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Vehicle-Based Wheel Alignment Diagnostic System: Wheel Alignment Monitoring System Incorporated in the Vehicle

Vignesh Elangovan

Senior Engineer, Platform, After Sales Engineering, Research & Advanced Engineering, Renault Nissan Technology & Business Centre India

Abstract:
Wheel alignment is a critical vehicle maintenance parameter influencing safety, handling stability, tire life, and fuel efficiency. Conventional alignment assessment relies on external alignment bays, making the process reactive and dependent on workshop visits. This paper presents an in-vehicle wheel alignment monitoring system that enables proactive detection of misalignment through embedded sensor diagnostics. The proposed system evaluates key alignment parameters—Toe, Camber, and Caster—using alignment sensors integrated into the suspension, supported by vehicle level sensors, steering angle sensors, gear position sensors, and yaw rate sensors. The Anti-lock Braking System control unit acts as the master ECU, validating predefined operating conditions, executing alignment algorithms, and comparing real-time sensor data with stored reference values. Alignment status and corrective recommendations are communicated to the driver via the vehicle command display. The paper describes the system methodology, sensor working principles, data flow, and system architecture, and compares the proposed approach with traditional alignment methods. This enables real-time monitoring, preventive maintenance, improved safety, and customer convenience.

Keywords: Wheel Alignment Monitoring System, Wheel Angle Alert System, Vehicle Alignment Monitor, Automated Wheel Angle Detection.

1.Introduction

1.1 Background

All innovations in drivetrain technology are primarily aimed at enhancing the customer driving experience. However, despite these advancements, the wheel and tires remain crucial components in achieving optimal performance. Wheel alignment is fundamentally a maintenance parameter, with issues in this system typically being monitored only once problems become evident. In the interim, misalignment can lead to uneven tire wear, vehicle pull, steering instability, reduced fuel efficiency, increased tire noise, shoulder tire chipping, and damage to suspension arm bushings. Any deviation in wheel angles can trigger alerts, prompting the driver to visit a workshop for necessary corrections.

- Misaligned wheels can cause excessive strain on suspension components, leading to costly repairs and diminished vehicle longevity.
- Wheel alignment is an often-overlooked aspect of vehicle maintenance, but its importance cannot be understated as it directly impacts safety, cost efficiency, and driving comfort.

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1.2 Objective

The objective of this study is to detect wheel misalignment without the need to access the wheel alignment pit or bay. Typically, wheel alignment maintenance relies on measuring the angles within the alignment bay. This dependency can be mitigated by incorporating a wheel alignment measurement feature into the vehicle's command display. The display would prompt the driver with a message stating, "Check the wheel alignment," along with the necessary pre-conditions. Upon completion of the required actions, the system will provide the results. If misalignment is detected, the display will recommend visiting a wheel alignment repair workshop for correction.

- The measurement of wheel alignment angles—Toe, Camber, and Caster—within the vehicle is facilitated by dedicated sensors integrated into the suspension system.
- The system architecture is designed specifically for efficient wheel alignment monitoring.
- Alerts or warning messages regarding wheel alignment are displayed at predetermined intervals to ensure that the necessary pre-conditions for accurate measurement are met.
- The strategic placement and routing of sensors within the suspension system are carefully planned to align with the vehicle’s dynamic characteristics.

1.3 Limitations & scope

Wheel alignment checks fall under the maintenance category, with no routine inspections conducted between scheduled maintenance intervals. Minor misalignments often go unnoticed until they lead to consequential damage to the tires or suspension components. As a result, wheel alignment issues are frequently left unmonitored. Currently, the only way to check wheel alignment is through a dedicated system that uses sensors placed on the wheels, which transmit signals to the alignment system. Additionally, to assess the status of wheel angles, one must visit the wheel alignment bay, which reduces the convenience of regular checks.

For example, if there is a toe-in issue with the front left wheel, it can cause uneven tire wear on one side. If left unchecked until the next maintenance period, this wear becomes more pronounced, necessitating tire replacement. In another scenario, an impact to the camber angle can result in vehicle pull. If the control arm becomes misaligned, it can cause excessive positive camber, particularly if the control arm's bushings are weak. This misalignment leads to variations in the caster bolt adjustment, and over time, the bushings will be permanently damaged, causing significant tire shoulder wear and chipping.

