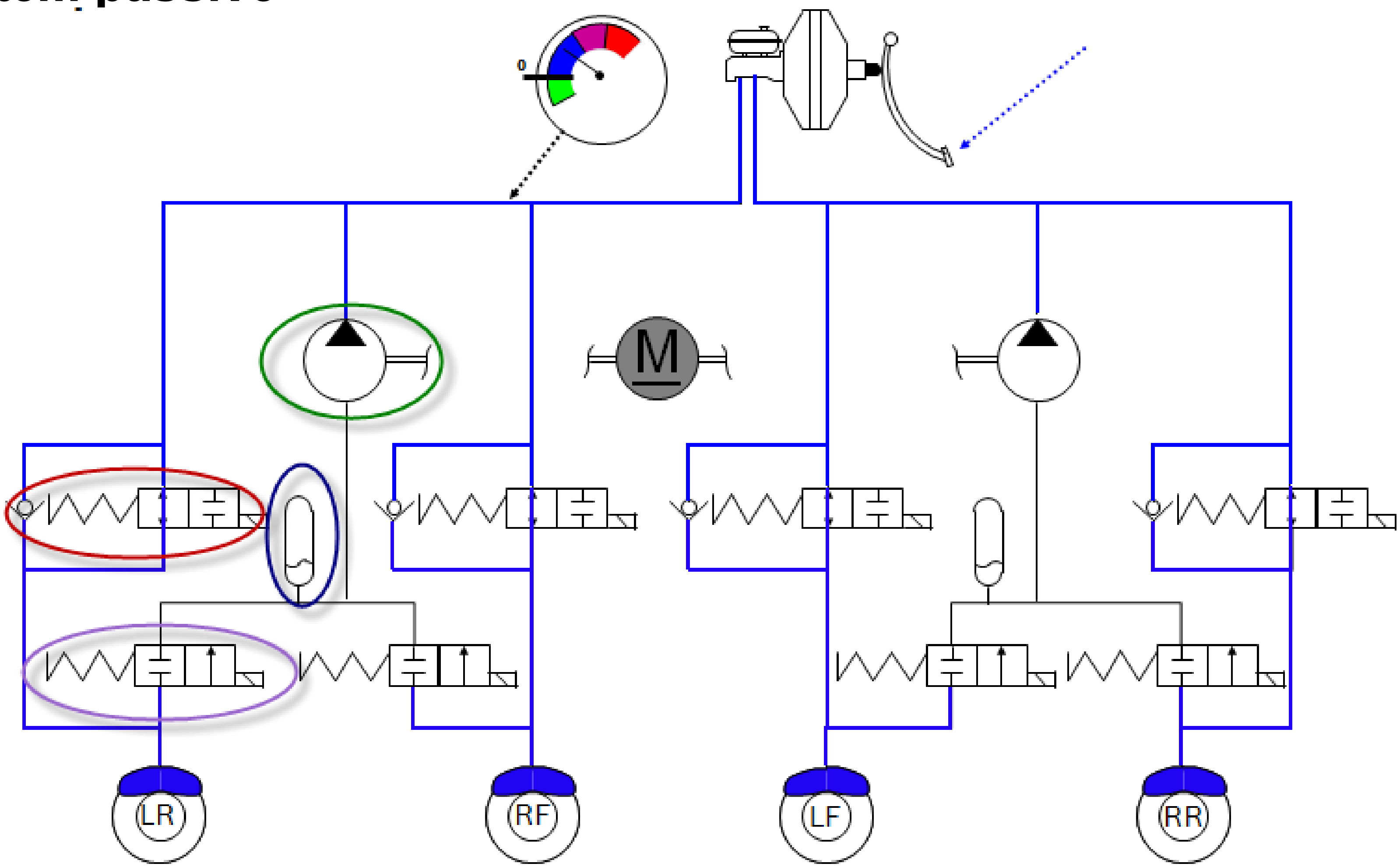
- Sensor network
- Calculates speed
- Monitors each wheel individually
- Modulates each wheel independently
- Can't build pressure over driver (in M4 and M5 modules)



