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PHYSICAL AND TECHNOLOGICAL

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RESEARCH ON ACTIVE SAFETY SYSTEMS IN AUTOMOBILES

ABSTRACT

of a dissertation for the acquisition of an the educational and scientific degree "DOCTOR"

Field of higher education:
5. Technical sciences

Professional field:
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Doctoral program:
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Scientific supervisors:
Prof. D.Sc. Georgi Atanasov Mishev
Assoc. Prof. Dr. Kaneta Ilieva Paskaleva

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The dissertation has a volume of 181 pages, including 54 figures and 32 tables, formatted into an introduction, four chapters, general conclusions, scientific and applied contributions, a list of terms and abbreviations used, a list of the author's publications, and two appendices. The list of cited literature includes 136 titles.

The designations of the formulas, figures, and tables in the abstract match those in the dissertation presented at a meeting of the scientific jury.

The dissertation was discussed and recommended for defense at a meeting of the extended department council of the Department of "Mechanical Engineering and Transport" at Plovdiv University "Paisii Hilendarski" on April 28, 2025, Protocol No. 70.

The defense of the dissertation will take place on July 9, 2025, at 11:00 AM, on the 1st floor, in the meeting room of the Rectorate at 24 Tsar Asen Street.

The materials for the doctoral defense are available to those interested in the office of the Faculty of Physics and Technology at the "PAISIUS HILENDARSKI" UNIVERSITY OF PLOVDIV,room 214.

Scientific jury: Prof. Dr. Slavi Yasenov Lyubomirov
Prof. D.Sc. Nikolay Dimitrov Menkov
Assoc. Prof. Dr. Georgi Georgiev Komitov
Assoc. Prof. Dr. Velko Slavchev Rupetsov
Assoc. Prof. Dr.Boyan Angelov Dochev

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GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

Road traffic accidents represent a social and economic issue of global significance, with a substantial contribution to their occurrence stemming from brake systems and their effectiveness. In this context, the investigation of active safety systems is of current interest, as their primary objective is to prevent incidents by assisting the driver and providing automated intervention in vehicle control during risky situations.

Active safety systems are one of the most significant advancements in modern automotive engineering and a leading trend in the pursuit of reducing the risk of road traffic accidents. Over the past few decades, the development of automobiles has been marked by the integration of increasingly sophisticated electronic systems designed to assist drivers and ensure a higher level of safety for all road participants.

Despite significant progress and widespread adoption of various active safety systems, there remains a necessity for in-depth research on their real effectiveness under different operational conditions. An analysis of existing scientific literature and experimental data indicates that factors such as road surface condition, speed, type and condition of tires, as well as the specifics of the systems themselves, can significantly influence their performance.

This dissertation is dedicated to the critical analysis and experimental investigation of the Anti-lock Braking System (ABS) and the Automatic Emergency Braking (AEB) system under conditions closely mirroring real-world usage, aiming to systematize improvement opportunities and assess their effectiveness. It provides a detailed overview of existing technologies and assessment methodologies, as well as an experimental analysis of key factors affecting vehicle dynamics during emergency braking, including road conditions, tire selection, and the functionality of the Anti-lock Braking System (ABS).

In the dissertation, a specialized methodology for evaluating the effectiveness of ABS and AEB has been developed and applied, utilizing high-tech contactless measuring equipment that facilitates precise measurement of braking distance and stopping time. More than 270 tests were conducted with various vehicles on diverse surfaces and speeds, analyzing key influencing factors—road conditions, tire types, and ABS performance.

The experimental results clearly indicate improved braking behavior in vehicles equipped with active safety systems, particularly under adverse conditions. The experimental analysis highlights the significance of proper maintenance and tire selection, as well as the role of automated systems in reducing the risk of incidents.

The conclusions drawn from this work serve as a foundation for future scientific research aimed at enhancing road safety and improving active safety systems in modern automobiles.

The purpose of the dissertation is to explore the potential of active safety systems in reducing the risk of road traffic accidents.
To achieve this objective, the following TASKS are outlined:

1. Conduct a comprehensive study and analysis of active safety systems.
2. Develop a methodology and instrumentation for the experimental investigation of the effectiveness of the Anti-lock Braking System (ABS) and Automatic Emergency Braking (AEB) systems.
3. Perform experimental studies on the factors influencing braking distance and braking deceleration.
4. Conduct experimental investigations into the effectiveness of the AEB active safety system.
5. Provide analysis, conclusions, and recommendations.