In summary, it is crucial to detect wheel alignment deviations as early as possible. A sensor capable of detecting misalignment directly within the vehicle would offer significant convenience, alerting the driver to visit a workshop when necessary. Wheel alignment checks should be conducted under specific conditions, such as a straight steering wheel, proper vehicle height, a flat surface, and the vehicle in a parked state, accounting for vehicle dynamics. By integrating these conditions, the system could trigger a “Check Wheel Alignment” message at regular intervals. Once the pre-conditions are met, the system will activate the sensors to measure and display the results on the command display. This approach eliminates the need to visit the service centre solely for alignment checks.

1.4 Methodology

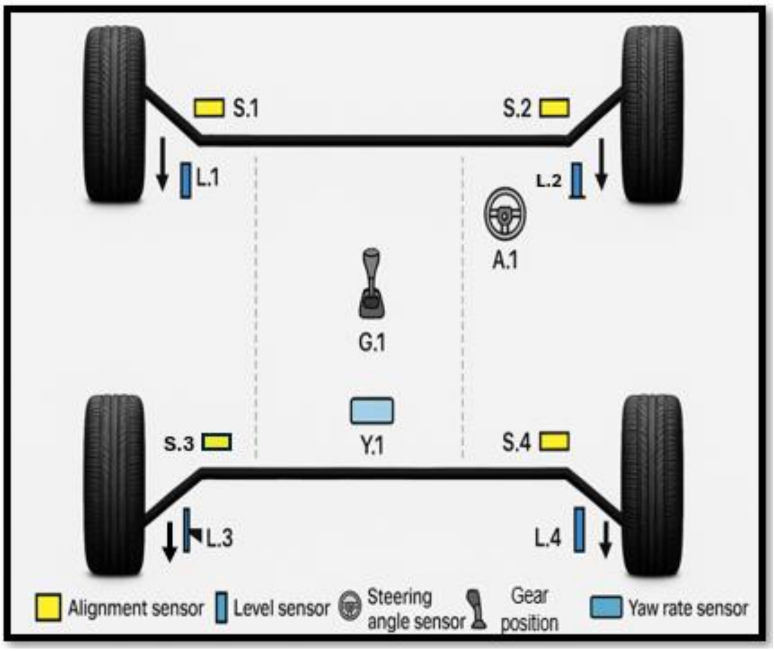
The proposed wheel alignment monitoring system operates by integrating multiple vehicle-mounted sensors with a centralized electronic control unit to enable in-vehicle assessment of wheel alignment parameters. The Anti-lock Braking System (ABS) control unit functions as the master ECU for this feature, as it already interfaces with several critical vehicle dynamics sensors and possesses sufficient computational capability to execute alignment algorithms.

The methodology begins with the acquisition of sensor inputs required to evaluate wheel alignment. Dedicated alignment sensors mounted at each wheel measure the primary alignment parameters—Toe, Camber, and Caster. These measurements are supplemented by inputs from vehicle level sensors, steering angle sensors, gear position sensors, and yaw rate sensors. Together, these inputs ensure that alignment calculations are performed only under valid and stable operating conditions.

Each vehicle has predefined nominal wheel alignment reference values established during the vehicle development phase. These reference values are stored in the ABS control unit and serve as baseline thresholds for alignment evaluation. The control unit continuously monitors sensor signals and validates predefined preconditions, including a centred steering wheel, stationary vehicle state, correct gear position, stable yaw condition, and appropriate vehicle height.

Once all preconditions are satisfied, the alignment check can be initiated either automatically at predetermined intervals or manually by the driver through the vehicle command display. The ABS control unit processes real-time sensor data, compares measured wheel angles with stored reference values, and determines the alignment status. If all parameters fall within permissible limits, the system displays a confirmation message indicating acceptable wheel alignment. If deviations exceed allowable thresholds, a warning message is displayed, advising the driver to consult a workshop for corrective action. This methodology enables proactive, reliable, and user-friendly wheel alignment diagnostics without dependence on external alignment equipment.

