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A Mobile Application for Measuring Vehicle Steering Dynamics Using Embedded Sensors

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ABSTRACT : *This paper presents the development of a mobile application designed to support engineering education by enabling the experimental evaluation of vehicle steering systems using embedded smartphone sensors. The tool captures and stores steering angle data, allowing students to obtain physical measurements directly from any available vehicle. Developed using Android Studio, the application leverages native libraries to access orientation data and store results for subsequent analysis. Laboratory tests demonstrated that the application is stable, low-cost, and user-friendly, with maximum deviations at steering limits of 5.54% (left wheel) and 12.31% (right wheel) when compared to reference values. Additionally, the analysis of measured data in a case study involving a passenger car identified a minimum turning radius of 6.3 meters based on the steering measurements. In addition to its technical functionality, the methodology promotes active learning by enabling students to engage with mechanical concepts through hands-on experimentation, reinforcing theoretical knowledge through data-driven exploration in both classroom and field settings.*

KEYWORDS *mobile tool, vehicle steering system, kinematics, camber and steering angle.*

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I. INTRODUCTION

Technological advances and more efficient production systems have enabled a large number of people to access mobile devices. According to [1], in Brazil, the estimated number of individuals aged 10 or older who owned a mobile phone in 2023 was 163.8 million, representing 87.6% of the Brazilian population in that age group. The evolution of mobile technology has allowed smartphones to perform functions such as navigation, photography, and the monitoring of users' physical activities, in addition to applications in scientific and technical contexts. Much of this innovation is attributed to the integration of embedded sensors in these devices, such as magnetometers, accelerometers, and gyroscopes, which, according to [2], enable the development of applications capable of monitoring motion, analyzing data, and instantly storing physical variables. Furthermore, the use of mobile technologies in teaching methodologies has been shown to enhance both student and teacher motivation [3]. The teaching of technical subjects in universities and technical schools, such as those found in mechanical engineering programs, is often challenged by students' limited interest in fundamental concepts and theories [4]. To address this issue, new methodologies based on active learning techniques require the implementation of innovative teaching tools [5].

One approach increasingly adopted by educational programs involves incorporating more hands-on activities and team-based project development [6]. Similar to interdisciplinary design courses, students are encouraged to apply theoretical knowledge in project-based development, using experimentation and data interpretation to better understand engineering challenges. This approach was analyzed by [7], who examined the application of problem-based learning principles in teaching methodologies. In this context, the use of mobile devices for experimental measurements and system data acquisition offers a low-cost and effective alternative for engineering applications [8]. For example, students from the Federal University of Santa Catarina, Joinville campus (Figure 1), used a mobile phone and a dedicated measurement application to estimate the vibration amplitude on a lawn tractor seat using the device's embedded sensors.

(a) (b)

Figure 1 – Measurement of vibration in the operator's seat of a lawn tractor at UFSC Joinville by students. (a) Mobile phone positioned on the seat; (b) Vehicle undergoing testing.

One example of a teaching tool developed for engineering education focuses on the vehicle steering system, applied in the Automotive Engineering Program. This system is directly linked to the design of mechanical mechanisms that ensure safe vehicle operation. According to [9], the steering system is responsible for adjusting the wheel angles in response to the driver's input, thereby acting as a reliable link between the steering wheel and the road wheels. Besides, the system maintains proper kinematic relationships to achieve the ideal steering angles for both the inner and outer wheels when managing a turn [10]. Notably, mechanical failure in the steering system can be a contributing factor to road accidents; [11] reported that in M1 class vehicles, steering-related failures accounted for over 17% of mechanical breakdowns involved in traffic incidents.

Thus, the motivation for this work is to develop a portable tool capable of measuring vehicle wheel steering angles with low cost and user-friendly operation. The goal is to create an application that serves as both an educational tool for engineering courses and a resource for non-expert users to identify potential misalignments in suspension geometry. By leveraging mobile devices, the approach reduces the need for specialized equipment, making data acquisition and analysis more accessible and efficient. This enables students to perform practical experiments directly on vehicles using everyday technology, reinforcing theoretical concepts through hands-on learning.

II. Vehicle Steering System

According to [12], Ackermann steering geometry is widely used in road vehicles, particularly in situations involving low lateral acceleration, as it allows the wheels to turn without generating slip angles. During low-speed maneuvers along a curved path, a significant difference is expected between the turning radii of the inner and outer wheels, with the inner wheel following a smaller radius. Regarding this turning radius, [9] illustrate the ideal Ackermann condition, where the wheels roll perfectly without lateral slip, as shown in Figure 2.

