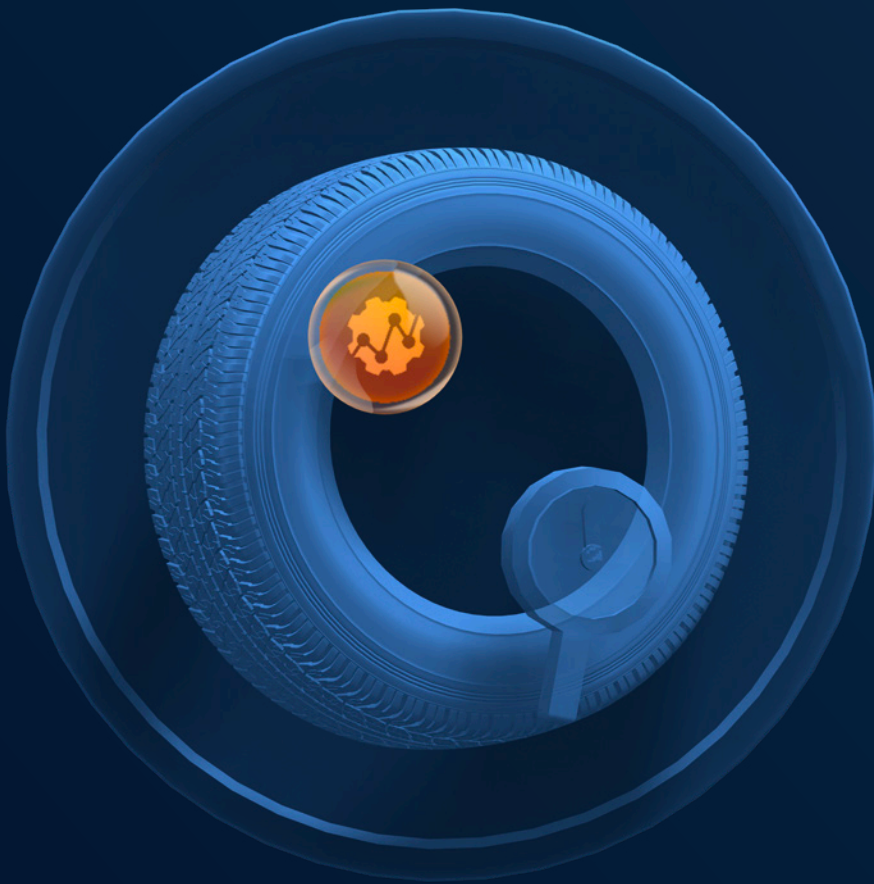




Virtual Tire Pressure Monitoring System (vTPMS)

Revolutionizing Tire Pressure Monitoring
without additional hardware



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INTRODUCTION

Conventional Tire Pressure Monitoring Systems (TPMS) rely on dedicated in-wheel pressure sensors, increasing system cost and complexity. This paper introduces COMPREDICT's virtual Tire Pressure Monitoring System (vTPMS), a 100% software-based virtual TPMS that provides real-time absolute tire pressure values, rather than simple pressure warnings, and is fully compliant with UNECE R141 requirements. Leveraging vehicle dynamics and powertrain signals already available on standard ECUs, the solution estimates pressure per tire with high accuracy. Several implementation options are discussed, including integration into existing ECUs or mobile applications, offering flexibility for OEMs. Validation results demonstrate that this approach achieves comparable accuracy to hardware TPMS while enabling significant cost and weight reductions at scale.

Business and Market Advantages of the vTPMS Solution

COMPREDICT's vTPMS presents three major business advantages that collectively enhance its performance and applicability (Figure 1).

The most obvious advantage of COMPREDICT's vTPMS is **the massive cost savings it brings**. By eliminating the need for physical sensors, OEMs and Tier 1 suppliers can save millions of euros, especially at scale. The absence of hardware not only reduces manufacturing costs but also cuts down on installation and maintenance expenses.

One of the common issues with traditional TPMS is the maintenance of physical sensors, which are prone to failure and compatibility issues, often requiring costly replacements. These defective sensors often trigger false warnings, leading to customer dissatisfaction and additional expenses. Our vTPMS, a **software-only solution with zero maintenance hassles**, eradicates these problems. Since it doesn't rely on any physical components, the system requires no maintenance and eliminates the risk of sensor malfunction.

COMPREDICT's innovation stands as **the first 100% Virtual Sensor capable of meeting all functional requirements of a traditional TPMS**. This includes accurate tire pressure readings, continuous monitoring, and the capability to trigger warnings when necessary all without physical sensors. The software solution offers efficiency, seamlessly integrating into existing vehicle architectures, regardless of tire brands and sizes.



Figure 1 - Main benefits of COMPREDICT's vTPMS

USE CASE: TIRE PRESSURE MONITORING

The next section introduces the concept of Virtual Sensors, provides an overview of the current state of the art in TPMS, and examines the regulatory issues and challenges related to their deployment.