Figure 1. Overview of Pre-condition sensors



Description:

Code	Name	Purpose
S.1	Alignment sensor (FL)	Sensor to measure the Toe, camber and Caster in front left side
S.2	Alignment sensor (FR)	Sensor to measure the Toe, camber and Caster in front right side

S.3	Alignment sensor (RL)	Sensor to measure the Toe, camber and Caster in rear left side
S.4	Alignment sensor (RR)	Sensor to measure the Toe, camber and Caster in rear right side
L.1	Level sensor (FL)	Vehicle height level in front left side
L.2	Level sensor (FR)	Vehicle height level in front right side
L.3	Level sensor (RL)	Vehicle height level in rear left side
L.4	Level sensor (RR)	Vehicle height level in rear right side
A.1	Steering angle sensor	Steering angle sensor
G.1	Gear position sensor	Gear position sensor
Y.1	G sensor / Yaw sensor	Yaw rate sensor

As part of the diagnostic methodology, the ABS control unit initiates the wheel alignment test only when all sensor readings are within their respective nominal values.
The process can be manually triggered by the customer through the command display interface.

Figure 2. Initiate in multimedia screen

Upon initiation, the system evaluates the preconditions required for the alignment check. If all conditions are satisfied, the test proceeds automatically. In cases where certain parameters are not met, the system provides real-time feedback, highlighting the unmet conditions and guiding the user to fulfil them. Once all prerequisites are confirmed, the ABS control unit reads the wheel alignment data. If the alignment is within acceptable thresholds, the system displays the message: "Wheel alignment found OK." If the values are not in limits displays “Consult workshop and correct it”

Figure 3. Message in multimedia screen

2. Literature Review

Wheel alignment plays a critical role in vehicle safety, handling, and efficiency. Traditional alignment systems rely on external alignment bays equipped with optical or laser sensors to measure Toe, Camber, and Caster angles. These methods, while accurate, are reactive and require workshop visits, making them inconvenient for frequent checks [1]. Misalignment often goes unnoticed until symptoms such as uneven tire wear or steering instability appear, leading to costly repairs [2].

Recent research emphasizes the integration of sensor-based monitoring systems within vehicles to enable real-time diagnostics. Studies have explored the use of embedded sensors, including accelerometers, gyroscopes, and steering angle sensors, to continuously monitor wheel geometry [3]. These systems leverage Electronic Control Units (ECUs) and CAN bus communication for data processing and alert generation, reducing dependency on external equipment [4]. IoT-enabled architectures have further advanced this concept by allowing remote diagnostics and predictive maintenance through cloud connectivity [6]. However, challenges such as sensor calibration, environmental sensitivity, and dynamic vehicle conditions remain significant barriers to widespread adoption. Literature suggests that accurate alignment checks require specific preconditions, such as a flat surface, parked state, and centred steering wheel, to avoid false readings [5].

The proposed system builds upon these advancements by integrating alignment sensors directly into the suspension system and using the ABS control unit as the master ECU. This approach ensures proactive alerts, user-friendly interaction via the command display, and preventive maintenance, aligning with the automotive industry's shift toward intelligent, connected vehicles.

Based on the literature reviewed, it is evident that recent advancements in wheel alignment monitoring emphasize the use of embedded sensors, ECUs, and intelligent diagnostic algorithms to enable real-time and proactive maintenance. While existing studies highlight the feasibility of sensor-based alignment detection, there remains a need for a clearly defined system-level implementation that integrates multiple sensor inputs with a centralized vehicle control unit under controlled operating conditions. To address this gap, the proposed system adopts an in-vehicle architecture that combines alignment, level, steering angle, gear position, and yaw rate sensors, with the ABS control unit acting as the master ECU. Before detailing the overall system architecture, it is essential to understand the individual sensors involved and their working principles, as these form the foundation for accurate wheel alignment estimation and reliable diagnostic decision-making. Accordingly, the following section describes the functioning, placement, and role of each sensor used in the proposed wheel alignment monitoring system.

