COMPREDICT
THE VIRTUAL SENSOR COMPANY

Suspension Displacement Virtual Sensor

Captures every move without dedicated hardware

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Table of contents

INTRODUCTION

Modern vehicles rely on suspension displacement information to support key chassis and safety functions. Traditionally, this information is provided by hardware ride height sensors that measure, in millimeters, the relative displacement between each wheel and the vehicle chassis. These sensors are widely used for applications such as headlight leveling, active and semi-active suspension control, and chassis dynamics management, particularly in premium, luxury, and sports vehicles. However, hardware-based solutions increase system cost, vehicle mass, and architectural complexity.

COMPREDICT's Suspension Displacement Virtual Sensor presented in this white paper offers a **100% software-based** alternative that estimates ride height displacement at each wheel in real time using existing vehicle signals. By eliminating dedicated hardware sensors, the solution helps **lower the total cost of ownership** while enabling accurate road condition estimation, automatic headlight adjustment, and advanced suspension control, making it scalable from mass-market vehicles to high-end automotive platforms.

SUSPENSION DISPLACEMENT - USE CASES

The following section presents the concept of Virtual Sensors and reviews current applications and use cases related to suspension displacement.

Introduction and definition of Virtual Sensors

In modern automotive systems, Virtual Sensors enable the estimation of physical quantities without relying on dedicated measurement hardware. Implemented entirely as software, they reconstruct time-varying signals by exploiting information already available from onboard vehicle sensors. Depending on the application, COMPREDICT's Virtual Sensors may rely on physics-based modeling, data-driven methods such as machine learning, or a combination of both approaches to achieve the required level of accuracy.

During development, dedicated high-precision sensors are temporarily used to capture reference measurements that serve as a benchmark for training, calibration, and validation.
Once the Virtual Sensor has been tuned to a specific vehicle platform and target function, it can reproduce the behavior of this reference signal in real-world operation without additional hardware.

Deployed directly in Electronic Control Units (ECUs), COMPREDICT's Virtual Sensors operate in real time with minimal latency and integrate seamlessly with in-vehicle networks and data flows, supporting the evolution toward Software-Defined Vehicle (SDV) architectures.

Enabling New SDV Capabilities

Unlock new possibilities for software-defined vehicles by enabling features such as vehicle mass estimation, wheel force measurement, drive shafts torque analysis, and tie rod force detection - capabilities that traditionally required expensive and invasive hardware.

Hardware Replacement

Virtual Sensors offer a scalable alternative to physical sensors, enabling significant cost savings. They eliminate issues related to hardware wear, failure, and the need for maintenance and replacement.

Aftersales and Predictive Maintenance

Virtual Sensors also open new revenue opportunities in the aftersales domain. They enable advanced monitoring solutions for components like tires and brakes, supporting both wear and non-wear part diagnostics. This paves the way for predictive maintenance, improving vehicle safety, reliability, and customer satisfaction.

***Figure 1** – Use Cases for Virtual Sensors*

SUSPENSION DISPLACEMENT - USE CASES

Suspension Displacement – State of the art

Suspension displacement hardware sensors are widely used in automotive systems to measure the relative vertical movement between the vehicle body and each wheel, providing essential inputs for several safety and performance-critical functions.

These measurements enable **automatic headlight leveling** by compensating for vehicle load and road profile, ensuring optimal illumination without glare, and they serve as key feedback signals for **active and semi-active suspension systems** to improve ride comfort, handling, and vehicle stability.
By providing real-time information on ride height and wheel dynamics, suspension displacement sensing supports precise chassis control and enhanced driving safety across a wide range of driving conditions.

However, when implemented using dedicated hardware sensors, these solutions introduce notable drawbacks, including increased bill of materials, added weight and packaging constraints, higher system complexity, and potential reliability and maintenance issues due to sensor wear, misalignment, or exposure to harsh environmental conditions.

SUSPENSION DISPLACEMENT VIRTUAL SENSOR CALIBRATION

We will now explain how our Suspension Displacement Virtual Sensor has been developed, presenting the physical foundation of the solution, outlining the virtualization process from data acquisition to calibration, and concluding with an analysis of its sensitivity to external factors such as temperature and tire wear.