Introduction and Definition of Virtual Sensors

Virtual Sensors are an entirely software-based approach designed to estimate physical time-series signals with high accuracy. These algorithms can be built on domain-specific physical models, data-driven approaches such as machine learning, or a hybrid of both methodologies. To develop and validate a Virtual Sensor, a high-precision reference signal is required. This is typically obtained via specialized hardware sensors during the development, serving as the reference (“ground truth”). The core objective of a Virtual Sensor is to intelligently combine data from the vehicle’s existing sensors to accurately replicate this reference signal, without the need for additional hardware at runtime.

Once calibrated for a specific vehicle and target, the Virtual Sensor can be deployed across identical vehicle models. The solution is integrated directly into the vehicle’s hardware, such as Electronic Control Units (ECUs) allowing real-time processing, reduced latency, and tighter integration with in-vehicle networks and sensor data within Software-Defined Vehicle (SDV) architectures.

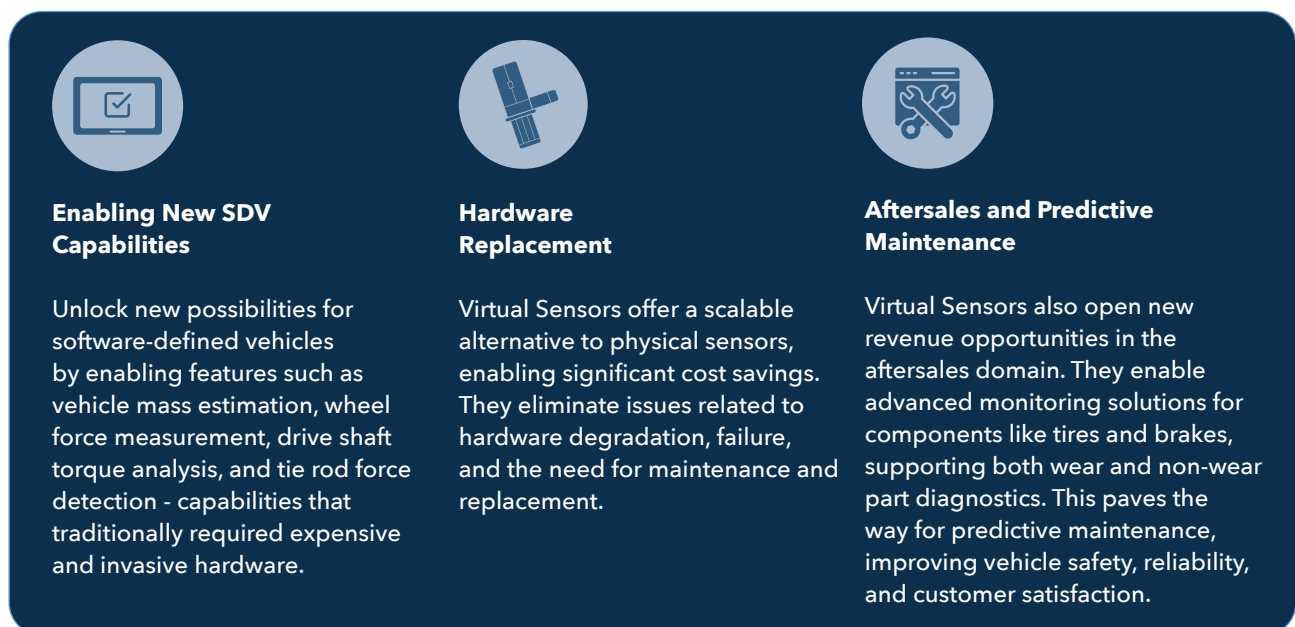


Figure 2 - Use Cases for Virtual Sensors

USE CASE: TIRE PRESSURE MONITORING

Tire Pressure Monitoring System State of the art

Tire pressure systems follow two main approaches: **Tire Pressure Warning (TPW)** and **Tire Pressure Monitoring Systems (TPMS)**.

Tire Pressure Warning (TPW) - also referred to as **indirect TPMS** - operates under strict regulatory frameworks and relies on data from existing vehicle sensors such as **ESP** or **ABS wheel speed sensors**. By analyzing variations in wheel rotation speed, TPW systems can detect a loss of pressure in one or more tires, providing a regulatory-compliant solution for tire pressure warning without requiring additional hardware on the wheel.

In contrast, **direct TPMS solutions** integrate dedicated pressure sensors mounted on each tire or rim, enabling the **accurate measurement of absolute pressure** in every tire. This direct approach provides higher precision and real-time monitoring capabilities, supporting enhanced safety, performance, and energy efficiency.

Compared to TPW, **TPMS offers superior safety, precision, and driver experience**, making it the more advanced and reliable solution for tire pressure management (Figure 3).