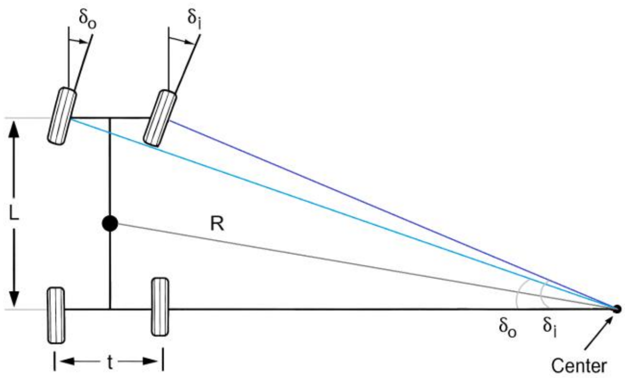


Figure 2 – Illustration of steering geometry based on Ackermann angles.

The steering angles of a vehicle's wheels can be calculated using Eqs. (1) and (2), where L represents the wheelbase, R the turning radius, and t the track width. The steering angle of the inner wheel, denoted as δ_i, is determined by Eq. (1), while the steering angle of the outer wheel, δ_o, is computed using Eq. (2).

$$\tan \delta_i = \frac{L}{R - t/2} \quad (1)$$

$$\tan \delta_o = \frac{L}{R + t/2} \quad (2)$$

According to [13], wheel alignment affects vehicle safety, driving comfort, and tire lifespan. Improper alignment can result in steering instability, difficulty in returning the steering wheel to the central position, and a tendency for the vehicle to pull to one side. It can also cause uneven and excessive tire wear. [14] showed that toe-in and toe-out misalignment increases fuel consumption due to higher rolling resistance. In a related study, [15] reported that fuel consumption and rolling resistance grow as the toe-in angle increases. The authors also observed that with excessive toe-in, tire wear typically begins at the outer edge. For this reason, maintaining alignment according to the manufacturer's specifications helps to reduce tire wear, lower fuel consumption, and limit pollutant emissions. As part of the teaching methodology, following the theoretical presentation, students conducted an experimental measurement manually, in a slow and detailed manner, as illustrated in Figure 3. The objective of this activity was to verify the actual steering angle and compare it with the ideal Ackermann geometry. However, the procedure was time-consuming and offered low measurement precision.

Figure 3 – Manual experimental procedure for measuring the steering angle during class.