Hardware sensing

COMPREDICT's Virtual Sensor aims to measure suspension displacement in vehicles, capturing the movement of the suspension system as it reacts to road conditions, vehicle load, and driving maneuvers. Essentially, suspension displacement quantifies the relative motion between the vehicle's chassis (body) and its wheels, influenced by factors such as road irregularities, cornering forces, acceleration, and braking.

SUSPENSION DISPLACEMENT VIRTUAL SENSOR CALIBRATION

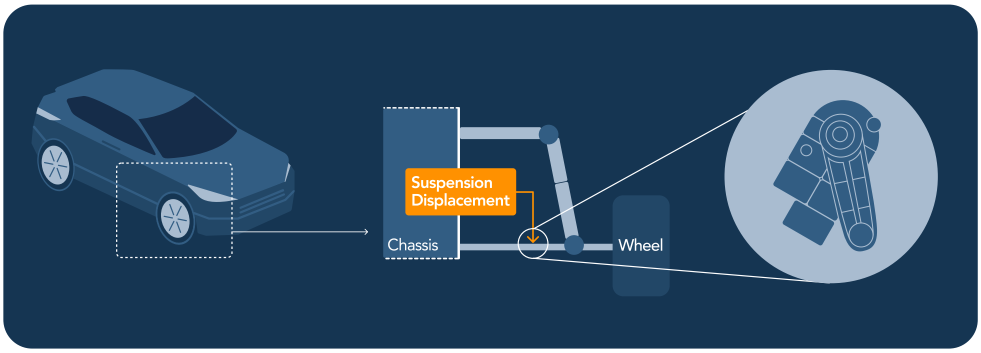


Figure 2 – Illustration of hardware Suspension Displacement sensor

The Virtual Sensor can be directly integrated in-vehicle and works as a hardware replacement for the physical sensor.
This led to:

- Reduced system costs
- Reduced hardware complexity and dependency
- Increased system robustness through redundant measurements when combined with hardware sensors

Virtualization Approach

For Suspension Displacement Virtual Sensor, an internally developed machine learning model is used to predict iteratively the suspension displacement.

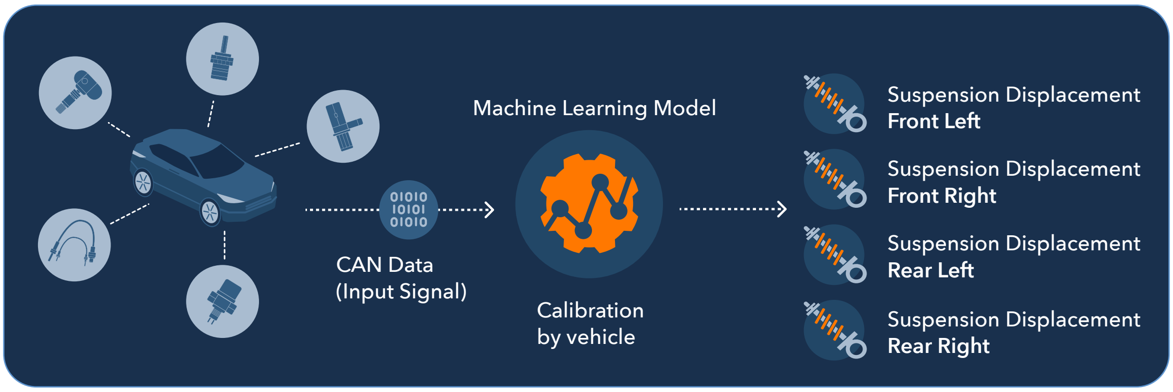
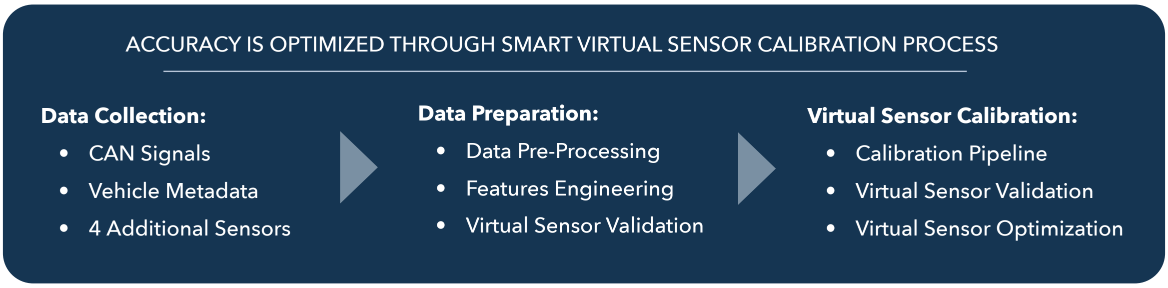