Hydraulic Overview



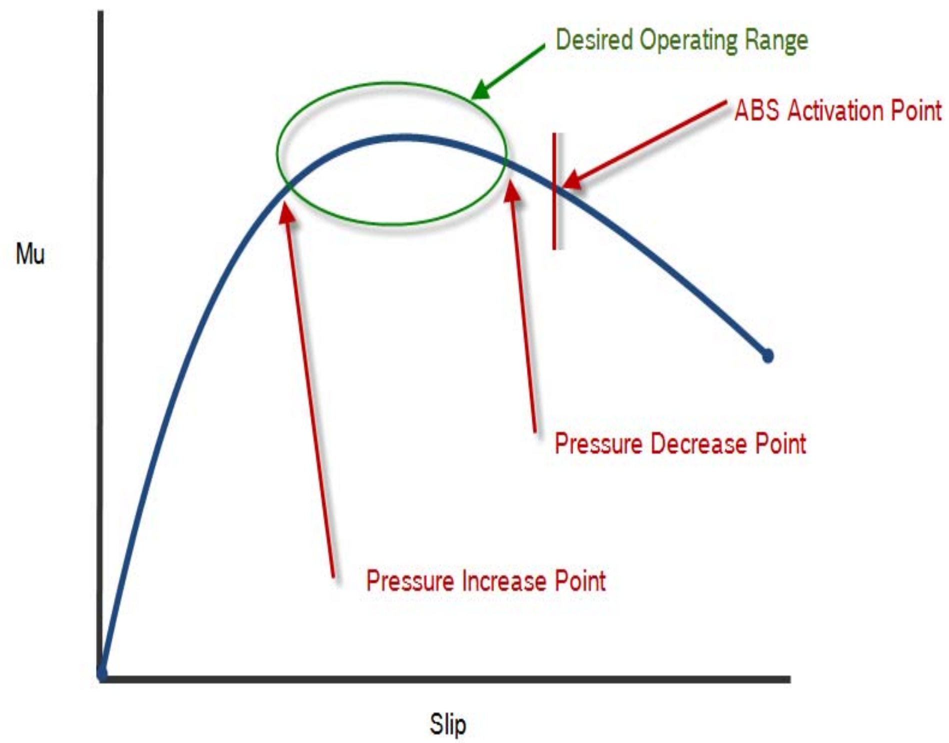
System passive



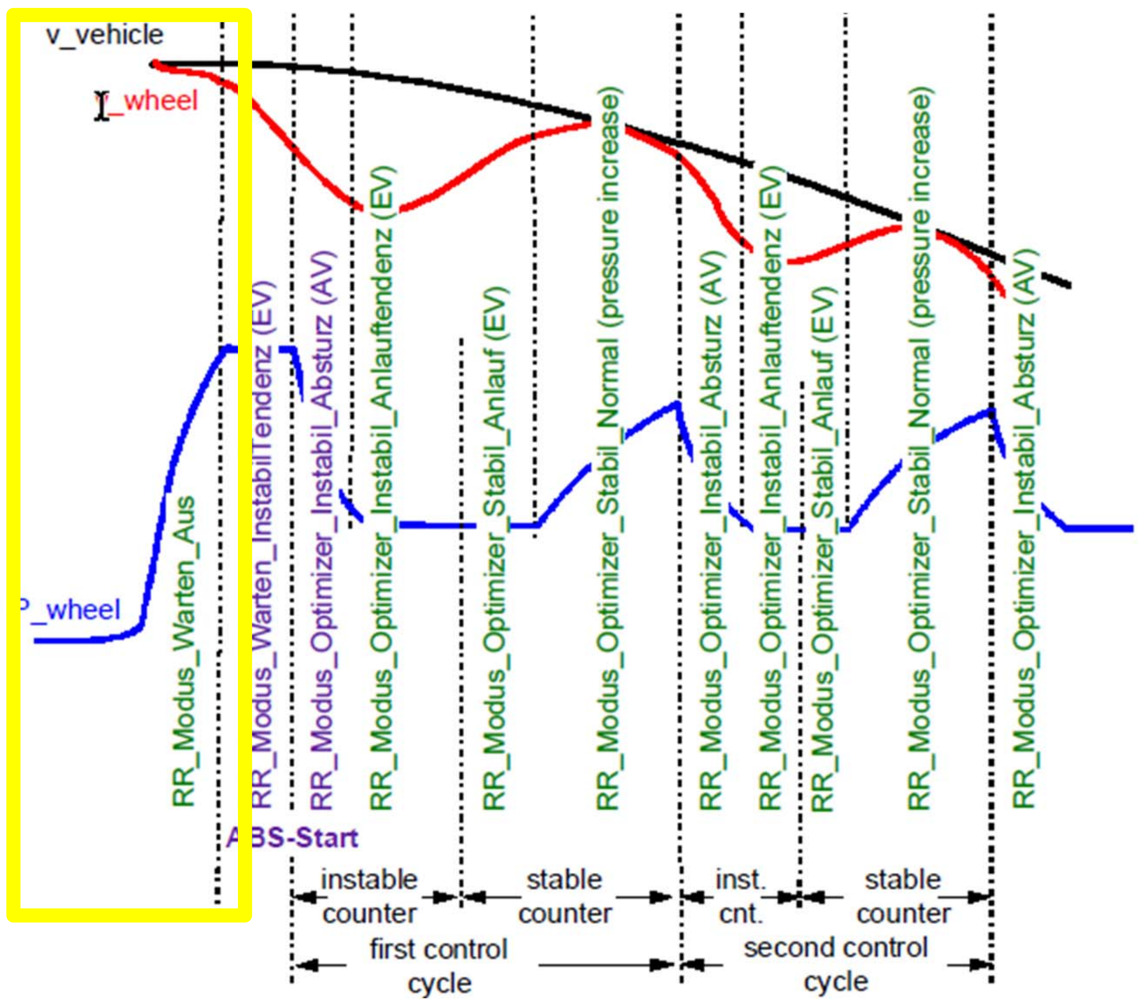
Pressure Increase Valve Pressure Decrease Valve Accumulator Pump

Control Objective

- Individually control brake force at each wheel to maximize vehicle deceleration