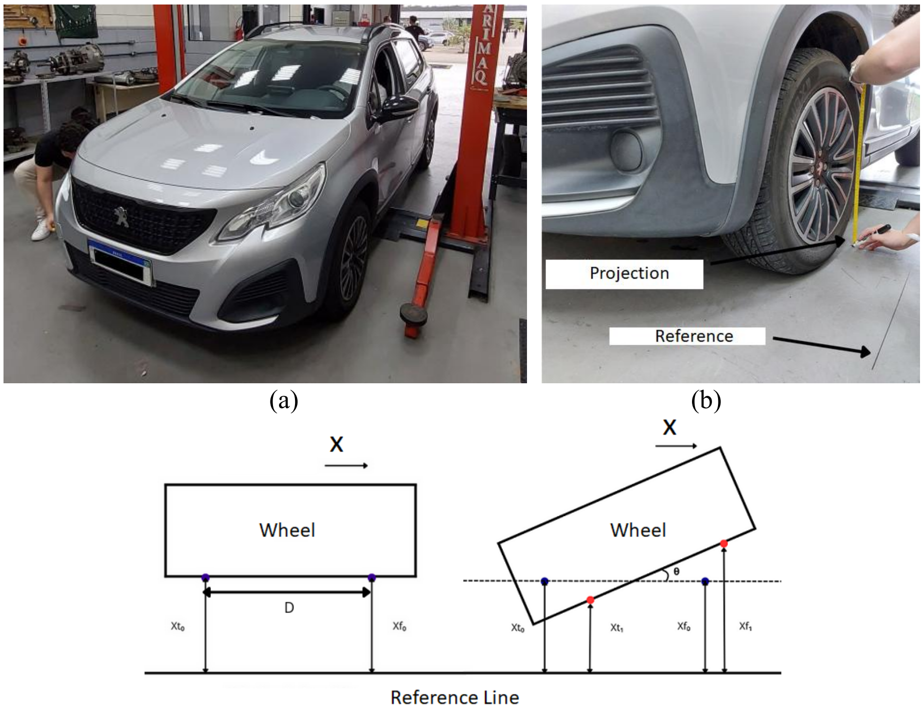
III. METHODOLOGY

Modern mobile devices incorporate Inertial Measurement Units (IMUs) based on Microelectromechanical Systems (MEMS) technology. According to [16], a typical IMU consists of three accelerometers and three single-degree-of-freedom gyroscopes, enabling three-dimensional motion measurements. Gyroscopes measure angular velocity relative to an inertial frame of reference, and by integrating these velocities, it is possible to determine changes in orientation relative to the initial position. Magnetometers usually include three sensors that provide measurements along the X, Y, and Z axes [17]. These embedded sensors are employed to capture motion data from the mobile device when positioned on the vehicle's wheel.

3.1 Test Vehicle Setup

The vehicle used for the laboratory tests was a 2020 Peugeot 2008 Allure, as shown in Figure 4a. It is equipped with a 1.6-liter flex-fuel engine, front-wheel drive, and an automatic transmission. The steering system is of the rack-and-pinion type, assisted by an electric power steering unit. The front suspension adopts a MacPherson strut configuration. The main dimensions of the vehicle include a wheelbase of 2,542 mm, a width of 1,739 mm, tire size of 205/60 R16, and a curb weight of 1,212 kg. To validate the data obtained from the application, a laboratory measurement was performed using physical methods (Figure 4b). The procedure involved projecting the outermost points of the wheel onto the ground and measuring the relative distances from a reference line. Trigonometric calculations were then used to determine the actual steering angle of the wheel. The variation in distance from the reference line, ΔX_{f_1} for the front side of the wheel and ΔX_{t_1} for the rear, is defined by the triangle shown in Figure 4c and expressed in Eq. (5).

$$\Delta X_{f_1} = X_{f_1} - X_{f_0} \tag{3}$$
$$\Delta X_{t_1} = X_{t_0} - X_{t_1} \tag{4}$$
$$\theta = \tan^{-1}\left(\frac{\Delta X_{f_1} + \Delta X_{t_1}}{D}\right) \tag{5}$$



(c)

Figure 4 – Measurement of the steering angle: (a) Tested vehicle; (b) Procedure for measuring the actual steering angle; (c) Wheel angle geometry.

3.2 Mobile Application Structure

The application was developed for devices running the Android operating system. Android Studio was used as the integrated development environment (IDE), supporting the creation of the graphical user interface, the implementation of sensor data acquisition logic, and the storage of collected data. The application was programmed using Kotlin, the native language for Android development. To measure the steering angles of the vehicle's wheels, the app utilizes the embedded sensors of the mobile device. Figure 5 presents the user navigation flow across the screens and illustrates the overall operation of the application.

The application consists of three screens. The main screen (MainActivity) allows the user to select which wheel to measure. Two buttons are available: Right Wheel and Left Wheel. These buttons redirect the user to new screens where the steering angle measurements can be performed. Figure 6a shows the application's main screen. This screen does not read sensor data; its function is solely to navigate the user to the appropriate measurement screen. After selecting which wheel to measuree, the user is directed to a new screen. Figure 6b shows the layout of this screen, where step-by-step instructions for the measurement process are displayed at the top. The initial instruction prompts the user to place the phone horizontally at the center of the wheel and press the “Next” button. At this point, the application begins reading and storing data from the device’s embedded sensors. As the user continues by pressing the button, the on-screen instructions update (Figure 6c), guiding the user to rotate the steering wheel by 90°. The data is recorded each time the “Next” button is pressed.

