A Sensor Fusion Approach To Tire Pressure Monitoring

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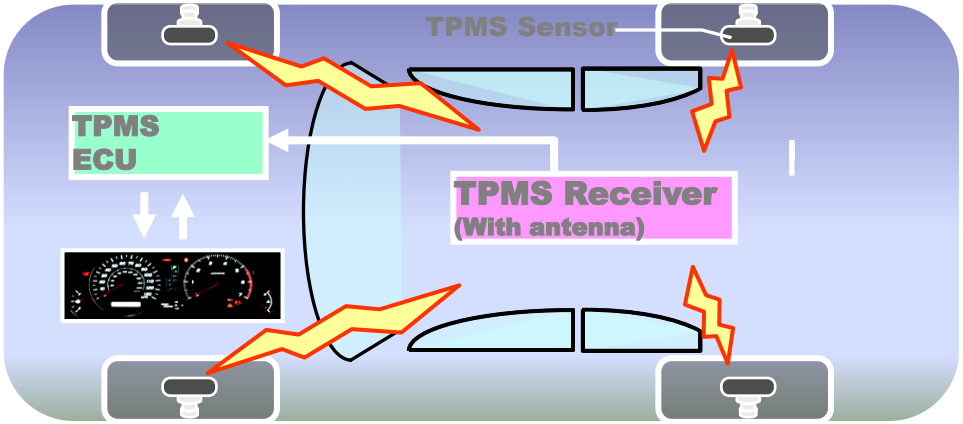
Two Types of TPMS

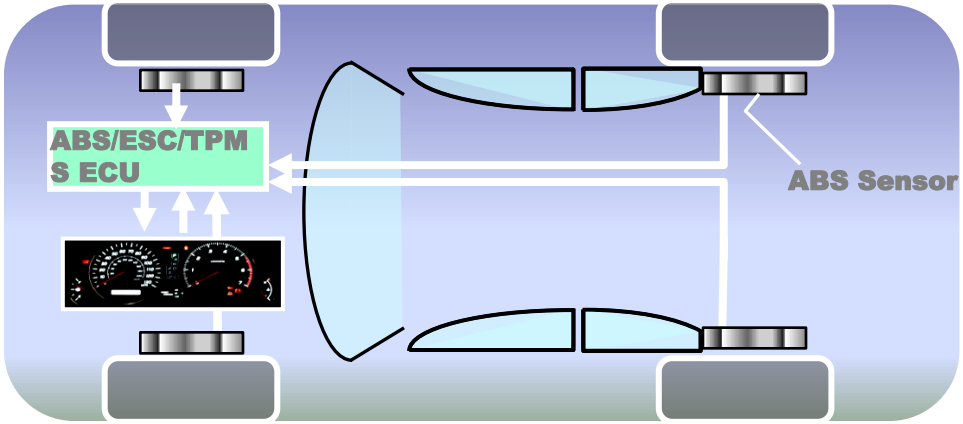
Direct TPMS:

- Hardware-based systems.
- Sensors mounted in the tires communicate pressure information to the dedicated TPMS ECU.



Indirect TPMS:

- Software-based systems.
- The pressure state in the tires inferred from the wheel speed signals and other sensor signals in the vehicle.



About NIRA Dynamics AB

- Privately owned Swedish company founded in 2001.
- Registered office in Linköping, Sweden. Branch office in Gothenburg, Sweden.
- Core expertise in signal processing and sensor fusion for active safety and infotainment applications.
- Develops, markets, and sells software products.
- Market leaders in advanced indirect TPMS.

Motivation For TPMS

TPMSs monitor the tire pressures and can alert the driver of pressure losses before he/she notices it.

- ✓ Increases safety (cf. TREAD Act, FMVSS 138)
- ✓ Reduces environmental impact (emissions, CO2, tire wear)
- ✓ Improves the cost of ownership (fuel consumption, tire wear)
- ✓ Increases driver comfort (no unwanted stops)

Nominal

-30%

Qualifiers To The Previous Statements

- Not all accidents caused by tire issues
- TPMSs will not prevent 100% of the accidents caused by tire issues
- The driver is always responsible for maintaining correct inflation pressure(s) in the tires
- Fuel consumption and CO2 reductions with TPMS ~0.5%
  (cf., e.g., GRRF TPMS cost/benefit analysis report from 2008)

Sensor Fusion

- ”Sensor fusion is the combining of sensory data or data derived from sensory data from disparate sources such that the resulting information is in some sense *better* than would be possible when these sources were used individually.” (Source: Wikipedia)

- Better!?
  - Improved precision of existing sensors.
  - New functionality (virtual sensing).
  - Improved diagnostics capabilities.
  - Low cost (software, no additional hardware).