	TPMS SOLUTION	TPW SOLUTION
SAFETY	PROACTIVE <ul style="list-style-type: none"> Real-time pressure reading Proactive maintenance 	REACTIVE <ul style="list-style-type: none"> Warning indicator only after critical pressure drop
PRECISION & ACCURACY	EXACT Tire Pressure Reading	GENERIC Alert without specific values
LEAK DETECTION	EARLY - ensuring accurate monitoring	LATE - after a dangerous low-pressure level is reached
COST EFFICIENCY	Proper Pressure Management reduces Rolling Resistance & improves Fuel Economy	Underinflated Tires undetected by simple warning wear out faster
DRIVING EXPERIENCE	Detailed Insights of Tire Health, increasing confidence and control	Uncertainty can remain (which Tire is affected and by how much)

Figure 3 - TPMS versus TPW

Despite its many advantages, TPMS remains a costly solution, which is why COMPREDICT's vTPMS emerges as a viable alternative, combining performance and affordability.

USE CASE: TIRE PRESSURE MONITORING

Regulation and Compliance Stakes

The UNECE R141 regulation defines the requirements for TPW, which must evaluate tire pressure or its variation over time and inform the driver while the vehicle is in motion.

Since 1 November 2014, all new vehicles in Europe must be equipped with a system capable of detecting tire pressure drops, making Europe a global leader in tire pressure regulation.

To comply with UNECE R141, systems must successfully pass three mandatory tests:

- **Puncture Test**, detecting a 20% pressure loss (or below 1.5 bar) in a single tire within 10 minutes
- **Diffusion Test**, detecting similar losses across multiple or all tires within 60 minutes
- **Malfunction Test**, identifying any system fault affecting signal generation or transmission within 10 minutes.

These stringent requirements underscore the critical role of TPMS technologies in ensuring vehicle safety, reliability, and regulatory compliance.

The following section details the development of COMPREDICT's vTPMS, designed to deliver hardware-level accuracy and performance while fully complying with the regulatory requirements defined in UNECE R141.

DEVELOPMENT OF THE VIRTUAL TPMS

We summarize how our vTPMS has been developed, presenting the physical foundation of the solution, outlining the virtualization process from data acquisition to calibration, and concluding with an overview of external factors influencing the Virtual Sensor, such as temperature and tire wear.

Physical Approach

The vTPMS predicts absolute tire pressure based on vehicle CAN data and a limited set of vehicle metadata.

The model is based on the principle that a change in tire pressure influences the tire's effective rolling radius, which in turn modifies the tire angular wheel speed for a given vehicle speed:



DEVELOPMENT OF THE VIRTUAL TPMS

$$\frac{r_i}{r_j} \approx \frac{\omega_i}{\omega_j} \text{ where } r \text{ is the radius and } \omega \text{ is the angular speed of tires } i \text{ and } j.$$

This relationship holds true under pure rolling conditions, but when enhanced with AI, the Virtual Sensor can predict the absolute tire pressure throughout every dynamic driving event.

Data Collection and Preparation

Virtual Sensor accuracy improves after a structured three-phase calibration process (see Figure 4) conducted outside the vehicle before integration. The **data collection phase** for each vehicle type gathers CAN signals, metadata, and sensor measurements into a comprehensive dataset. The **data preparation phase** includes pre-processing, filtering, and quality checks for data consistency. The **calibration phase** then runs the calibration pipeline, validates Virtual Sensor predictions, and optimizes accuracy.

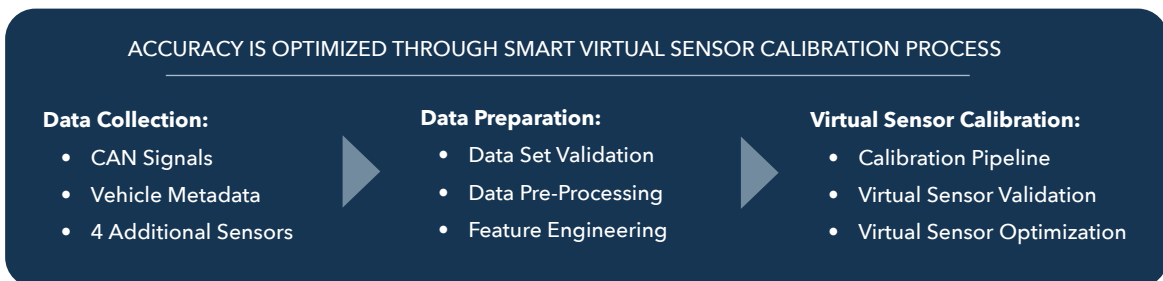


Figure 4 - Virtual Sensor calibration process

The main objective of the **data collection phase** is to acquire comprehensive datasets directly from the vehicle's CAN network. The image below illustrates COMPREDICTOR, a Renault Megane e-TECH, our demonstration vehicle. (Figure 5).



Figure 5 - COMPREDICTOR demo vehicle (Megane e-TECH)

DEVELOPMENT OF THE VIRTUAL TPMS

The Virtual Sensor requires a basic list of CAN signals and frequencies, such as wheel speeds, longitudinal acceleration, and brake pressure, which are commonly found in standard vehicle architectures. To obtain reliable ground-truth data, automotive-grade TPMS sensors with accuracy comparable to series production systems were used as reference.