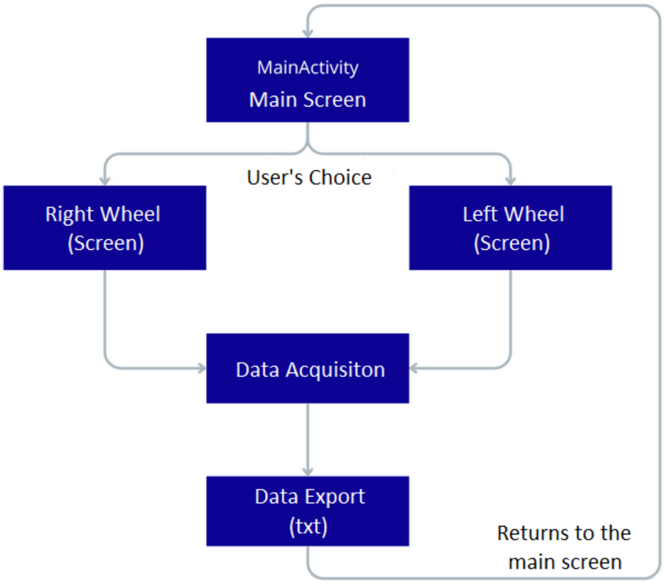
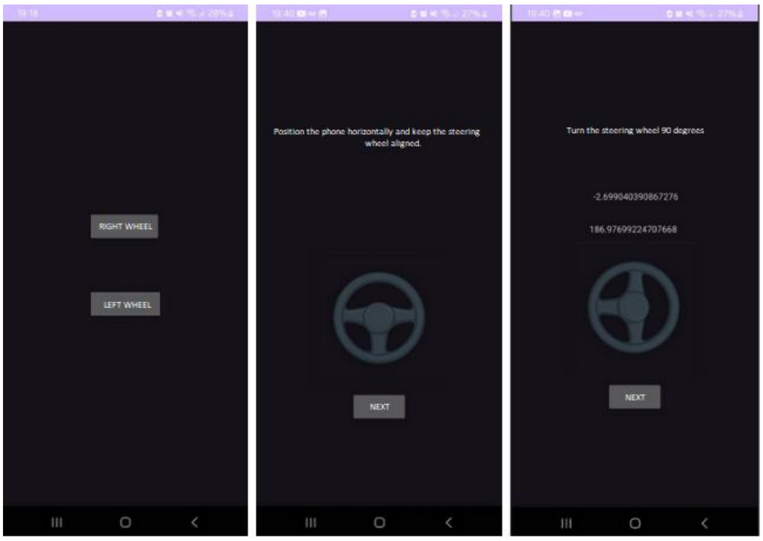


Figure 5 – Flowchart of the user interface screens.

Additionally, the values displayed on the screen represent real-time readings from the sensors, serving as a reference for the user. These values correspond to the camber and steering angles of the vehicle's wheel. The steering wheel image at the center of the screen also provides a visual cue for steering alignment. After the measurement process is completed, the application returns to the main screen and saves two text files: steering.txt and camber.txt, containing the recorded data points. By offering a clear step-by-step interface, the application supports learner autonomy, allowing students to engage with the experimental procedure at their own pace and revisit procedures for improved retention. Most students preferers this method of assessment than the traditional methodology [18].



(a) (b) (c)

Figure 6 – Application screens with user interface: (a) main screen, (b) measurement start screen, and (c) waiting screen for saving sensor readings.

In the data acquisition process, the embedded sensors of the mobile device were accessed through a synthetic sensor known as TYPE_ROTATION_VECTOR, which combines data from the accelerometer, magnetometer, and gyroscope, when available. This sensor calculates the rotation angle of the global reference frame relative to the device's coordinate system. To manage the application's sensors, the SensorManager and SensorEventListener classes were employed in the algorithm:

• SensorManager is a class from the Android API responsible for coordinating the device's physical sensors, such as the gyroscope, accelerometer, and magnetometer. It enables the detection of motion changes and environmental data, such as temperature and orientation;
• SensorEventListener was programmed to trigger whenever a change is detected in the TYPE_ROTATION_VECTOR sensor. The data acquired from these sensors are transformed into a rotation matrix, then converted into orientation vectors, and finally expressed in degrees.

Figure 7 shows a diagram illustrating the application's data acquisition process for measuring the pitch (steering angle) and roll (camber angle) of the vehicle's wheel.