- Sensor fusion intensively studied in academic research and widely applied in, e.g., defence, aerospace, and vehicle industries.

Theoretical Foundation

- Statistical inference:

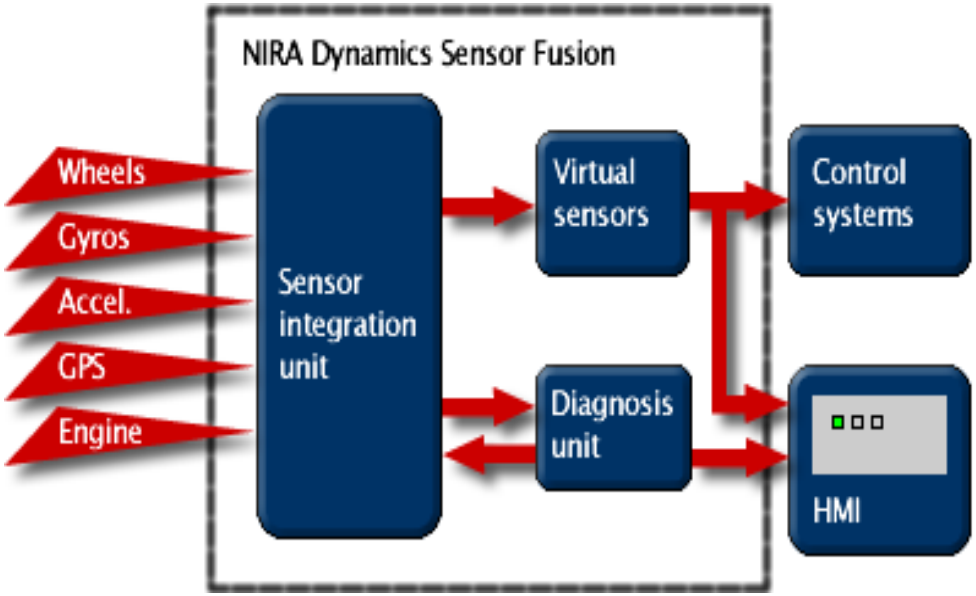
  The probability for observing a state $x(t)$ given measurements $y(1:t)$ is given by Bayes' rule:

$$p(x(t) \mid y(1:t)) = \frac{p(y(1:t) \mid x(t))\, p(x(t))}{p(y(1:t))}$$

  where $p(y(1:t) \mid x(t))$ conditional probability, $p(x(t))$ prior probability, and $p(y(1:t))$ marginal probability.

- Estimation methods: Kalman filtering, particle filtering

NIRA Dynamics Sensor Fusion



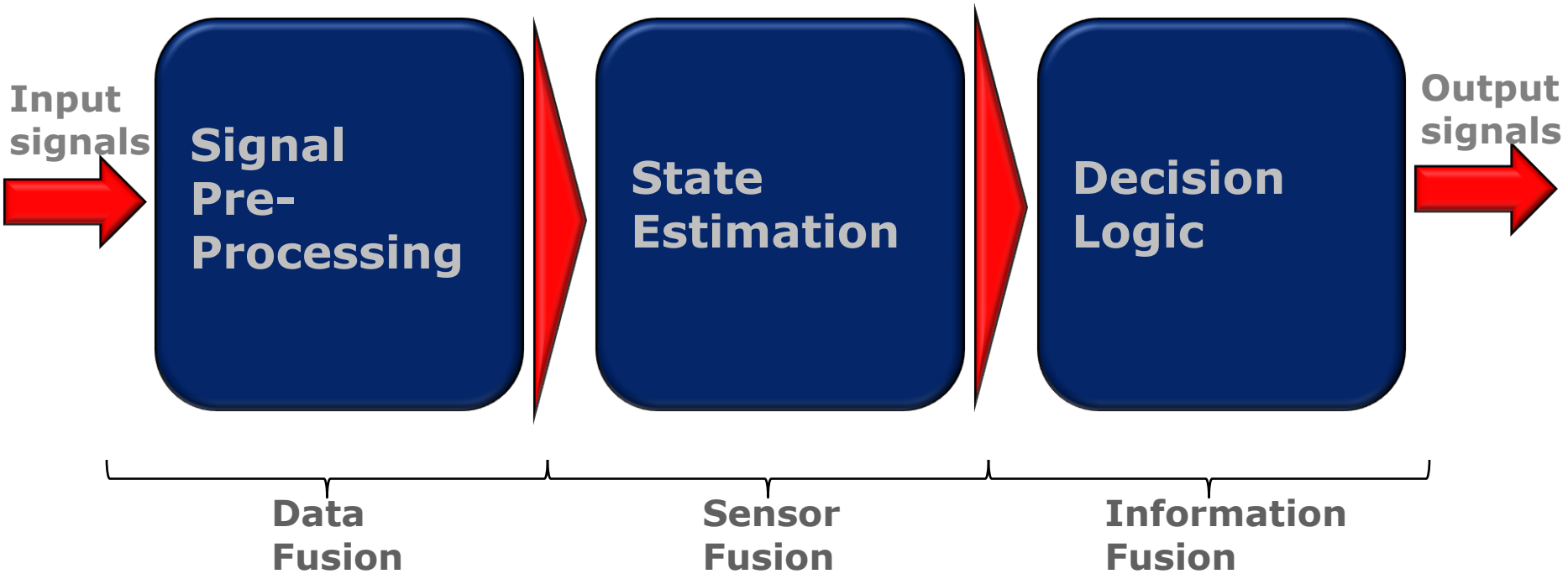
Holistic approach:

Use information from all available sensors in the vehicle and calculate *virtual sensor* signals which can be used in different control and driver information systems.

Application examples:

- MAP – GPS-free positioning
- RFI – Road friction monitoring
- TPI – Tire pressure monitoring

TPI System Design – Multi-Level Sensor Fusion



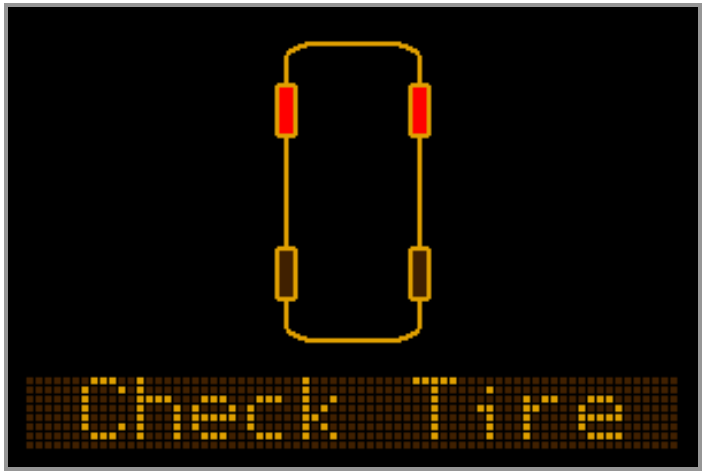
TPI Input/Output Signals

Input Signals

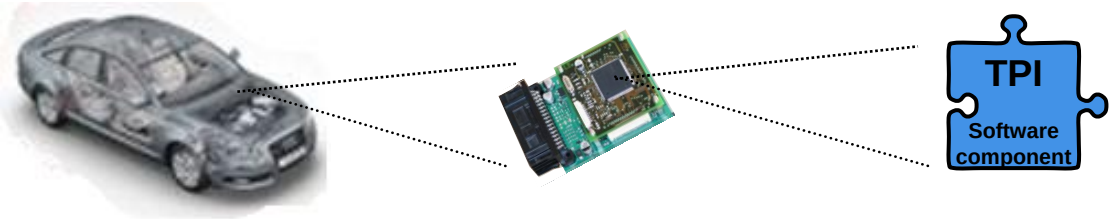
- Wheel speeds
- Engine torque
- Engine RPM
- Yaw rate
- Lateral acceleration
- Longitudinal acceleration
- Status flags
  - Brake active
  - Gearshift in progress
  - Etc.
- AWD state
- Suspension state
- Load state
- …

Output Signals

- Pressure state per tire
- Type of under-inflation detected per tire
- System state
- Error codes