3. Sensor Functioning and Working Principles

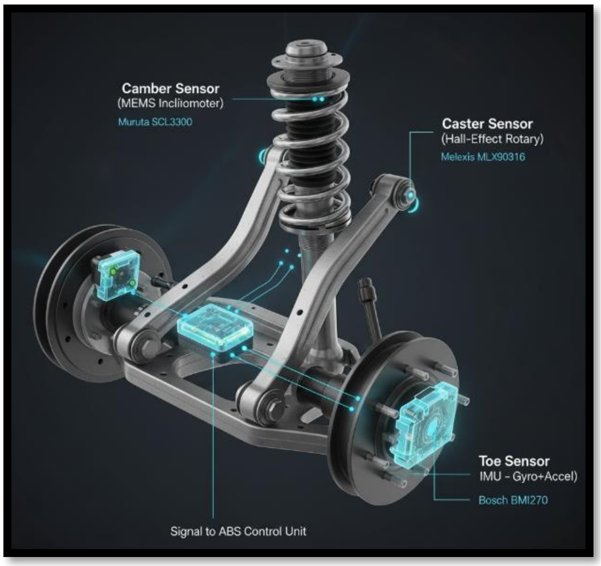
3.1 Alignment Sensors (S.1 to S.4)

Function: Measure Toe, Camber, and Caster angles at each wheel.

Sensor Strategy for Suspension Integration

1. Camber (Tilt relative to vertical):
- MEMS Inclinometer on the upper control arm or wheel knuckle.
- Example: Murata SCL3300 or Analog Devices ADIS16209.
- Reason: Measures tilt directly, robust for dynamic conditions.
2. Caster (Steering pivot angle):
- Hall-Effect Rotary Sensor on the upper control arm pivot or strut mount.
- Example: Melexis MLX90316.
- Reason: Detects rotation of suspension pivot points accurately.
3. Toe (Wheel pointing angle):
- IMU (Gyro + Accelerometer) mounted on the wheel hub.
- Example: Bosch BMI270.
- Reason: Tracks wheel orientation relative to vehicle centreline.

Figure 4. Sensors in alignment detection



3.2 Level Sensors (L.1 to L.4)

Function: Measure vehicle height at each wheel to ensure proper suspension geometry.

Working Principle:

Level sensors are typically **ultrasonic**, **capacitive**, or **potentiometric** devices.

- They detect the vertical displacement between the wheel and the chassis.
- This data helps correct alignment readings by accounting for suspension compression or uneven terrain.

- Accurate height measurement ensures that wheel angle readings are not distorted by dynamic load changes.

3.3 Steering Angle Sensor (A.1)

Function: Detect the position of the steering wheel.

Working

Principle:

This sensor uses **rotary encoders** or **Hall-effect sensors** to measure the angular position of the steering column.

- It ensures the steering wheel is centred during alignment checks.
- Misalignment readings are only valid when the steering is in a neutral position, avoiding false diagnostics.

3.4 Gear Position Sensor (G.1)

Function: Confirm the vehicle is in a parked or neutral gear state.

Working

Principle:

This sensor uses **magnetic switches** or **mechanical linkages** to detect gear lever position.

- It ensures the vehicle is stationary and safe for alignment measurement.
- Prevents activation of the alignment system while the vehicle is in motion.

3.5 Yaw Rate Sensor (Y.1)

Function: Measure rotational movement around the vertical axis (vehicle turning behaviour).

Working

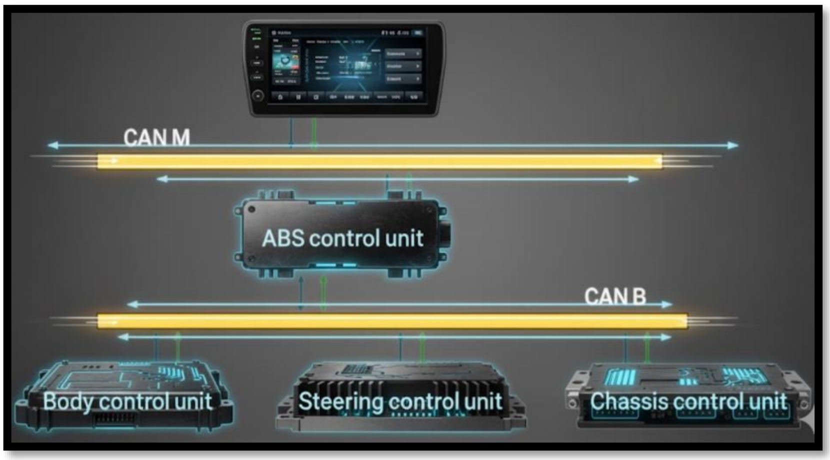
This sensor is part of an **Inertial Measurement Unit (IMU)** and uses **gyroscopic technology**.