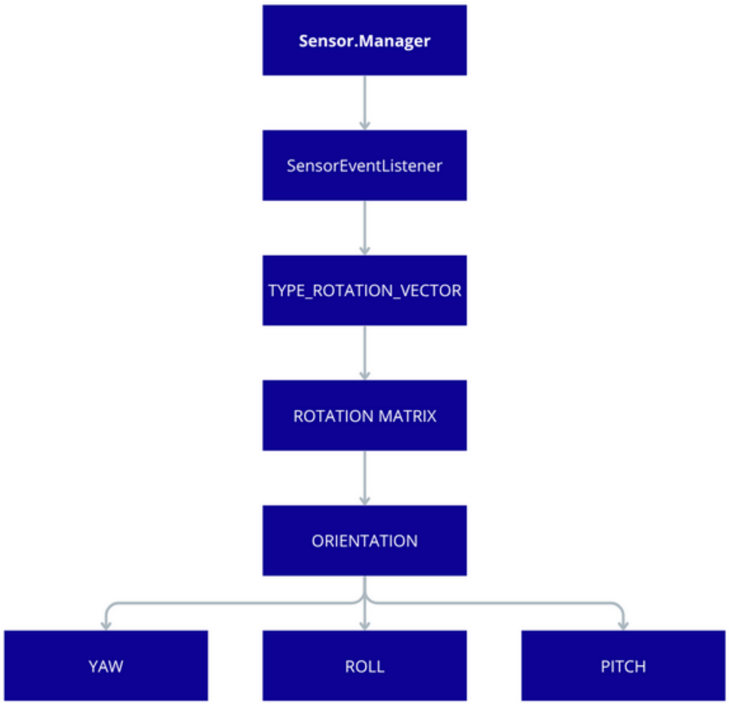


Figure 7 – Flowchart of the application's data acquisition process.

According to [17], the SensorManager class allows applications to register and unregister for sensor-related events. Once registered, the application begins receiving data directly from the device's hardware sensors. As described by [19], the SensorEventListener interface includes two types of callbacks: one that is triggered whenever there is a change in sensor values, and another that responds to changes in sensor accuracy. The getRotationMatrixFromVector method is used to compute the rotation matrix, which maps the device's coordinate system to the global coordinate system. This matrix is then passed to the getOrientation method, which converts it into an orientation vector, providing the yaw, roll, and pitch values, corresponding to rotations around the Z, X, and Y axes, respectively [17]. The global coordinate system, assuming the device is positioned at the Earth's equator with the screen facing downward toward the planet, the Z-axis points in the direction of gravity, the X-axis (longitudinal) points west, and the Y-axis points toward magnetic north.

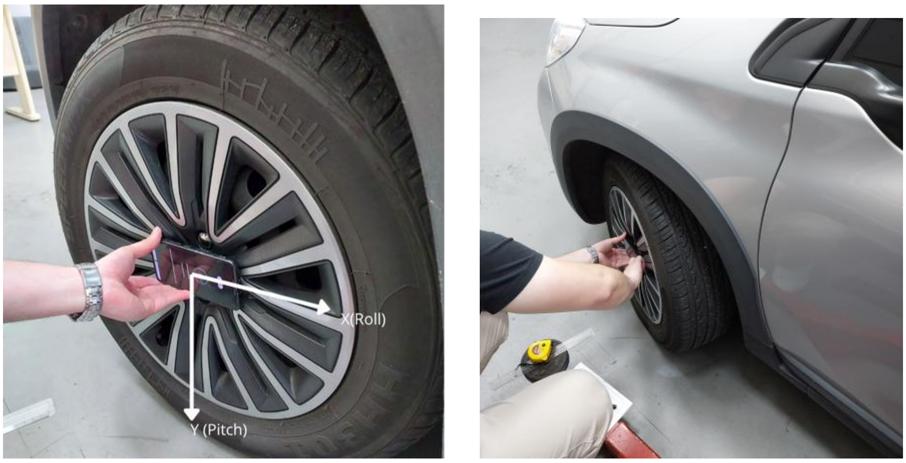
3.3 Experimental Test Procedure

In the measurement process using the application, a Samsung S22 smartphone was employed. This device is equipped with a gyroscope, accelerometer, and magnetometer. The specifications of these sensors are presented in Table 1.

Table 1 – Sensor specification with 16-bit digitization (LSB = Least Significant Bit).

	Accelerometer	Magnetometer	Gyroscope
Type	LSM6DSO	AK09918	LSM6DSO
Resolution	$2.3928.10^{-3}$ m/s²/LSB	0.15 µT/LSB	$6.1086.10^{-4}$ rad/s/LSB
Range	±78.4532 m/s² (±8g)	±4912 µT	±17.45 rad/s (±1000 dps)

Three measurements were performed on each wheel using the mobile application. The procedure involved placing the phone horizontally at the center of the vehicle's wheel (Figure 8a) and following the application's step-by-step instructions to steer the wheel (Figure 8b). The steering angle of the wheel was determined by measuring the device's rotation around the Y-axis (Pitch), while the camber angle was obtained from the rotation around the X-axis (Roll). This procedure is incorporated into classroom activities, allowing students to independently assess vehicle conditions using their own mobile devices. Thus, the application serves as a bridge between theoretical instruction and practical experience, engaging students with engineering concepts through real problem-solving tasks [20].