Control Principle: Stable



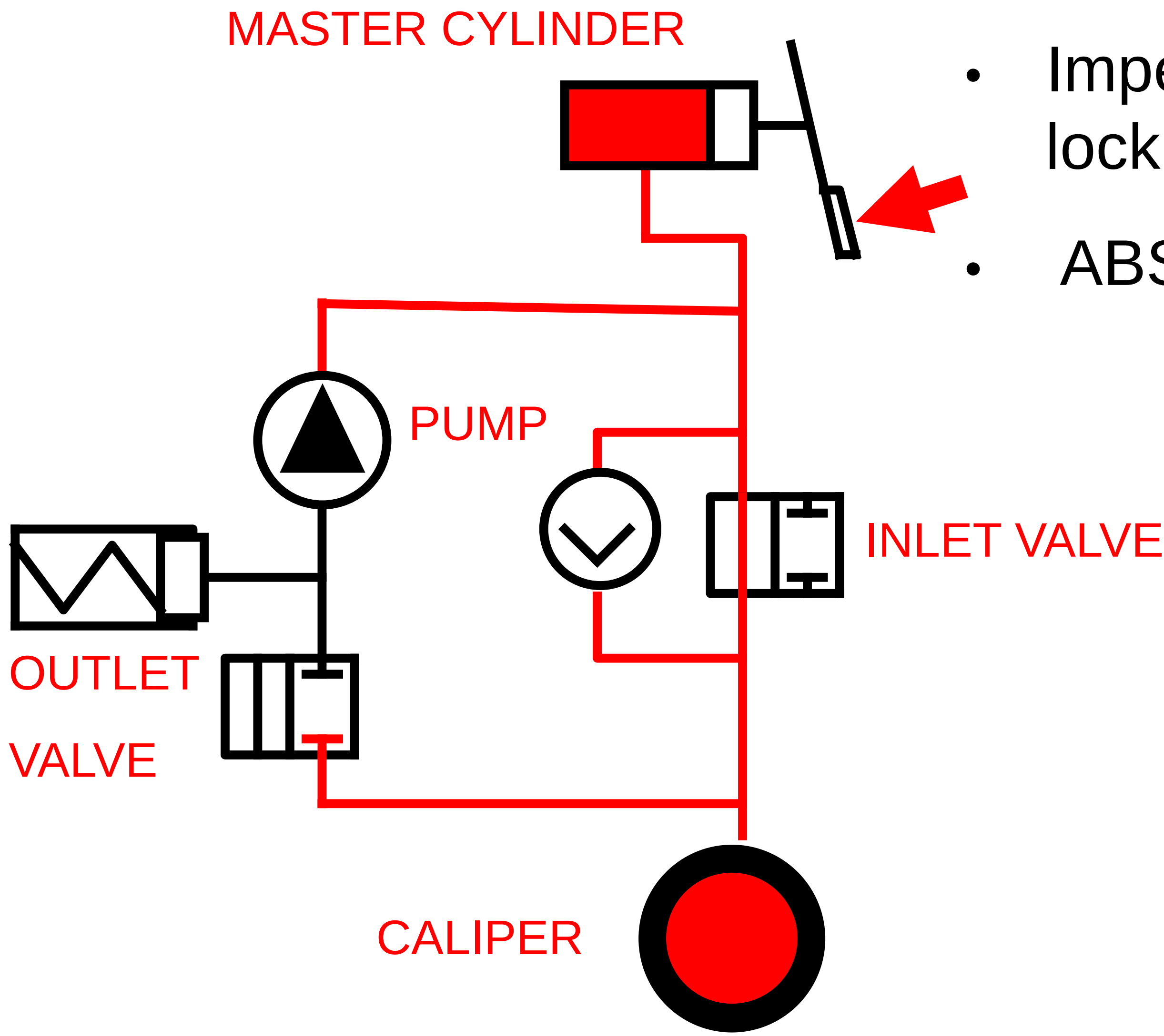
ABS Sequence – Step 1 – Pressure Build

High Pressure

Isolated Pressure

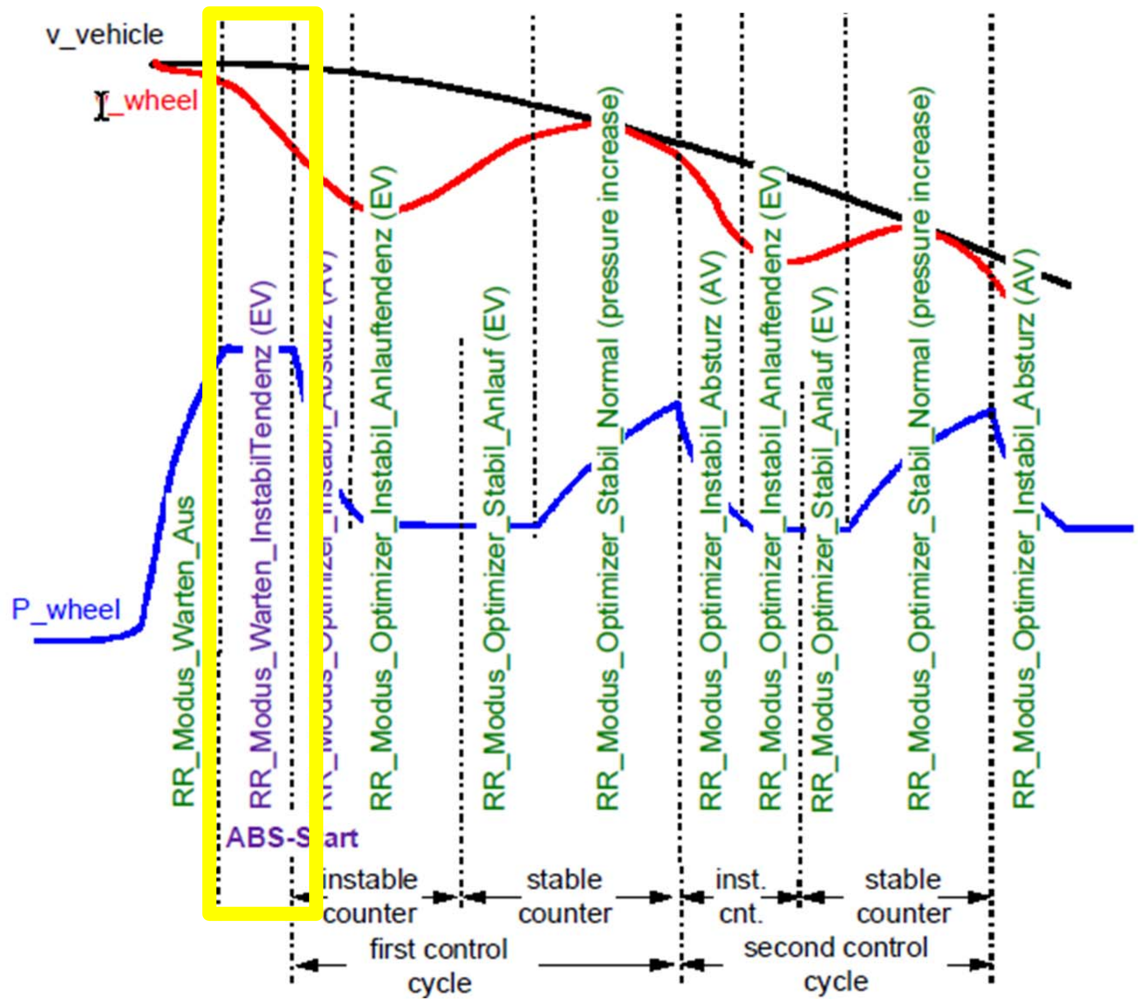
Low Pressure

Atmospheric