Figure 6 - Hardware TPMS sensor mounted on COMPREDICTOR

The third component of the data collection phase involves gathering detailed **vehicle metadata**, including parameters such as wheel diameter, tire specifications or OEM nominal pressures, that will be used during the calibration phase.

The data collection follows a structured measurement campaign encompassing a wide range of **driving maneuvers, tire pressures (including regulation requirements), tire specifications, road surfaces, weather conditions, and vehicle load configurations** executed over a short measurement campaign (two days) (Figure 7). This diversity ensures the robustness and generalizability of the Virtual Sensor across varying operational scenarios.



Figure 7 - COMPREDICTOR on testing tracks - UTAC Mortefontaine

DEVELOPMENT OF THE VIRTUAL TPMS

After data collection, the next essential stage is **data pre-processing**, which ensures the dataset is clean, consistent, and ready for analysis. In this stage, data scientists refine the raw input by organizing, formatting, and validating it to maintain reliability and accuracy.

The process begins by identifying and handling missing values, followed by resampling the data to the appropriate frequency and applying scaling techniques. Several additional steps are then carried out, such as:

- Addressing logging imperfections like outliers or signal noise
- Deriving key features from the raw data
- Aligning signals to correct any time shifts or lags introduced by the OEM internal systems, which could otherwise distort the machine learning results

Once pre-processing is complete, the refined dataset enters COMPREDICT's end-to-end processing pipeline, where a sequence of transformation stages derives it into a virtual Tire Pressure Monitoring Algorithm.

Virtual Sensor Calibration & Recalibration

The goal of the calibration process is to establish how variations in tire pressure translate into changes in vehicle input signals under a wide range of external conditions. By understanding these relationships, the Virtual Sensor can reliably infer tire pressure without requiring dedicated hardware. Once calibrated, the model can be deployed across identical vehicles.

A key challenge lies in ensuring the model generalizes well: it must remain accurate when tires differ in size or season, or when external factors such as temperature or load vary. The calibration parameters are therefore designed to account for these variations and enable the model to adjust when tires are changed or pressures are reset.

To support long-term adaptability, the system includes a lightweight recalibration step that the user can trigger. Once the driver confirms that tires have been replaced or pressures reset, assuming all tires are back to their nominal values, the model performs an online recalibration using fresh nominal driving data, keeping performance consistent over time.



DEVELOPMENT OF THE VIRTUAL TPMS

Tire Pressure estimation is influenced by a variety of external factors, including load, temperature, tire wear or weather conditions (Figure 8).



Figure 8 - External factors with potential impact on vTPMS

To quantify and understand these effects under diverse conditions, we conduct a dedicated Design of Experiment (DoE) campaign, carefully structured to isolate and measure the impact of each factor. This allows us to accurately model their behavior and improve the reliability of tire pressure estimation across different operational scenarios.

Inference and Operations of the model

The vTPMS operates fully in **real-time**, running on the vehicle's embedded system and processing input data at **10 Hz**. At this frequency, the model continuously interprets CAN-based signals to estimate absolute tire pressure. A first reliable estimation is produced only after the system has collected sufficient trigger points, typically a combination of reaching a minimum speed threshold and observing stable signal patterns. This convergence time can be tailored to each customer's requirements, balancing responsiveness with robustness.

To support different product strategies and integration needs, the vTPMS's output can be displayed through multiple interfaces: directly in the **in-vehicle infotainment (IVI)** system (primary use case), via a **smartphone application** connected to the vehicle, or through a **dedicated screen** in demonstration vehicles such as COMPREDICTOR (Figure 9). Since raw real-time estimation happens at 10 Hz, a lightweight post-processing layer smooths the output to avoid oscillations in the displayed absolute pressure value, ensuring a stable and intuitive user experience.

DEVELOPMENT OF THE VIRTUAL TPMS



Figure 9 - COMPREDICTOR illustration - vTPMS

The model is designed to withstand the most influential external factors, particularly **vehicle load** and **ambient temperature**. Additional factors are handled through an **AI-assisted calibration** procedure that ensures the model remains accurate across diverse driving scenarios, tire types, and environmental variations.

The proposed solution leverages a **hybrid physical and AI-infused modeling** framework to account for the complex interactions between tire behavior, vehicle dynamics, and environmental conditions. This physics-informed learning approach enables robust and scalable estimation of tire pressure under real-world driving conditions, surpassing the capabilities of conventional indirect TPMS concepts.

To maintain accuracy across trips, the model uses **persistent variables** that preserve essential internal states between drives.

When the driver replaces tires or resets pressures, a user-triggered **recalibration** routine updates the model online using nominal driving data, ensuring fast reconvergence without requiring specialized tools or long procedures.



RESULTS, ACCURACY AND REGULATORY COMPLIANCE

In this section, we present the results of our vTPMS, beginning with a brief overview of the key metrics used to evaluate the performance of our model. These metrics provide a quantitative basis for assessing accuracy, robustness, and consistency under various operating conditions.