(a) (b)

Figure 8 – Illustration of the mobile phone positioned next to the wheel: (a) reference coordinate system, and (b) measurement of the steering angle using the mobile device.

IV. RESULTS

The possibility of using the application in laboratory classes and practical exams requires validation of the system, both the mobile device and the app, to ensure accurate parameter measurement. Therefore, the results presented in this section include an evaluation of the implemented application for analyzing a vehicle's steering system. During the measurement process, three measurements were taken for each wheel to evaluate data repeatability. Table 2 presents the rotation values along the Y-axis (Pitch) relative to the device's reference frame, as exported from the application. For each steering wheel position, the arithmetic mean and standard deviation were calculated. The standard deviation for the left wheel ranged from 0.76° to 2.16°, while for the right wheel it ranged from 1.67° to 2.12°. These results indicate that most standard deviation values remained below 2°, demonstrating good repeatability of the application's measurements and low variability across samples.

For the left wheel, the results are presented in Figure 9. Positive values of the steering wheel angle correspond to clockwise rotation, while negative values indicate counterclockwise rotation. The two resulting curves are closely aligned, showing no significant difference between the clockwise and counterclockwise steering inputs. Additionally, both curves exhibit high stability and an approximately linear behavior, with an R-squared value exceeding 99.88%. The angular coefficients of the two linear regression lines differ by only 2.21%.

Table 2 – Absolute measurements of steering angle based on mobile phone global reference.

Driver Steering Wheel [°]	Right Wheel		Left Wheel	
	Mean [°]	Standard Deviation [°]	Mean [°]	Standard Deviation [°]
360	30.86	2.12	65.47	2.16
270	35.74	1.92	71.08	1.85
180	40.72	1.89	76.72	1.56
90	45.58	1.82	81.88	1.31
0	50.08	1.75	87.73	0.76
-90	54.90	1.67	92.38	0.97
-180	60.34	1.68	97.25	0.95
-270	65.78	1.72	102.34	0.68
-360	71.81	1.82	106.89	0.84

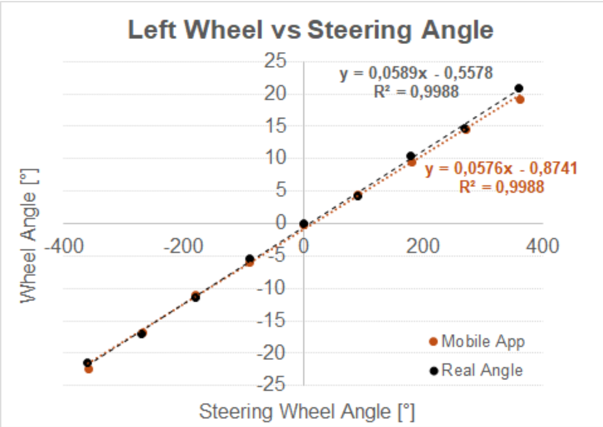


Figure 9 – Comparison between actual steering angles and application-based measurements for the left wheel.

The steering angle values obtained for the right wheel are shown in Figure 10. When the steering wheel is rotated clockwise, the measurements recorded by the application closely match those obtained through laboratory testing. However, during counterclockwise rotation, slight discrepancies are observed between the application and physical measurements, with the differences becoming more pronounced at the -270° and -360° steering wheel positions. At -360°, the absolute deviation between the actual and measured values is 3.35°, corresponding to a 14.84% error relative to the reference measurement. Additionally, the average percentage error between the application's results and the actual measurements was 5.54% for the left wheel and 12.31% for the right wheel. The difference in linear regression coefficients also increased, reaching 10.84% when compared to the left wheel.

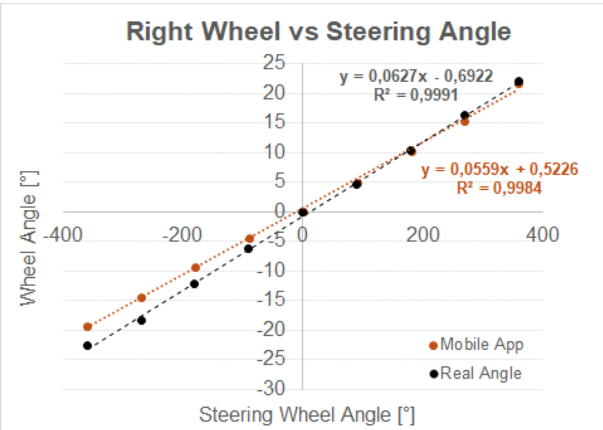


Figure 10 – Comparison between actual steering angles and application-based measurements for the right wheel.