Methods and instruments of research

The research methods employed are drawn from the scientific fields of active safety systems in vehicles, vehicle dynamics, measurement technologies for speed and acceleration, experimental modeling of braking characteristics, and statistical methods for processing experimental data.

Implementation and practical applicability

Data on the influence of the Anti-lock Braking System (ABS) on braking characteristics under various road conditions have been collected, analyzed, and implemented. Investigations and analyses have also been conducted regarding the probability of activation and the effectiveness of the Automatic Emergency Braking (AEB) system.

Publications on the topic

The main results have been published in the following venues: one publication in the scientific series "Innovative STEM Education," one in the proceedings of the University of Southern Bulgaria – Smolyan, one in the "Journal of Physics and Technology," and one in the proceedings of the "International Scientific Conference Electronics." Two of the publications are co-authored, and two are authored independently.

Volume and structure of the dissertation

The dissertation consists of 181 pages, including 54 figures and 32 tables, organized into an introduction, four chapters, general conclusions, scientific and practical contributions, a glossary of terms and abbreviations, and a list of the author's publications. The bibliography includes 136 titles, of which two are in Bulgarian, with the remainder in Latin script. Additionally, the appendices contain 19 figures and 18 tables.

CONTENT OF THE DISSERTATION

Chapter 1. Analysis of the state of the problem

The first chapter of the dissertation is dedicated to a literature review focusing on active safety systems in vehicles. It provides a detailed analysis of current braking control systems, including Anti-lock Braking Systems (ABS) and Autonomous and Automated Emergency Braking (AEB and AEBS). The chapter also examines traction control and stability systems, such as Electronic Stability Program (ESP) and Traction Control System (TCS).

The importance of warning and assistance systems is emphasized, including Forward Collision Warning (FCW) and Lane Departure Warning (LDW) systems, as well as technologies for automatic parking (parking sensors). An analysis of intelligent control systems is also conducted, such as Adaptive Cruise Control and Adaptive Front Lighting Systems, alongside modern communication technologies enhancing driving safety.

Special attention is given to the research on braking distance and braking delay, identifying the main factors influencing these parameters. Results from experimental studies conducted in various countries, including Bulgaria, regarding braking dynamics and vehicle behavior in critical situations are analyzed.

The theoretical foundations and methodological approaches for analyzing braking efficiency are thoroughly examined, exploring the interrelationships among the various parameters affecting the braking process.

The chapter highlights the significance of active safety systems for the modern automotive industry as a key factor in reducing the risk of traffic accidents.

In the conclusion of the chapter, it is summarized that the automotive industry continuously seeks new approaches to enhance active safety systems. Despite the availability of numerous technical solutions aimed at reducing the risk of incidents, there is a need for further research on the effectiveness of these systems under different road conditions. Based on the conducted analysis, the goals and tasks of the dissertation are formulated, focusing on exploring the capabilities of active safety systems in reducing the risk of traffic accidents.

Chapter II. Methodology and instruments for experimental research

The methodology involves conducting experimental research both with a normally functioning Anti-lock Braking System (ABS) and with the system intentionally deactivated, allowing for comparative analysis and assessment of braking characteristics. The experimental investigations include measuring the braking distance and braking deceleration of a passenger car during emergency braking on various road surfaces with different friction coefficients.

The study encompasses three main experiments, each aimed at analyzing different aspects of braking efficiency under various speeds, road conditions, and vehicle models.

The experimental research on the capabilities of the active safety system ABS to reduce the risk of traffic accidents was conducted in two directions:

- Determining the braking delay with the ABS active safety system, with three different models of passenger cars, under three differentiated types of road conditions.
- Conducting a comparative assessment of the braking delay with the ABS active safety system for a passenger car equipped with summer and winter tires.

II.1. Object of the study

For conducting experimental investigations to determine the braking delay with the Anti-lock Braking System (ABS), three different passenger cars equipped with an active safety system (ABS) were utilized. The vehicles selected belong to different generations, and their technical specifications are provided in Table 2.1.