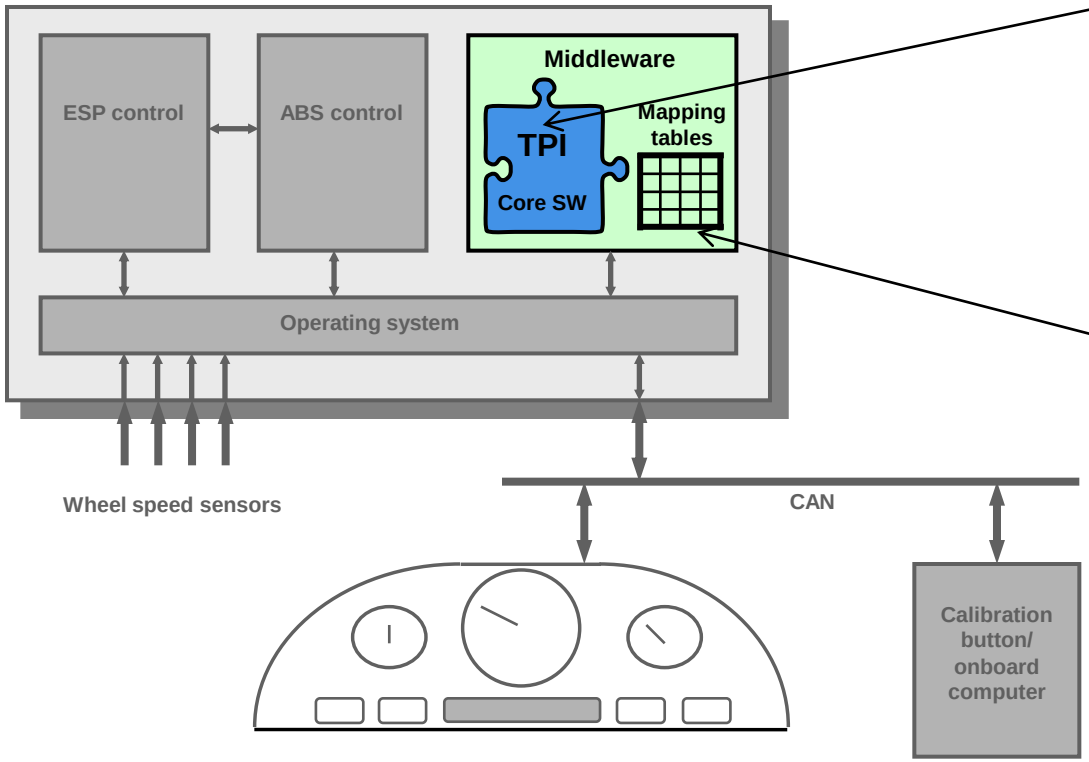


TPI Integration In The Vehicle



- TPI uses only existing sensors in the vehicle and does not require any extra hardware
- TPI can be integrated as is in different target systems such as:
  - ABS/ESC ECU
  - Airbag ECU
  - Chassis/Body ECU
- The TPI software is delivered as a standardized software component compiled for the chosen target processor
- The TPI function is accessed through a well-defined, easy-to-use, public API
- The API controls the signal flow and execution of the TPI software

TPI System Architecture

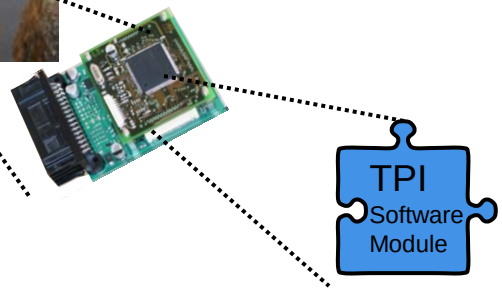


- **TPI core software**
  - Implemented in ANSI C code
  - Delivered as binary file
  - Realizes the TPI function and the API
- **Middleware**
  - Manages
    - TPI execution control
    - I/O handling
    - EEPROM handling
    - Diagnostics
  - Includes application specific mapping tables

TPI Feature Summary

- Low cost, high performance
- Competitive performance:
  - detects under-inflation in 1-4 tires
  - identifies the under-inflated tire(s)
  - meets the requirements in FMVSS 138
  - robust against nuisance warnings

TPI featured in the new Audi TT



- Simple, software-based system design
  - no wheel electronics necessary
  - no RF components necessary
- Long service life, no maintenance
  - no battery change
  - function follows the car not the wheels