We examine the model's behavior across a range of use cases, beginning with nominal tire pressure scenarios, followed by regulatory conditions that demonstrate the model's compliance and reliability within standardized frameworks, and concluding with edge cases designed to test the system's performance under extreme conditions.

Metrics

We defined several metrics to evaluate the performance of our model.

Among them, the **Mean Absolute Error (MAE - Figure 10)** computed across all tires (both for individual trips and aggregated over all trips) serves as a primary indicator of accuracy.

The MAE is calculated from the end of each trip until completion of the trip, ensuring that transient effects during the initialization phase do not bias the evaluation. MAE is reported in mbar to match TPMS engineering conventions.

METRICS	PURPOSE	FORMULA
MAE (Mean Absolute Error)	Measures the average magnitude of errors (true pressure value vs prediction) in a / different trips	$MAE = \frac{1}{n} \sum_{i=1}^n y_i - \hat{y}_i $ <p> <i>y_i</i> : Pressure true value <i>ŷ_i</i> : Pressure prediction <i>n</i> : number of predictions </p>

Figure 10 - Mean Absolute Error purpose and formula

At the conclusion of each trip or at a specified time, we calculate the **Absolute Error (Figure 11)** as outlined below to measure the model's accuracy at a specific point.

METRICS	PURPOSE	FORMULA
Absolute Error (at the end of the trip / after x minutes)	Measures the absolute error (pressure true value vs prediction) at the end of the trip or at a predefined time	$AE = y_i - \hat{y}_i $ <p> <i>y_i</i> : Pressure true value <i>ŷ_i</i> : Pressure prediction </p>

Figure 11 - Absolute Error purpose and formula

RESULTS, ACCURACY AND REGULATORY COMPLIANCE

In addition to the MAE and AE, specific evaluation metrics are introduced for puncture detection and diffusion detection, which are directly related to regulatory requirements. A correlation (confusion) matrix (Figure 12) is constructed based on a pressure detection threshold defined according to the values specified in the regulatory framework, to verify that the model correctly identifies all relevant cases.

METRICS	PURPOSE	FORMULA		
Correlation Matrix	Compares the values predicted by the model with the true values.	Prediction : Positive	Prediction : Negative	
		True Value : Positive	TP (True Positive)	FN (False Negative)
		True Value : Negative	FP (False Positive)	TN (True Negative)

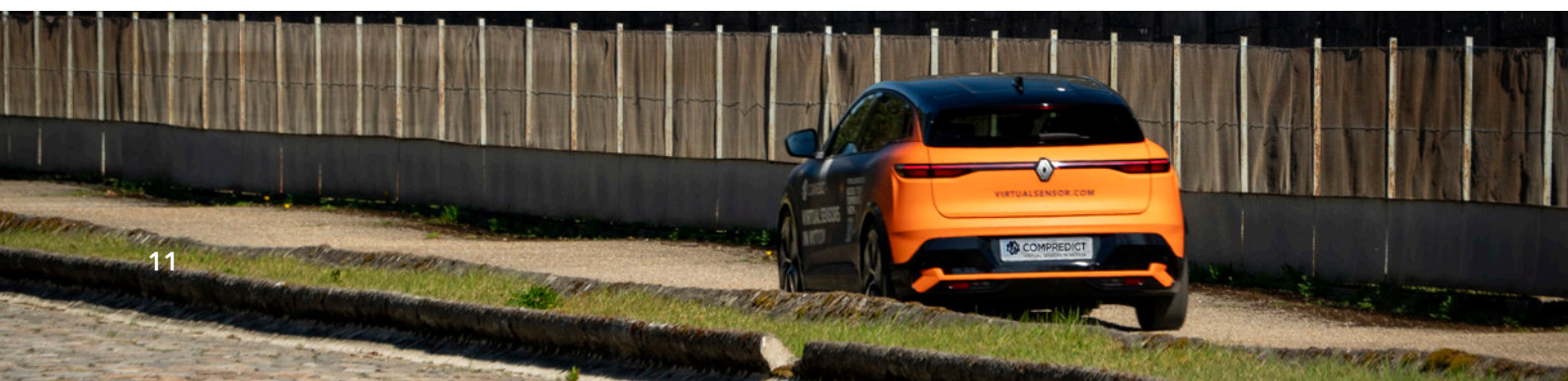
Figure 12 - Correlation (confusion) matrix purpose and formula

From this matrix, we particularly monitor two key metrics (Figure 13):

- **Recall**, which measures the model's ability to identify all true positive events (i.e., successfully detecting every puncture or diffusion case)
- **Precision**, which quantifies the proportion of correctly identified positive detections among all detections made by the model

METRICS	PURPOSE	FORMULA
Puncture and Diffusion RECALL After 10 min driving	Measures model ability to find all true positive (TP) - Important for regulation point of view	$RECALL = \frac{TP}{TP + FN}$
Puncture and Diffusion PRECISION After 10 min driving	Measures the reliability of the positive predictions	$PRECISION = \frac{TP}{TP + FP}$

Figure 13 - Recall & Precision purpose and formula



RESULTS, ACCURACY AND REGULATORY COMPLIANCE

COMPREDICTOR General Results

As part of a validation campaign we conducted the following 15 trips with COMPREDICTOR on a test track:

- 2 warm-up trips
- 6 trips with all tires at nominal pressure (varying loads and conditions)
- 3 trips with a punctured tire
- 4 trips with all tires deflated.