- It detects angular velocity and helps determine if the vehicle is stable or undergoing dynamic motion.
- Alignment checks are only valid when the vehicle is stationary and not experiencing yaw, ensuring accurate readings.

4. System Architecture

The system architecture illustrates a centralized electronic control framework in which the ABS control unit functions as the master ECU for the wheel alignment monitoring system. The ABS control unit is positioned between two Controller Area Network buses, namely CAN-M and CAN-B, enabling bidirectional communication with multiple vehicle subsystems. The command display unit is connected via the CAN-M bus, serving as the primary human–machine interface for user interaction, system status visualization, and diagnostic message display. Through the CAN-B bus, the ABS control unit communicates with the Body Control Unit, Steering Control Unit, and Chassis Control Unit, allowing access to essential vehicle dynamics and state information such as steering angle, vehicle motion, suspension behaviour, and stability parameters. Sensor data related to wheel alignment, vehicle height, yaw rate, and gear position are processed centrally within the ABS control unit, where alignment algorithms are executed and operating preconditions are validated. Based on the processed results, alignment status and corrective recommendations are transmitted to the command display. This architecture ensures reliable data exchange, efficient processing, and seamless integration with existing vehicle electronic systems while enabling real-time, in-vehicle wheel alignment diagnostics.

Figure 5. CAN network



4.1 System Components

1. **Sensor Network:**

- Alignment Sensors (S.1–S.4): Measure Toe, Camber, and Caster angles at each wheel.
- Level Sensors (L.1–L.4): Monitor vehicle height at each wheel to ensure proper suspension geometry.
- Steering Angle Sensor (A.1): Ensures the steering wheel is centred during measurement.
- Gear Position Sensor (G.1): Confirms the vehicle is in a parked or neutral gear.
- Yaw Rate Sensor (Y.1): Detects vehicle stability and motion status.

2. **Master ECU – ABS Control Unit (ABS)**

- Acts as the central processor for the alignment system.
- Stores reference values for wheel angles.
- Executes alignment algorithms based on sensor inputs.
- Validates preconditions before initiating alignment checks.

3. **Command Display Interface**

- Provides user interaction and feedback.
- Displays messages such as "Check Wheel Alignment," "Wheel Alignment Found OK," or "Consult Workshop."
- Guides the user through precondition checks and alignment status.

4.2 Data Flow and Operation Sequence

1. **Sensor Initialization**

- Upon vehicle startup or at scheduled intervals, all sensors are initialized and calibrated.

2. **Precondition Validation**

   The system checks for:

- Steering wheel centred (A.1)
- Vehicle parked (G.1)
- Stable vehicle state (Y.1)
- Proper suspension height (L.1–L.4)

3. **Alignment Check Trigger**

- If all preconditions are met, the ABS control unit initiates the alignment check.
- Alternatively, the driver can manually trigger the check via the command display.

4. Sensor Data Acquisition

- Alignment sensors (S.1–S.4) transmit wheel angle data to the ABS control unit.
- Level sensors provide height compensation data.

5. Data Processing and Comparison

- The ABS control unit compares real-time sensor data with stored reference values.
- If values are within tolerance, the system confirms alignment status.

6. User Notification

- If alignment is correct: “Wheel Alignment Found OK”
- If misalignment is detected: “Consult Workshop and Correct It”

4.3 Advantages of the Architecture

- Real-time Monitoring: Eliminates dependency on external alignment bays.
- Integrated Diagnostics: Uses existing vehicle ECUs and sensors.
- User-Friendly Interface: Provides actionable feedback to the driver.
- Preventive Maintenance: Detects misalignment before damage occurs.