Comparison TPI vs. Other Types of TPMSs

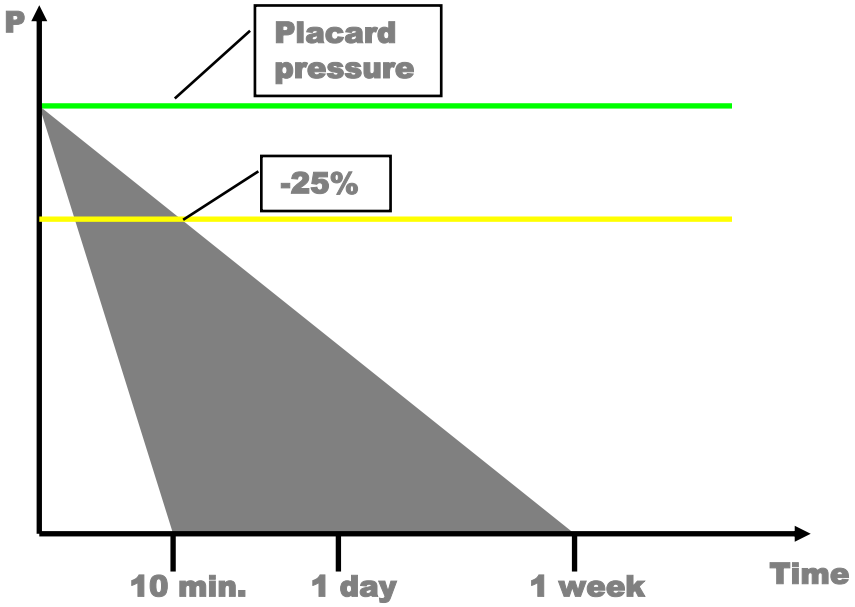
	Direct TPMSs		Indirect TPMSs	
	Advanced	Basic	TPI	1st gen.
Puncture detection 1 tire	✓	✓	✓	✓
Diffusion detection in up to all 4 tires	✓	✓	✓	-
Identification of which tires are under-inflated	✓	-	✓	-
Pressure display possible	✓	-	-	-
Absolute pressure monitoring	✓	✓	-	-
Warning threshold	arbitrary	arbitrary	20-25 %	30-35 %
Reset / calibration button	✓	-	✓	✓

Cost Comparison Direct/Indirect TPMS

	Direct TPMSs	Indirect TPMSs
Piece price 2014 (high volume)	~50 €	~8 €
Maintenance costs over vehicle lifetime	~350 €	0 €
Total	~400 €	~8 €

TPMS Requirements in Real-World Pressure Drop Scenarios

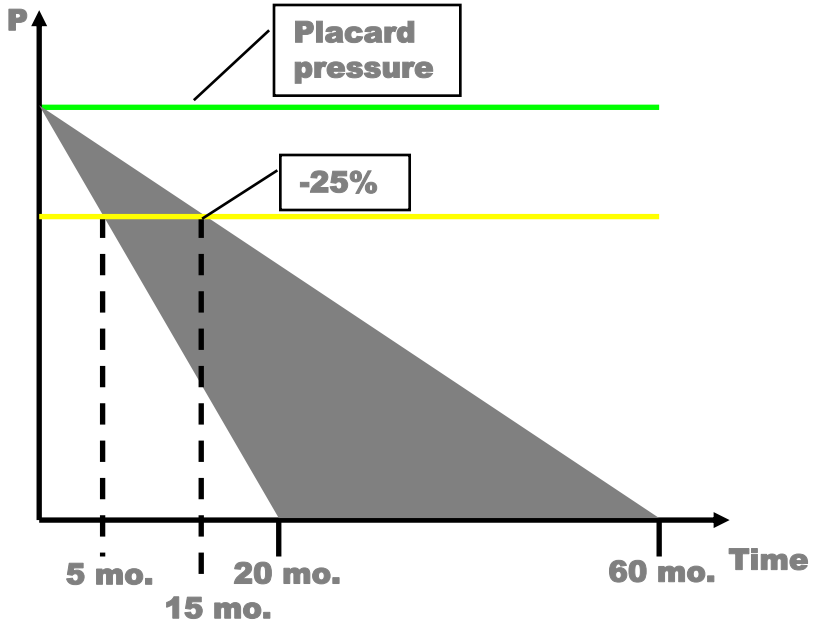
Punctures



Main requirement: quick warning

(Non-requirement: warning threshold)

Diffusion



Main requirement: monitoring of all four tires

(Non-requirement: detection time)

Summary

- **Why TPMS?**
  - ✓ Safety
  - ✓ Environment
  - ✓ Economy
  - ✓ Comfort

- **Why indirect TPMS?**
  - ✓ **Cost.** No additional sensors needed, no maintenance costs.
  - ✓ **Easy to integrate.** Software-based solution, uses only existing sensors, requires no additional hardware.
  - ✓ **Performance.** Advanced indirect TPMS like TPI detect pressure drops in up to all 4 tires, are robust against nuisance warnings, work with all kinds of tires.
  - ✓ **Reliability.** Software doesn't break.