4.1 Statistical Analysis

To assess the agreement between the measured values, Bland–Altman plots were used. This method enables the evaluation of paired measurements by plotting the differences against their means. Figure 11 compares the values obtained in the laboratory and through the application. The horizontal axis represents the mean of each pair of measurements, where positive values correspond to clockwise steering and negative values to counterclockwise rotation. The vertical axis indicates the differences between the paired measurements. The black dashed line represents the mean difference, while the red dashed lines indicate the limits of agreement (LoA), defined as the mean ±1.96 times the standard deviation. For the left wheel, as shown in Figure 11, the results revealed minimal variation, with a mean difference of –0.26°, and the largest difference remaining below -1.5°. Consequently, 95% of the measurement differences are expected to lie within the LoA, corresponding to an error margin of less than 1.5°.

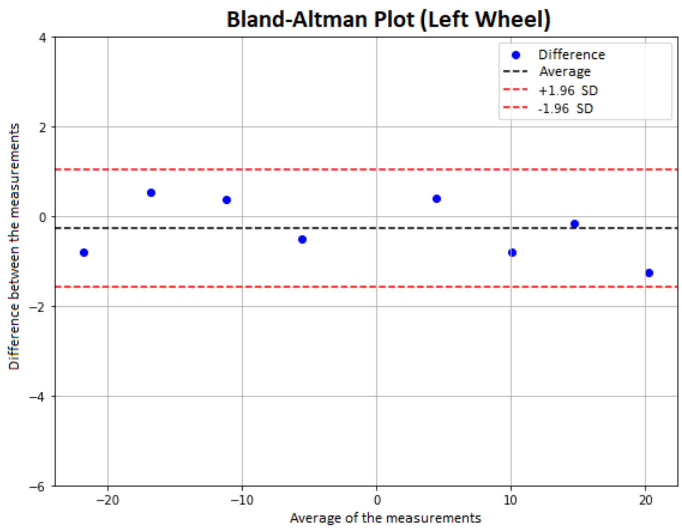


Figure 11 – Bland-Altman plot of measurements from the left wheel.

For the right wheel, the mean difference was -1.42°, as shown in Figure 12. During clockwise steering, the measurement differences were relatively small. However, during counterclockwise steering, the differences increased, reaching up to 4°, which corresponds to a percentage error of 21.99% relative to the actual measurement in the maximum difference. Nevertheless, the overall distribution of the differences remained close to zero.

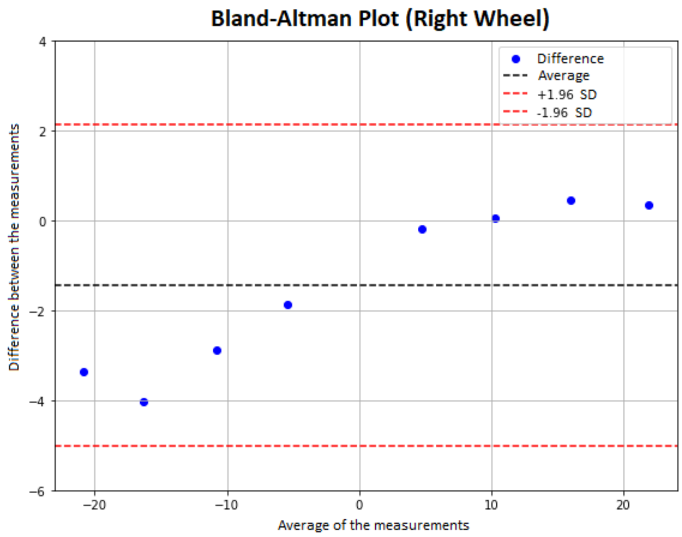


Figure 12 – Bland-Altman plot of measurements from the right wheel.