5. Comparative analysis of traditional method of wheel alignment check and whe2l alignment monitoring incorporated in vehicle:

Traditional wheel alignment relies on specialized alignment bays at service centres, where external optical or laser sensors are mounted on the wheels to measure Toe, Camber, and Caster angles [1]. This process is highly accurate but requires significant time, specialized equipment, and a workshop visit, making it reactive rather than proactive. Drivers typically seek alignment checks only after experiencing symptoms such as uneven tire wear, steering pull, or vibration, which often leads to additional repair costs. In contrast, the proposed in-vehicle wheel alignment monitoring system integrates alignment, level, steering angle, gear position, and yaw sensors directly into the vehicle’s suspension and control architecture. These sensors continuously monitor wheel geometry and communicate with the ABS control unit via the CAN bus [4]. The system validates preconditions automatically and allows the driver to initiate checks through the command display interface. Results are displayed instantly, with alerts for misalignment and recommendations for corrective action. This approach eliminates dependency on workshops for routine checks, reduces maintenance costs, and enables real-time, preventive diagnostics, aligning with the trend toward smart, connected vehicles [6].

6. Key Differences:

6.1. Location of Measurement

- Traditional Method: Requires a dedicated alignment bay at a service centre with external optical or laser sensors [1].
- Proposed Method: Performed inside the vehicle using integrated sensors without visiting a workshop.

6.2. Frequency and Convenience

- Traditional Method: Alignment is checked only during scheduled maintenance or when issues arise [2].
- Proposed Method: Allows frequent or on-demand checks through the command display, improving convenience.

6.3. Equipment and Cost

- Traditional Method: Involves expensive alignment machines and specialized tools at service centers.

- Proposed Method: Uses existing vehicle ECUs and embedded sensors, reducing dependency on external equipment [3], [4].

6.4. Time Required

- Traditional Method: Takes 30–60 minutes, including setup and calibration.
- Proposed Method: Takes 2–5 minutes, as the system automatically validates preconditions and processes data.

6.5. Maintenance Approach

- Traditional Method: Reactive issues are detected after symptoms like uneven tire wear or steering pull appear [2].
- Proposed Method: Proactive real-time monitoring alerts the driver before significant damage occurs.

7. Advantages

- Real-time wheel alignment monitoring without workshop visits.
- Proactive alerts prevent tire and suspension damage.
- Reduces maintenance cost and downtime.
- Enhances driver convenience and safety.
- Integrates with existing ABS ECU and CAN bus [4].

8. Challenges

- High initial integration cost.
- Sensor calibration complexity.
- Environmental factors affecting accuracy [5].
- Increased ECU processing load.
- Potential false alerts if preconditions fail [5].

9. Future Work

- AI-based predictive alignment analytics.
- Integration with cloud for remote diagnostics [6].
- Adaptive calibration for dynamic conditions.
- Mobile app connectivity for user alerts.
- Multi-vehicle fleet monitoring systems.

10. Conclusion:

This paper presented a comprehensive in-vehicle wheel alignment monitoring system that addresses the limitations of conventional alignment assessment methods by enabling proactive, sensor-based diagnostics integrated within the vehicle architecture. By leveraging dedicated alignment sensors along with supporting inputs from level, steering angle, gear position, and yaw rate sensors, and utilizing the ABS control unit as the master ECU, the proposed system ensures accurate evaluation of wheel alignment parameters under validated operating conditions. The centralized processing approach, combined with CAN-based communication and an intuitive command display interface, enables reliable real-time monitoring and clear driver feedback without dependence on external alignment bays. Compared to traditional workshop-based alignment methods, the proposed solution offers improved convenience, reduced maintenance dependency, and early detection of misalignment, thereby minimizing tire wear, suspension damage, and associated costs. Although challenges such as sensor calibration complexity and environmental sensitivity remain, these can be addressed through adaptive algorithms and advanced data processing techniques. Overall, the proposed wheel alignment monitoring system represents a practical and scalable step toward intelligent, connected, and preventive vehicle maintenance, contributing to enhanced safety, improved vehicle longevity, and a superior customer driving experience.

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