Figure 3 – Virtualization approach of Suspension Displacement Virtual Sensor

SUSPENSION DISPLACEMENT VIRTUAL SENSOR CALIBRATION

Then, for a dedicated vehicle, the performance of the Virtual Sensor is enhanced using a systematic calibration workflow consisting of three main stages **(Figure 4).**

First, during signal acquisition, datasets are recorded, combining CAN bus signals, contextual metadata, and reference measurements obtained from dedicated hardware sensors. Next, the dataset is refined through data conditioning steps such as preprocessing, filtering, and quality evaluation to ensure reliability and consistency. In the final stage, the calibration framework is applied to train and tune the COMPREDICT Suspension Displacement Virtual Sensor, followed by performance assessment and iterative refinement to maximize estimation accuracy.



ACCURACY IS OPTIMIZED THROUGH SMART VIRTUAL SENSOR CALIBRATION PROCESS

Data Collection:

- CAN Signals
- Vehicle Metadata
- 4 Additional Sensors

Data Preparation:

- Data Pre-Processing
- Features Engineering
- Virtual Sensor Validation

Virtual Sensor Calibration:

- Calibration Pipeline
- Virtual Sensor Validation
- Virtual Sensor Optimization

Figure 4 *– Virtual Sensor calibration process*

The purpose of the data acquisition phase is to gather datasets directly from the vehicle's CAN bus. **Figure 5** presents COMPREDICTOR, our Renault Mégane E-TECH used as the demonstration platform, which formed the basis for the development and experimental validation of the Suspension Displacement Virtual Sensor solution.

Figure 5 *– COMPREDICTOR's demo vehicle (Megane E-TECH)*

SUSPENSION DISPLACEMENT VIRTUAL SENSOR CALIBRATION

A specific list of CAN signals and frequencies, all commonly available in standard vehicle architectures, are required for the Suspension Displacement Virtual Sensor (**Figure 6**).

CAN Signals list - Examples
Brake Pressure
Wheel Speed x 4
Engine Torque & Speed
Lateral and Longitudinal Acceleration

Figure 6 *– Examples of CAN signals required for COMPREDICT's Suspension Displacement Virtual Sensor*

To generate accurate ground-truth measurements, dedicated suspension displacement hardware sensors were temporarily installed to record reference signals during test and measurement activities (**Figure 7**).

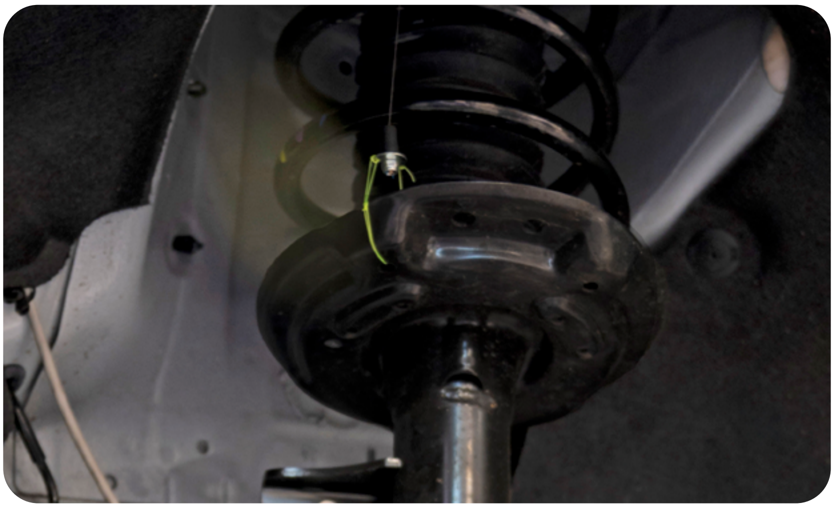


Figure 7 *– Suspension Displacement hardware sensors mounted on COMPREDICTOR*

The third component of the data collection phase involves gathering detailed vehicle metadata, including parameters such as wheelbase, vehicle weight, vehicle length, spring stiffness or suspension angle, that will be used during the calibration phase.
The data collection is conducted according to a precise and structured measurement campaign encompassing a range of:

- **Driving maneuvers** (acceleration, braking, slalom)
- **Road surfaces** (potholes, paved roads, slopes, gravel tracks – **Figure 8**)
- **Vehicle load configurations** (driver only, all passengers, trunk full load…)

SUSPENSION DISPLACEMENT VIRTUAL SENSOR CALIBRATION

This diversity ensures the robustness and generalizability of the Virtual Sensor across varying operational scenarios and leads to a couple of hours of data.