4.2 Ackermann Steering Geometry

To analyze the test vehicle's Ackermann steering geometry, two graphs were generated, as shown in Figure 13. These graphs compare the data obtained from the application with the ideal Ackermann values calculated using Eqs. (1) and (2). In Figure 13a, the inner wheel angles during both clockwise and counterclockwise steering are plotted against the ideal Ackermann curve. The measured curves were similar to each other and closely followed the ideal curve. For tight turns (i.e., with smaller turning radii), the measured steering angles were slightly lower than the Ackermann-predicted values, whereas in wider turns, the measured angles aligned closely with the theoretical predictions. This behavior indicates a well-calibrated steering system, designed to minimize lateral tire slip and enhance maneuverability in higher speeds.

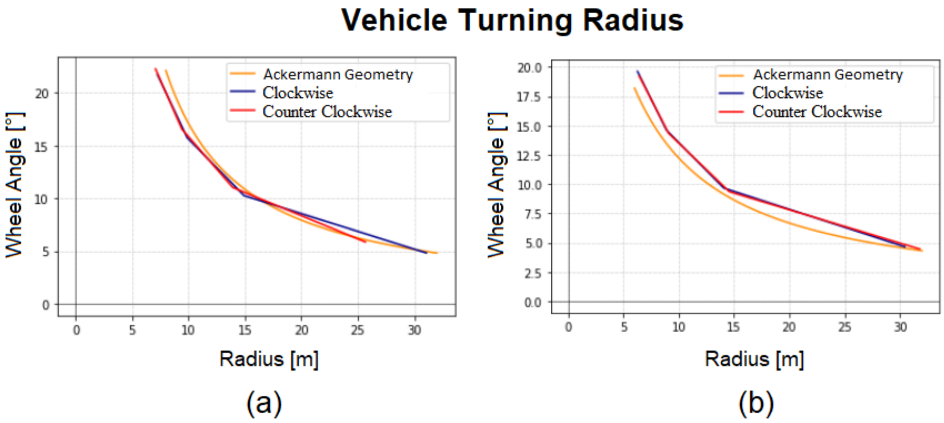


Figure 13 – Evaluation of steering behavior based on turning radius: (a) inner wheel and (b) outer wheel during cornering.

Analyzing the behavior of the outer wheel during cornering, as shown in Figure 13b, the results were closely aligned. Additionally, the curves estimated by the application exhibited stable behavior with minimal variation between them, indicating also a well-aligned steering system. The vehicle's maneuverability is directly associated with its turning radius. Based on the measurements obtained from the application, as shown in Figure 13a and Figure 13b, the minimum inferred turning radius was 6.3 meters. A smaller turning radius corresponds to greater vehicle maneuverability.

4.3 Pedagogical use of mobile devices

The parameters obtained through the application and the analyzed data assist students in physically identifying steering angles and understanding their influence on vehicle dynamics and safety. In classroom applications, feedback collected through an anonymous student survey conducted by the internal evaluation committee was positive. One student described the experience as a "very cool evaluation method, with practical questions on the tests." This indicates that the use of mobile devices in active learning environments is a viable and well-received strategy among students. The app is available to students through the Vehicular Systems Laboratory website at: https://labsistemasveiculares.ufsc.br/en/ferramentas-computacionais/estercamento-de-sistema-de-direcao/.

V. CONCLUSION

This study aimed to develop and validate a low-cost methodology for evaluating a vehicle's steering system. The methodology was implemented through the creation of an Android-based mobile application designed to measure wheel steering angles using the embedded sensors of a smartphone. The solution offers a portable and accessible alternative to conventional measurement methods, which often require specialized equipment and trained personnel. The application was developed using the Android Studio IDE, utilizing native Android libraries for sensor data acquisition. The algorithms were written in Kotlin, and the user interface was designed to be simple, minimizing the potential for user error during measurements. Additionally, the application was structured to export the acquired data in ASCII (.txt) format, facilitating access and post-processing. Validation was conducted through laboratory experiments using a 2020 Peugeot 2008. Each wheel was tested three times, and the average of the results was used for analysis. The findings demonstrated good stability and repeatability, despite some divergence at specific test points, with differences of approximately

10%. The mobile application proved to be a promising auxiliary tool for evaluating vehicle steering systems and comparing them with the ideal Ackermann geometry. Furthermore, it can serve as an educational aid in engineering programs, allowing students to conduct hands-on experiments using their own mobile devices. By correlating theoretical concepts, such as steering kinematics, Ackermann geometry, and suspension alignment, with practical measurements, the application fosters active learning and strengthens students' understanding of mechanical systems. However, accurate operation requires suitable conditions, including a level surface, correct device positioning, and minimal environmental interference that could affect sensor readings.

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