- Impending wheel lockup
- ABS control starts

Control Principle: Unstable tendency



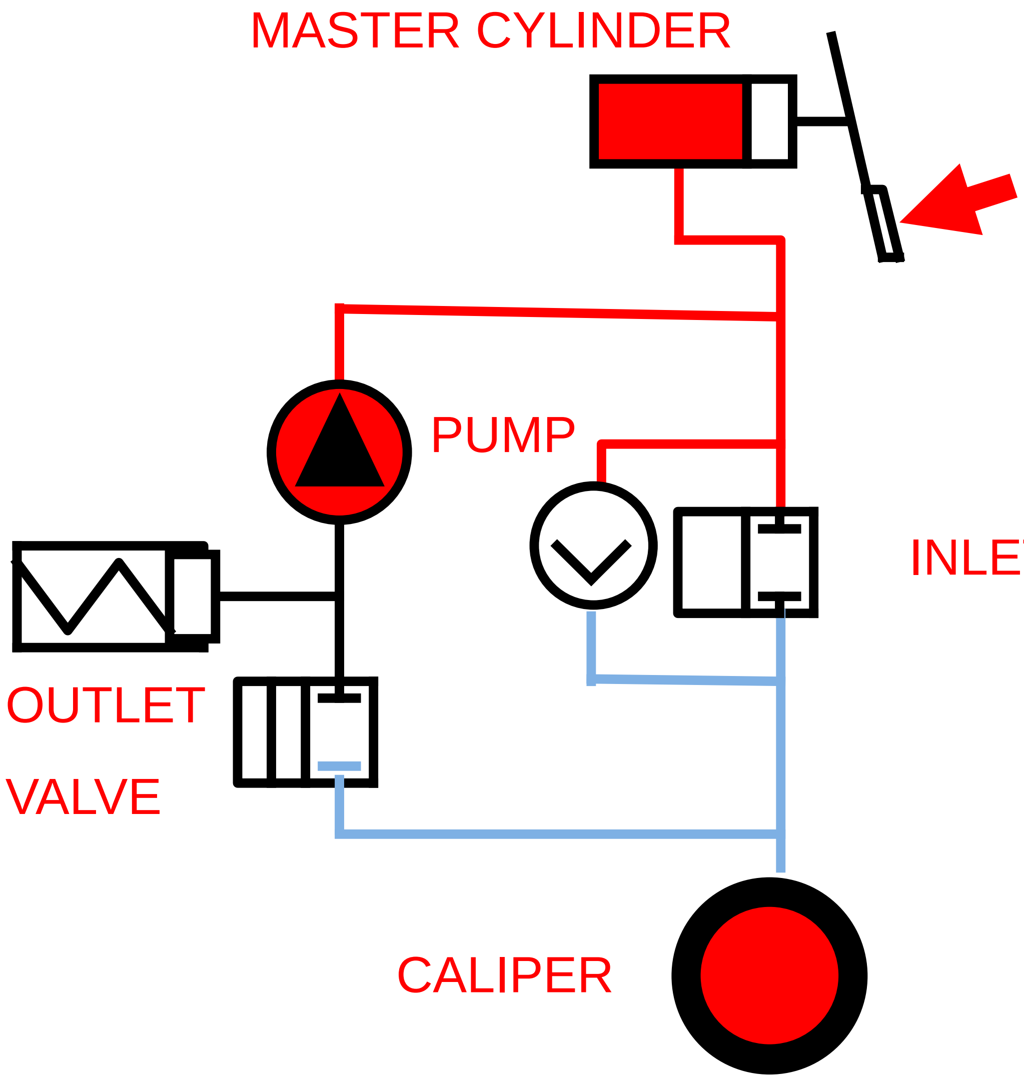
ABS Sequence – Step 2 – Pressure Hold

High Pressure

Isolated Pressure

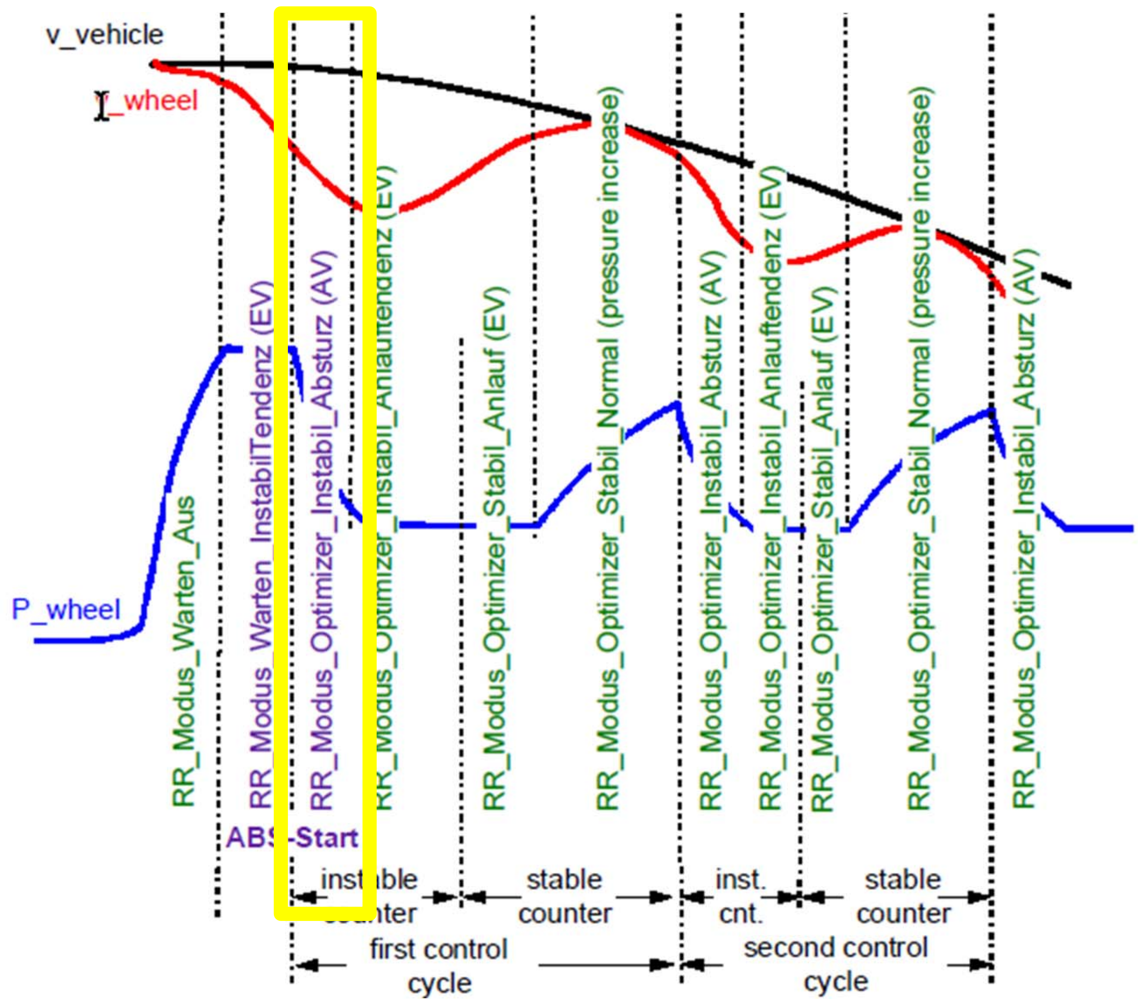