TPMS sensors provided reference values. We calculated the Mean Absolute Error (MAE) for each trip and tire. The overall MAE for all trips and tires is shown below:

$$MAE (all\ tires\ all\ trips) = 108\ mbar$$

This result is highly precise, matching hardware sensor deviation, and can be further improved with a few additional calibration trips when higher MAE is observed.

Next, we will discuss the different types of trips in detail.

Nominal pressure

We drove under normal city conditions for 15 minutes with all tires at **nominal pressure** (Figure 14). You will find below the Absolute Error for the 2 front tires after 5 and 10 minutes, with the plots of the first 5 (Figure 15) and last (Figure 16) minutes. Dashed lines represent predicted values, while solid lines indicate actual values.

COMPREDICTOR	Front Tires	Rear Tires
Nominal Tire Pressure (mbar)	2600 mbar	2500 mbar

Figure 14 - Definition of COMPREDICTOR OEM nominal pressures

In Figure 15, the initial five minutes of the trip are presented. The model begins its predictions at the OEM nominal pressure. Hardware TPMS sensors show real tire pressure, which should match the nominal value but is usually lower due to inflation differences and measurement tolerance. For both tires, the readings begin to converge after one minute, achieving satisfactory accuracy by the end of the five-minute duration.

RESULTS, ACCURACY AND REGULATORY COMPLIANCE

The discrete behavior observed in hardware TPMS measurements results from sensor resolution and embedded filtering constraints, whereas the Virtual Sensor achieves absolute pressure accuracy on par with conventional hardware TPMS.

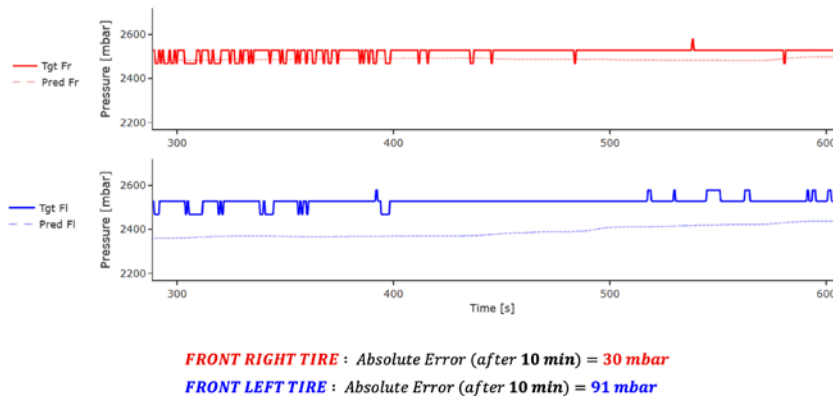


Figure 15 - First 5 minutes of prediction for Front Tires

Figure 16 shows that after a 10 minute trip, prediction converges.

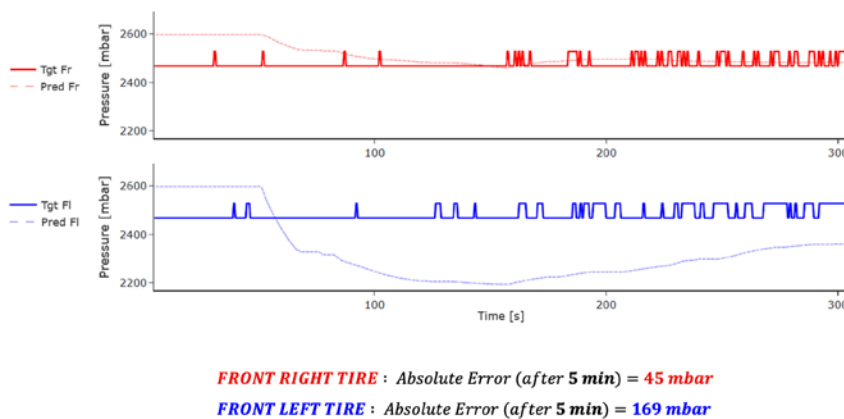


Figure 16 - Prediction for front tires during the 5th to 10th minute interval

These results demonstrate that the vTPMS converges rapidly toward the true tire pressure under nominal conditions. After a short initialization phase, the model achieves stable and accurate pressure estimation, with absolute errors below 100 mbar after 10 minutes of driving for both front tires. This level of accuracy is comparable to that of hardware TPMS sensors and fully compatible with OEM expectations for absolute pressure monitoring.

RESULTS, ACCURACY AND REGULATORY COMPLIANCE

Puncture Detection

As a reminder, the Puncture Test is specified in UNECE R141, which requires that vTPMS must detect a 20% pressure loss (or a drop below 1.5 bar) in a single tire within 10 minutes to satisfy requirements.