Thank you for your attention!

Backup

TPI Test Results, Example 1: 2 Tires, -25%

Test Information

Purpose:
2 tire deflation

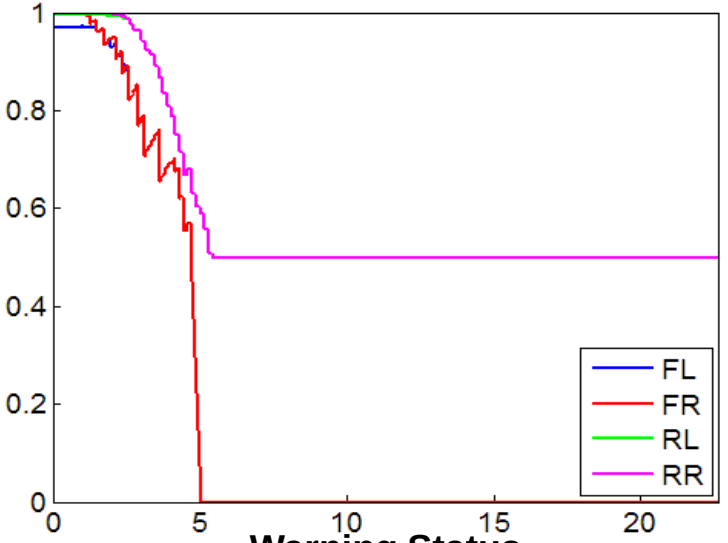
Road surface:
Asphalt

Vehicle:
Audi A6 3.2 FSI FWD

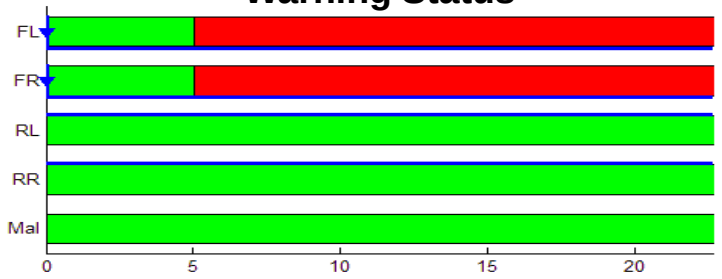
Tires:
Bridgestone Potenza 255/40-R18

Pressures (kPa):
FL: 230 -> 173
FR: 230 -> 173
RL: 270
RR: 270

Pressure Indicators



Warning Status



TPI Test Results, Example 2: 4 Tires, -25%

Test Information

Purpose:
4 tire deflation

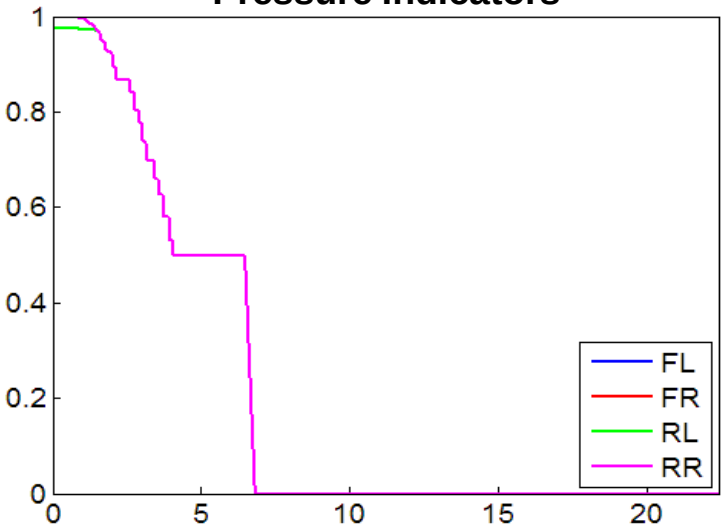
Road surface:
Asphalt

Vehicle:
Audi A6 3.2 FSI FWD

Tires:
Bridgestone Potenza 255/40-R18

Pressures (kPa):
FL: 230 -> 173
FR: 230 -> 173
RL: 270 -> 203
RR: 270 -> 203

Pressure Indicators



Warning Status