Low Pressure

Atmospheric



- Pump turns on
- Inlet closes
- Outlet remains closed

Control Principle: Instability



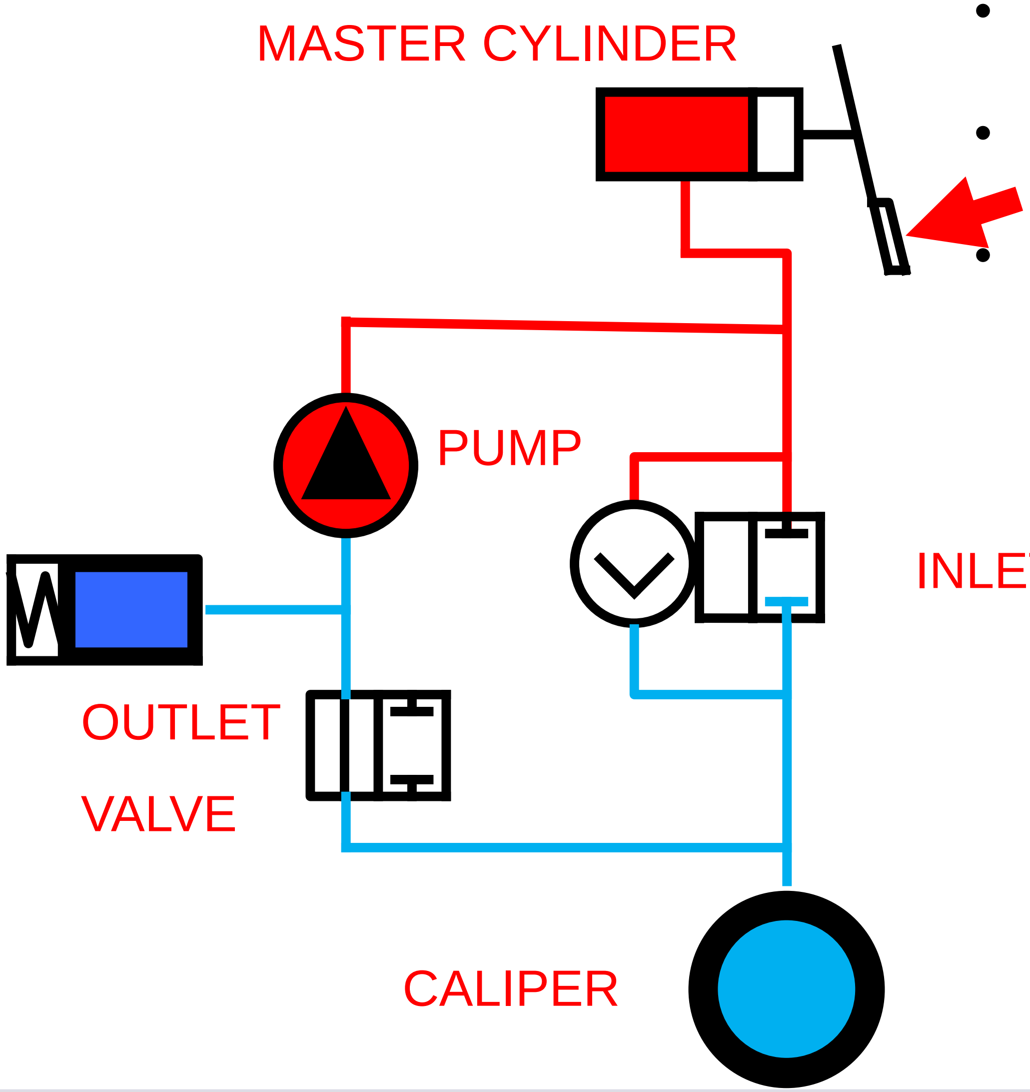
ABS Sequence – Step 3 – Pressure Decrease