Figure 8 – COMPREDICTOR on a paved road - UTAC Mortefontaine

Following data collection, the next critical step is data pre-processing, which prepares the dataset for accurate analysis by ensuring it is clean, consistent, and reliable. During this stage, data scientists organize, format, and validate the raw inputs to preserve data integrity.
The workflow begins with the data cleaning, which is done with COMPREDICT's DataPilot SaaS solution. In this way an automatic identification and treatment of missing values, followed by resampling to the desired frequency and applying normalization or scaling techniques is applied.
Additional procedures include:

- Correcting logging errors such as outliers and signal noise
- Extracting meaningful features from the raw signals
- Synchronizing data streams to compensate for time shifts or delays introduced by the OEM's internal systems, which could otherwise compromise predictive performance

Once these pre-processing steps are completed, the refined dataset is fed into COMPREDICT's end-to-end processing pipeline, where it undergoes a series of transformations that ultimately produce COMPREDICT's Suspension Displacement Virtual Sensor.

RESULTS AND ACCURACY ON COMPREDICTOR

In this section, we present the results of COMPREDICT's Suspension Displacement Virtual Sensor by first outlining the key performance metrics used to evaluate the model. These metrics offer a quantitative basis for assessing accuracy, robustness, and consistency across diverse operating conditions. We then analyze the model's behavior in a range of driving and road conditions, before concluding with edge cases that test the system's performance under extreme conditions.

Metrics

We use the metrics described below to evaluate the performance of our model across the different runs and use cases defined in previous section.
These metrics provide a consistent and quantitative framework for comparing results, enabling us to assess the model's accuracy, stability, and robustness under varying operating conditions.

RMSE (Root Mean Square Error): Sum the squared errors of all trips and then calculate the mean and the square root.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i} \Sigma_{j_i}^{N_i}\left(y_{pred} - y_{true}\right)^2}$$

y_{pred} : *predicted value at time i*
y_{true} : *true value at time i*
i : *Trip index*
j_i : *Sample j of trip i*
N_i : *Number of samples in trip i*

$$N = \sum_{i} N_i$$

DUTY VALUE: Compute a fatigue-related damage indicator independently for the true and predicted values using a cumulative duty value method and compare the resulting relative difference.

$$DutyValue = 100 * \frac{DV\left(y_{pred}\right) - DV\left(y_{true}\right)}{DV\left(y_{true}\right)}$$

y_{pred} : *predicted value at time i*
y_{true} : *true value at time i*

$$DV(x) = \Sigma|x|^k$$

RAINFLOW: Compute a fatigue-related damage indicator independently for the true and predicted values using a rainflow counting method and compare the resulting relative difference

$$Rainflow = 100 * \frac{RF\left(y_{pred}\right) - RF\left(y_{true}\right)}{RF\left(y_{true}\right)}$$

y_{pred} : *predicted value at time i*
y_{true} : *true value at time i*

$$RF(x) = Rainflow\ Count\ of\ x$$

RESULTS AND ACCURACY ON COMPREDICTOR

Results

The 10 Hz sampling frequency was selected for COMPREDICTOR's use case, but higher frequencies are supported and can be configured depending on application requirements and available resources. COMPREDICT's Suspension Displacement Virtual Sensor based on this 10 Hz model shows overall good performance across most driving scenarios (**Figure 9**).

The accuracy is satisfactory, with the Duty Value remaining within acceptable limits. However, the Rainflow results are less reliable during acceleration and braking phases as well as in normal city driving, likely due to the higher dynamic variability and transient load changes in these conditions, which are more difficult for the model to capture at this sampling frequency. Despite this, the RMSE remains at a very good level for typical use cases, including acceleration and braking, slalom maneuvers, and normal in-city driving.