Table 2.1. Technical specifications of the vehicles

Technical specifications		A1 BMW 318i	A2 Seat Leon	A3 Opel Astra	Opel Zafira
Year of manufacture		1991	2005	2013	2005
Engine displacement, cm3		1796cm3	1896 cm3	1686 cm3	1995 cm3
Weight of the empty vehicle, kg		1215 kg	1306 kg	1460 kg	1495 kg
Active safety system		ABS	ABS	ABS	ABS
tires	Size (Conditions)	185/65 R15 (winter)	195/65 R15 (winter)	205/60 R16 (winter)	205/55 R16 (summer)/ 195/65 R15 (winter)
	Tread Depth, mm	6 mm	8 mm	7 mm	6 mm/8 mm

For conducting the experimental research to perform a comparative assessment of braking delay, a passenger car, specifically the Opel Zafira A, was utilized, with its technical specifications listed in Table 2.1.

The braking systems of the selected vehicles for the experimental investigations were inspected at a licensed technical inspection station, and the results confirmed their proper functionality. The tires of the vehicles were also examined and adjusted to meet the requirements of the manufacturer.

The primary conceptual context established in this section of the dissertation is the development of a systematic and scientifically grounded approach for evaluating modern active safety systems, providing comprehensive data on their effectiveness and reliability under various operating conditions.

II.2. Measuring equipment

In measuring braking deceleration, initial braking speed, and stopping time, a non-contact system, the EnergoSM 4.0 (Figure 2.1), developed by ENERGOTEST, was utilized. The maximum braking delay was measured by the "Energo-SM 4.0" decelerometer, capturing the time from brake activation to the complete stop of the vehicle. The obtained results were processed using the software ESM2: EnergoSM Decelerometer Windows Software Ver. 2.0.5, which provides graphical representations of the parameters over time, including the vehicle's speed.

Fig.2.1. EnergoSM 4.0

The EnergoSM 4.0 provides the capability to measure the current speed of the vehicle and braking delay with high precision. The system can record the accelerations and decelerations of the vehicle in real time, which is beneficial for analyzing braking efficiency and other dynamic characteristics.

The Energo-SM 4.0 device represents a modern tool for precise measurement and analysis of the dynamic characteristics of vehicles, making it highly valuable in the field of automotive research and development.

II.3. Experimental test track


Fig. 2.2. Polygon with asphalt pavement.

The investigations were conducted at a specialized test track (Figure 2.2) located in the town of Smolyan, featuring a coarse-grained asphalt surface that provides a homogeneous and standardized area for measurements. The research was carried out on a straight and level section, simulating various road conditions: dry pavement, wet pavement, and a sand-dusted surface.

For the purposes of the experiment, three passenger cars from the same class were utilized, but from different production years, in order to assess the influence of technological improvements and component wear. The experimental investigations on the first aspect, regarding the determination of braking deceleration with the Anti-lock Braking System (ABS), were conducted during the winter season. The second aspect (with a passenger car equipped with summer and winter tires) was carried out during the summer season.

II.4. Planning of experimental research

The experimental investigations on the first aspect were designed to evaluate the effectiveness of the braking system and the impact of ABS under different conditions and speeds. Each experiment was carefully planned to simulate real road situations and provide data on braking deceleration. The studies include:

- Low Speed (around 40 km/h) - The vehicle moves at a constant speed of 40 km/h on three different surfaces: dry, wet, and sand-dusted.

- Medium Speed (around 50 km/h) - The same conditions are applied.
- High Speed (around 60 km/h) - Again, tested on the three types of surfaces.

The developed studies provide an in-depth assessment of ABS performance under various conditions. Each scenario is repeated three times with three different vehicles (BMW 318i, SEAT LEON, and OPEL ASTRA) to ensure statistically significant data for measurement reliability.

The second aspect includes a comparative assessment of braking deceleration for a passenger car (Opel Zafira) equipped with summer and winter tires. Here, a speed of 30 km/h is added, and the sand-dusted surface is removed.

Figure 2.3 shows the scheme of conducting the experimental research.