High Pressure

Isolated Pressure

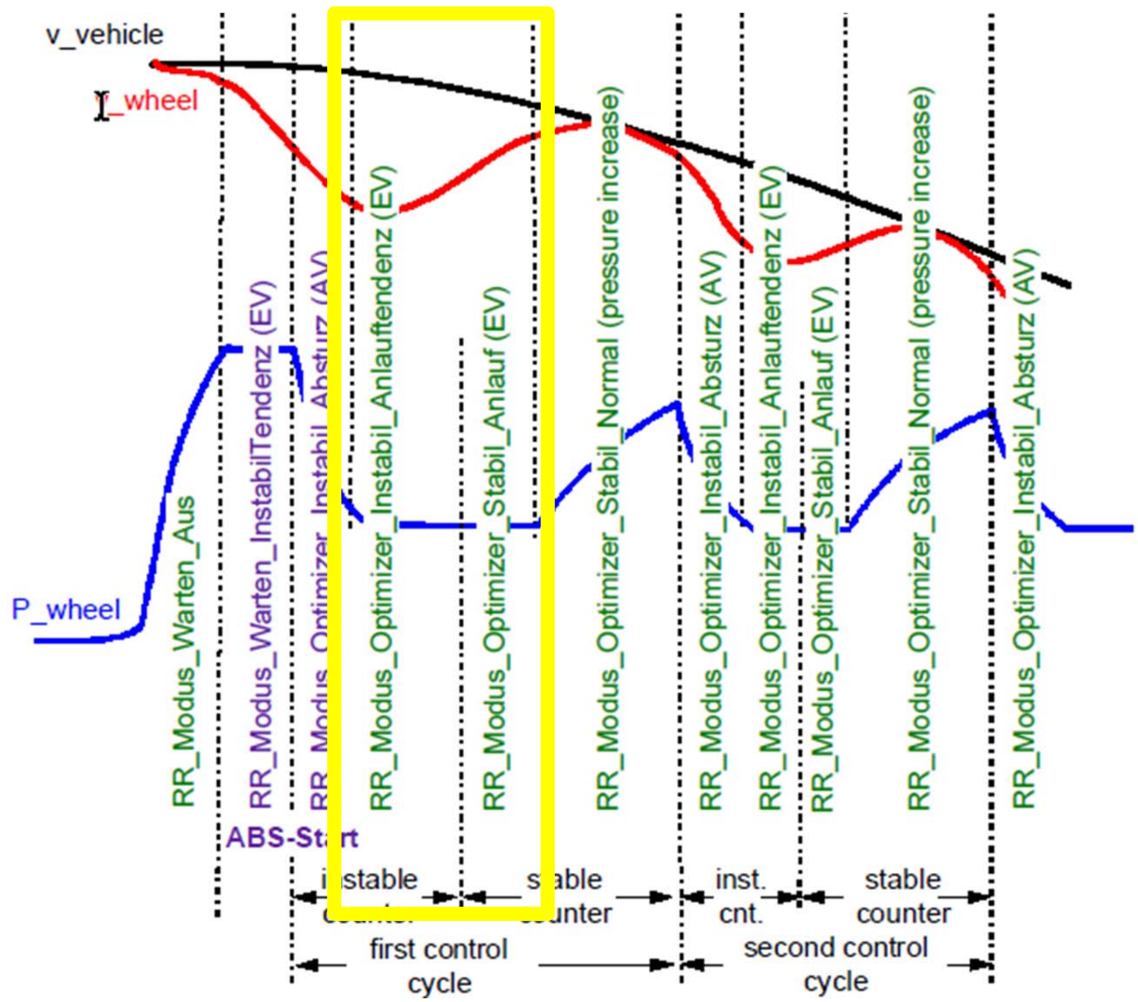
Low Pressure

Atmospheric

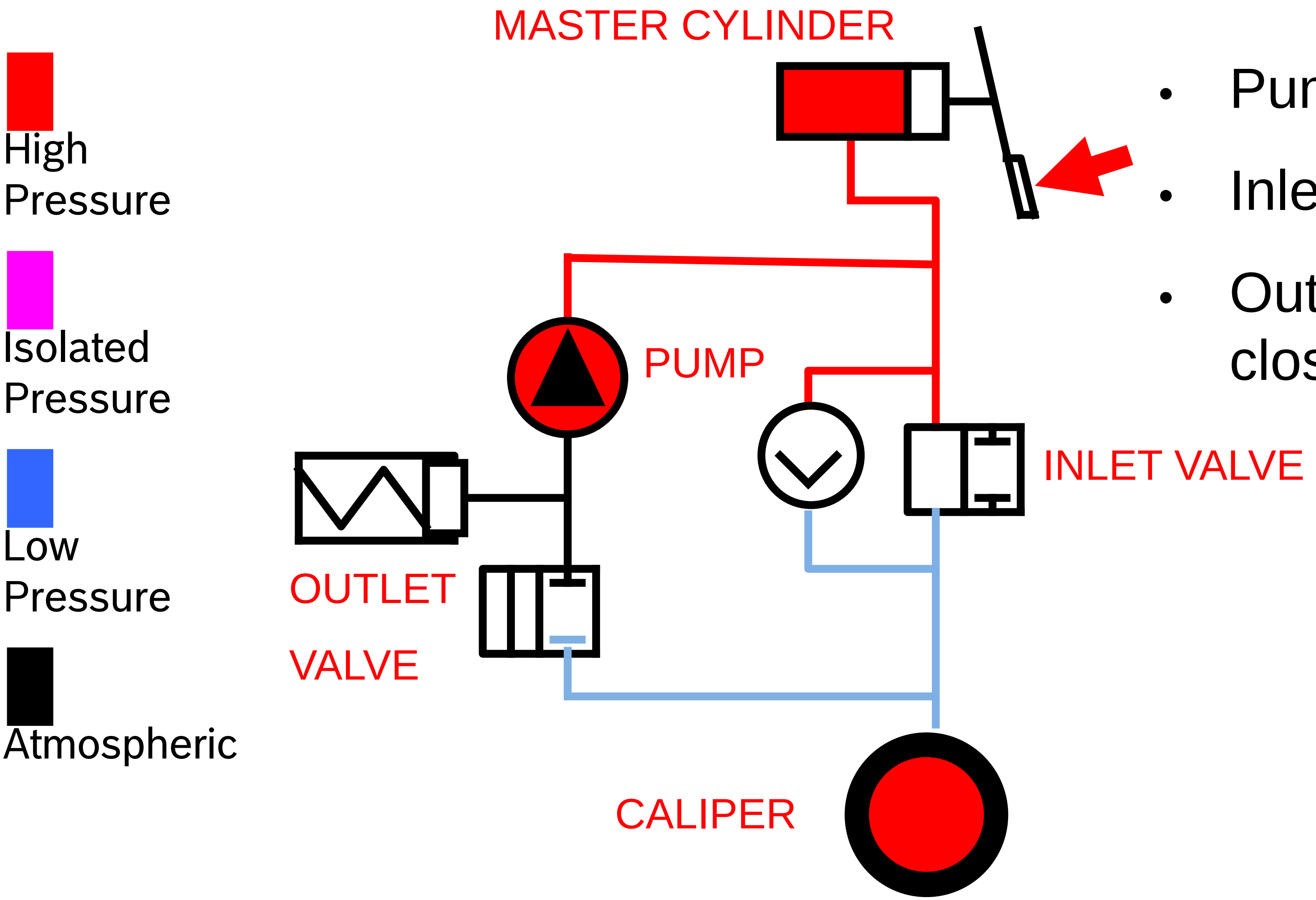


- Pump stays on
- Inlet remains closed
- Outlet opens

Control Principle: Stable tendency

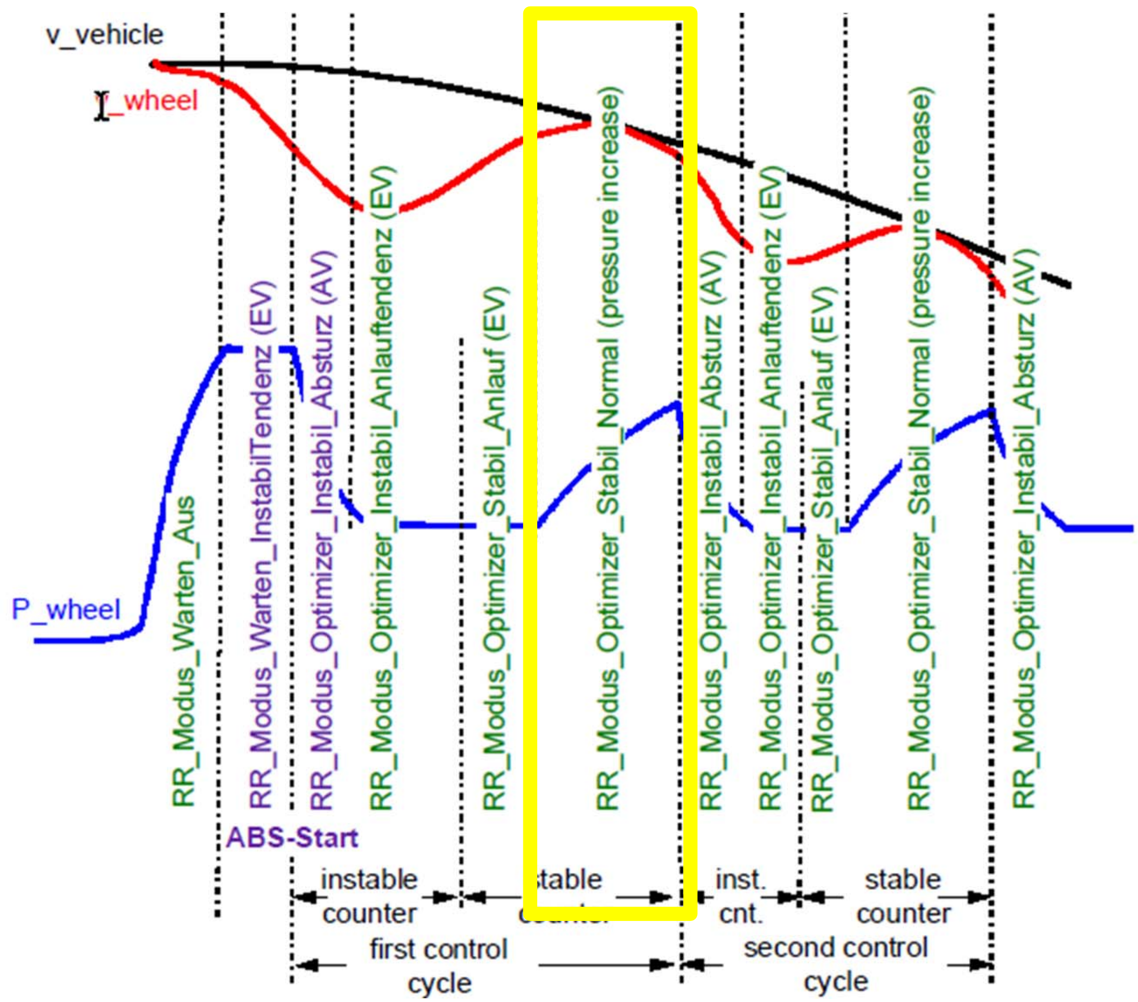


ABS Sequence – Step 4 – Pressure Hold

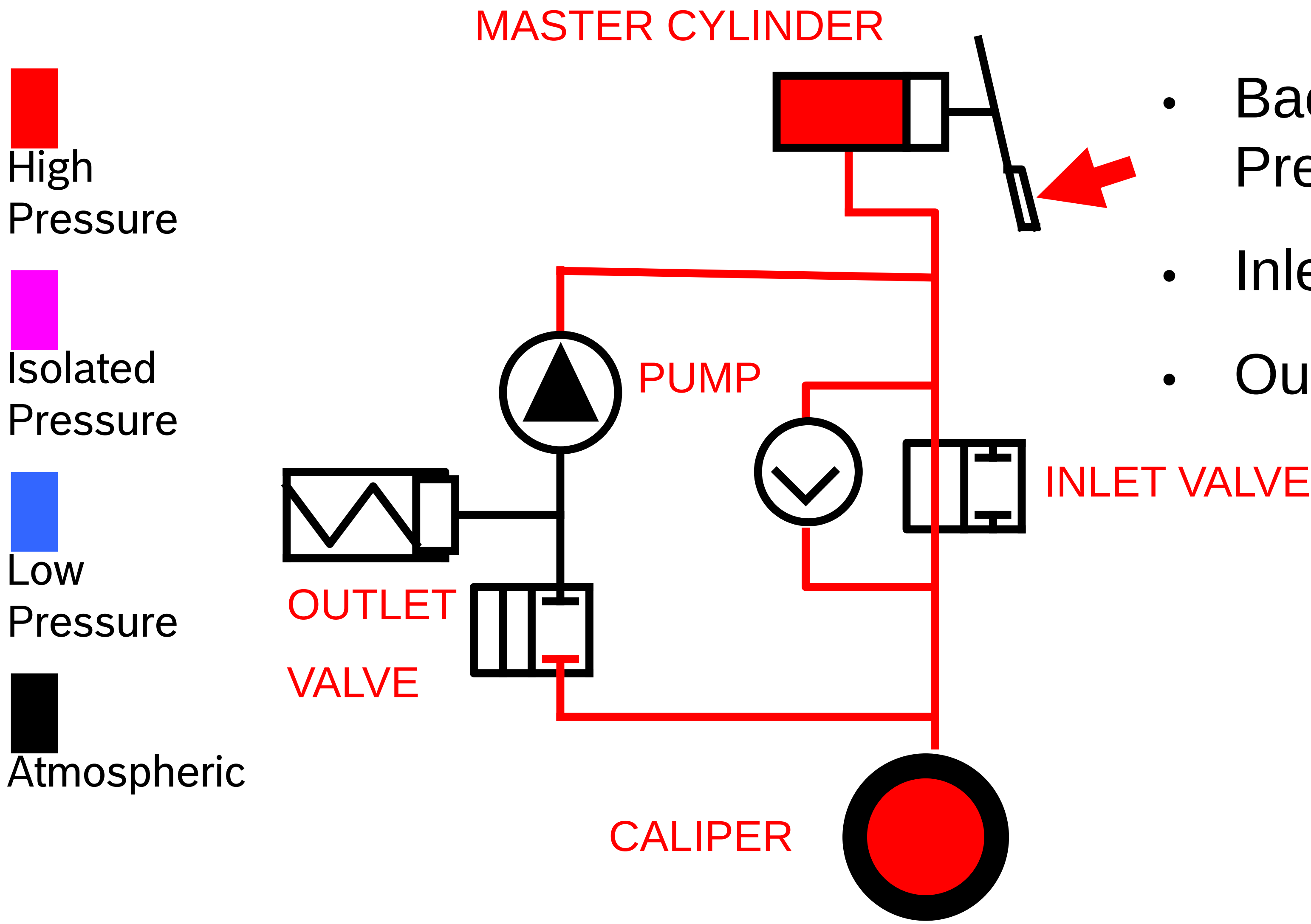


- Pump turns on
- Inlet closes
- Outlet remains closed

Control Principle: Stability



ABS Sequence – Step 4 – Pressure Build



- Back to Step 1: Pressure build
- Inlet Opens
- Outlet closes

ABS Calibration: 2 main subjects

Hydraulic to Friction Model

- Models the relation between a pressure change and a wheel force change
- Compliance can be modeled statically
- The dynamic reaction of the system can be partly modeled statically, but needs track time.
- Depends on teh brake system architecture

Slip Targeting

- Based on tire model and track data
- Mostly a function of the tire, car mass and CG location, downforce, lateral acceleration, etc.
- Can be calibrated to change the car‘s attitude at corner entry: increasing or decreasing rotation whilt trail braking

Conclusion

- ABS Braking is equal or better than non ABS braking in all situation
- A well designed brake system is key to proper ABS operation
- Most brake systems are not properly sized for the car
    - Too much braking power is always better than not enough