Overall, the model performs well in standard scenarios such as acceleration and braking, slalom or curved paths, and normal driving characterized by slow to moderate steering inputs and soft to normal acceleration and braking.

Controlled Scenario	RMSE (mm)				DutyValue (%)				Rainflow (%)			
	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR
Acceleration and Braking	3.0	2.9	2.6	3.0	-7.2	-3.8	-18.7	-15.7	-32.0	-25.8	-46.8	-42.3
Slalom	2.8	3.0	2.3	2.8	8.6	14.6	15.3	-1.6	-6.0	-4.0	2.3	-14.8
In city "Normal" Driving	3.2	3.1	2.3	3.0	14.1	6.8	19.2	13.4	35.0	25.8	34.3	29.2

***Figure 9** – COMPREDICTOR Suspension Displacement Virtual Sensor results*

The following plots (**Figure 10**) present the results for acceleration, braking, city driving, and slalom maneuvers. They illustrate the previously described performance of Suspension Displacement Virtual Sensor, showing very high accuracy during acceleration and braking as well as slalom maneuvers, with some small deviations observed in city driving conditions.

RESULTS AND ACCURACY ON COMPREDICTOR

Figure 10 – COMPREDICTOR Suspension Displacement Virtual Sensor plots in different maneuvers

RESULTS – TESTING DATASET

Edge Cases

In edge case scenarios, such as driving on corrugated roads (**Figure 11**), the prediction remains visually consistent with the measured signal, indicating that the model can capture the overall dynamic behavior of the suspension. However, peak amplitudes tend to be underestimated, which results in degraded performance metrics compared to the previously discussed cases.
High-frequency events may lead to poorer results, as rapid dynamics are more challenging for the Virtual Sensor to represent accurately with the given input. Similarly, under high-load conditions corresponding to large suspension displacement peaks, the predicted amplitudes can become less accurate, further contributing to reduced performance in these extreme scenarios.

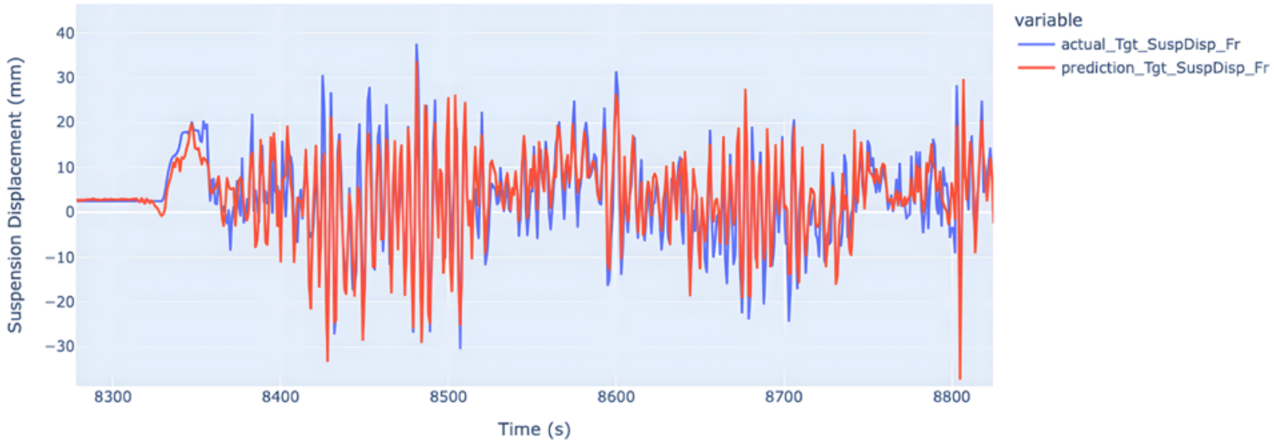


Figure 11 *– Results from Suspension Displacement Virtual Sensor for Front Right Wheel. This was tested in COMPREDICTOR by driving on a bumpy road.*

INTEGRATION

COMPREDICTOR Integration

The Suspension Displacement Virtual Sensor was implemented and tested within COMPREDICTOR.
A Simulink real-time system integrated the model with preprocessing from our calibration pipeline.
Data was collected using DEWESoft acquisition hardware, including:

- CAN signals for the Virtual Sensor to predict per-wheel values.
- Suspension displacement measurements for each wheel (hardware sensors)

INTEGRATION

The predictions could be viewed and compared in real time with hardware sensors measurements through a dedicated UI displayed on a screen accessible from the passenger seat (**Figure 12**).