As outlined earlier, three trips with punctured tires were performed among a total of fifteen test trips. A detection threshold was established at 85% of nominal pressure to account for tolerance detection, followed by the calculation of a correlation matrix to assess puncture recall and precision (Figure 17).

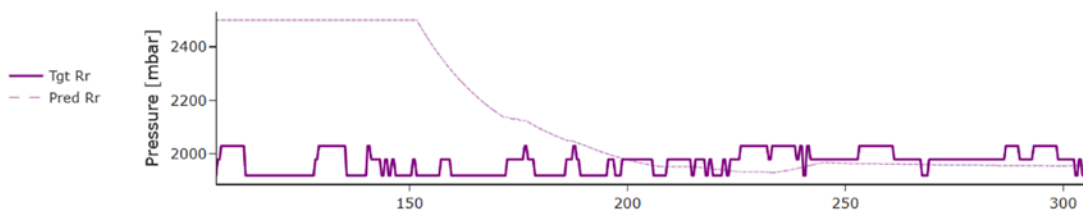
	Prediction : Positive	Prediction : Negative	
True Value : Positive	3 TP (True Positive)	0 FN (False Negative)	Puncture RECALL After 10 min driving 1 (all True Positive found)
True Value : Negative	0 FP (False Positive)	12 TN (True Negative)	
			Puncture PRECISION After 10 min driving 1 (all positive predictions are correct)

Figure 17 - Confusion Matrix and Metrics - Puncture Detection

All three puncture incidents were accurately classified as true positives, with no false positives observed. This demonstrates the model's reliability and its capability to detect punctures while satisfying regulatory standards.

We will now examine one of these trips in greater detail to assess the time required to reach the defined threshold or value.

The following is an example of a rear right tire puncture (Figure 18). The nominal pressure for the tire is 2500 mbar. For testing purposes, the tire is deflated to 2000 mbar (nominal -20%). The detection threshold, set at 85%, is reached at 2125 mbar (85% of 2500 mbar).



REAR RIGHT TIRE : Absolute Error (after 3 min) = 180 mbar – (Absolute Estimation = 2094 mbar)

REAR RIGHT TIRE : Absolute Error (after 5 min) = 24 mbar – (Absolute Estimation = 1956 mbar)

Figure 18 - Estimation of Rear Right Tire Puncture

RESULTS, ACCURACY AND REGULATORY COMPLIANCE

The detection threshold is met within the first 3 minutes of the drive, and after 5 minutes, the absolute error settles below 30 mbar, which is an excellent result. Additionally, the other tires are set to their nominal pressure during this trip.

After 5 minutes, we observe the following absolute errors for each tire:

- FRONT LEFT TIRE: Absolute Error = 32 mbar
- FRONT RIGHT TIRE: Absolute Error = 95 mbar
- REAR LEFT TIRE: Absolute Error = 5 mbar

The puncture detection results highlight the robustness and responsiveness of the vTPMS under critical safety scenarios. In all tested cases, punctures were correctly detected within the regulatory time limits defined by UNECE R141, with no false positives observed. The system reaches the detection threshold within the first minutes of driving and rapidly stabilizes. These results confirm that the vTPMS not only meets regulatory requirements but also provides precise absolute pressure estimation during and after puncture events, ensuring both compliance and driver confidence.

Diffusion Detection

The Diffusion Test requires vTPMS to detect a 20% pressure loss in several or all tires within 60 minutes. We completed four diffusion trips, each beginning with a 20% reduction in tire pressure, setting the front tires to 2080 mbar and the rear tires to 2000 mbar. With the same detection threshold set, the associated confusion matrix is the one below (Figure 19).

	Prediction : Positive	Prediction : Negative		
True Value : Positive	4 TP (True Positive)	0 FN (False Negative)	Diffusion RECALL After 10 min driving	1 (all True Positive found)
True Value : Negative	0 FP (False Positive)	11 TN (True Negative)		Diffusion PRECISION After 10 min driving

Figure 19 - Confusion Matrix and Metrics - Diffusion Detection

The diffusion detection results demonstrate the ability of the vTPMS to reliably identify simultaneous pressure losses across multiple tires within the regulatory time window. All diffusion events were correctly detected, with high recall and precision, confirming full compliance with UNECE R141 requirements. In addition to accurate detection, the model maintains low absolute pressure errors shortly after the beginning of the trip, even in reduced-pressure conditions.

INTEGRATION OF vTPMS

Our model can be implemented in a vehicle via different integration strategies. The first example involves embedding it within a conventional Electronic Control Unit (ECU) running classic AUTOSAR architecture, such as an ABS ECU. A second example involves deploying the model on the NXP GoldBox, demonstrating integration performance metrics.

In addition, the Virtual Sensor can be integrated with a smartphone application connected to the vehicle, or directly within the in-vehicle infotainment (IVI) system, offering flexible deployment options across different vehicle architectures and use cases.

These multiple integration options allow OEMs to align vTPMS deployment with their current E/E architecture maturity and SDV roadmap. In the following section, we focus on the two first implementation examples.

Classic AUTOSAR ECU - ABS example

Figure 20 illustrates a possible integration of our model in a Classic AUTOSAR ECU architecture. This implementation could be adapted to separate the vTPMS functionality from the regulatory components if required. Such integration can be carried out either in collaboration with the OEM or through a Tier 1 supplier, depending on the vehicle development strategy.

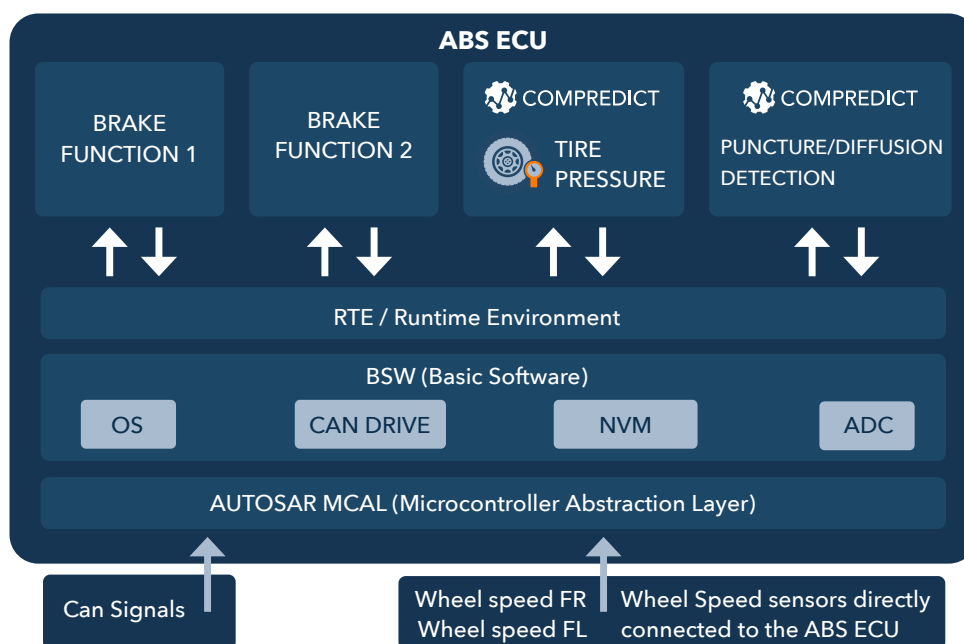


Figure 20 - Example of Model integration in ABS ECU

INTEGRATION OF vTPMS

NXP GoldBox Integration

The model was additionally deployed on the NXP GoldBox for a vTPMS demonstration, an automotive-grade platform representative of a central vehicle PC.

The deployment metrics for this Tire Pressure Virtual Sensor case study are the following (Figure 21):

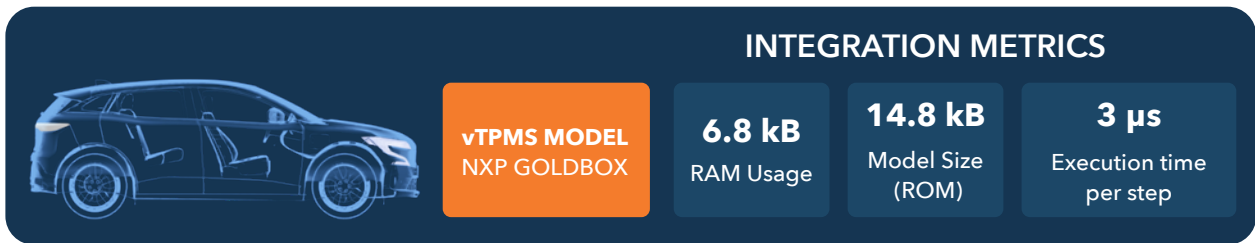


Figure 21 - Integration metrics in NXP GoldBox



CONCLUSION

This white paper demonstrates that COMPREDICT's Virtual Tire Pressure Monitoring System represents a major step forward in this domain. By leveraging existing vehicle signals and advanced calibration techniques, the vTPMS delivers accurate, real-time absolute tire pressure estimation without relying on dedicated in-wheel hardware.

The validation results confirm that the solution achieves hardware-comparable accuracy, robust puncture and diffusion detection, and full compliance with UNECE R141 regulatory requirements. Beyond regulatory compliance, vTPMS provides significant business value by reducing system cost, weight, and maintenance complexity while offering flexible integration options across existing ECUs or centralized vehicle computing platforms.

As vehicles increasingly evolve toward Software-Defined Vehicle architectures, COMPREDICT's vTPMS is designed for series deployment and illustrates how virtual sensors can replace traditional hardware systems while improving scalability, upgradability, and total cost of ownership. This positions vTPMS as a future-proof solution for OEMs and Tier 1 suppliers seeking to combine safety, performance, and economic efficiency in next-generation vehicle platforms.



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