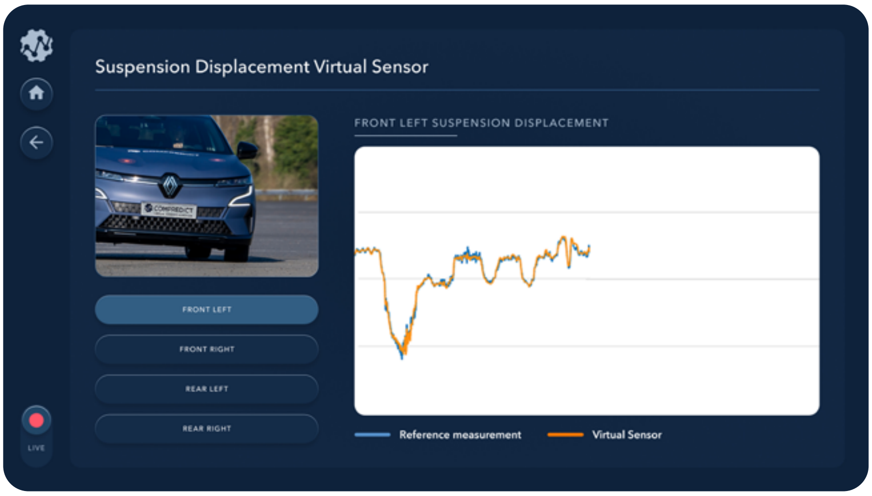


Figure 12 – Live Demo available in COMPREDICTOR for Suspension Displacement Virtual Sensor

NXP GoldBox Integration

As part of the Sonatus AI Director demo, the model was additionally deployed on the NXP GoldBox for a dynamic Headlight Leveling Virtual Sensor demonstration, an automotive-grade platform representative of a central vehicle PC.
The demo highlighted:

- Deployment testing using Sonatus AI Director, a platform for managing, scaling, and running AI models on vehicles (edge AI).
- ML model optimization through the NXP eIQ toolchain, enabling efficient execution on edge hardware.

All sensors were operated on the NXP GoldBox, and although the demo used playback data, it ran through a vehicle UI interface with real hardware. The deployment metrics for the Suspension Displacement Virtual Sensor within the dynamic Headlight Leveling Virtual Sensor case study using the Sonatus AI Director demo are the following:

- **CPU** Execution Time: **3.2 ms** (~4% of a single core)
- **RAM** usage: approximately **4.5 MB**

CONCLUSION

This white paper demonstrates that COMPREDICT's Suspension Displacement Virtual Sensor is a mature, accurate, and production-ready solution capable of replacing traditional hardware-based suspension displacement sensors. Leveraging advanced machine learning techniques and commonly available vehicle signals, the Virtual Sensor reliably reconstructs wheel-specific suspension displacement in real time, without the need for dedicated measurement hardware.

Extensive validation on COMPREDICTOR confirms that the solution delivers a high level of accuracy and robustness across a wide range of driving maneuvers and road conditions, including normal driving, dynamic events such as acceleration, braking, and slalom maneuvers, as well as more demanding edge cases. The selected performance metrics consistently demonstrate stable behavior, predictable accuracy, and meaningful correlation with reference measurements, establishing a strong level of confidence in the Virtual Sensor's reliability for real-world automotive applications.

Beyond performance, the solution is designed with industrial deployment in mind. Its software-only architecture significantly reduces system cost, weight, and complexity, while improving reliability by eliminating mechanical wear, sensor drift, and packaging constraints associated with physical sensors. Integration results on both COMPREDICTOR and an automotive-grade central computing platform (NXP GoldBox) further confirm that the Virtual Sensor meets real-time execution requirements and fits seamlessly into modern E/E architectures and Software-Defined Vehicle (SDV) strategies.

By combining automotive-grade AI, a structured calibration workflow, and proven in-vehicle integration, COMPREDICT's Suspension Displacement Virtual Sensor provides OEMs and Tier-1s with a scalable and future-proof sensing solution.

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