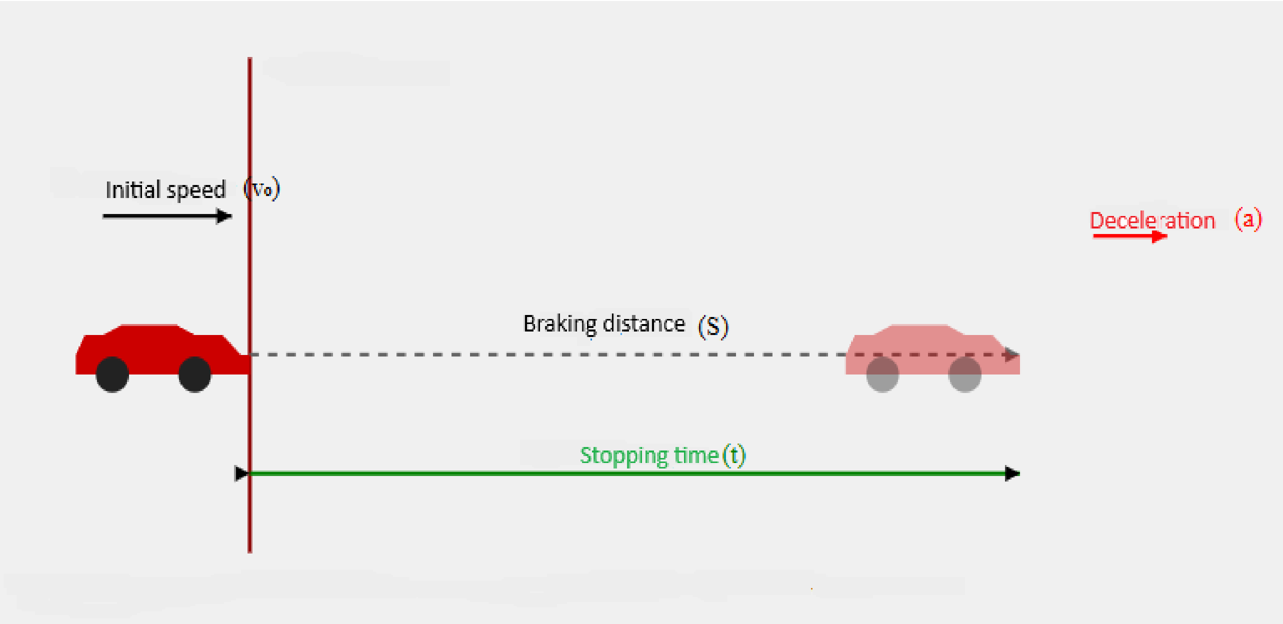

Fig. 2.3. Scheme of experiments related to the ABS research

The experimental investigations were conducted with vehicles passing through a starting line at a set speed of 30, 40, 50, or 60 km/h. The driver initiated the braking system with maximum force, simulating an emergency stop.

In the first aspect, 162 tests were carried out with three vehicles on three different surfaces at speeds of 40, 50, and 60 km/h.

In the second aspect, 96 tests were conducted with the Opel Zafira equipped with summer and winter tires at speeds of 30, 40, 50, and 60 km/h on two surfaces.

Each experiment was conducted under controlled conditions to ensure the accuracy and repeatability of the results.

II.5. Methodology for calculation and comparative assessment of braking distance

The presented methodology for theoretically calculating the braking distance is based on the fundamental principles of classical mechanics and kinematics of uniformly accelerated motion.

The determination of the relationship between braking distance and initial speed V_0, stopping time t, and the acceleration a (in this case negative, since it pertains to deceleration) is carried out using formula 2.1:

$$S = V_0 . t + \frac{a.t^2}{2}, \qquad (2.1)$$

where:

S – braking distance, [m]

V_0 - initial speed, [km/h]

t - stopping time, [s]

a – acceleration, [m/s^2]

The task is to calculate the theoretical values of braking distance for various speeds and road conditions, which will then be compared with the practically measured values obtained from the experimental investigations. This approach allows for the assessment of the accuracy and reliability of the theoretical model, as well as the identification of potential deviations caused by real road conditions and vehicle characteristics.

The formula represents a basic theoretical model for estimating the braking distance. It is derived from the kinematic equations of uniformly accelerated motion and allows for an analytical tracing of the influence of initial speed V_0, average braking deceleration a, and stopping time t.

CHAPTER III. EXPERIMENTAL STUDIES OF FACTORS AFFECTING THE BRAKING CHARACTERISTICS OF VEHICLES

The research encompasses two main experimental modules: the first investigates the braking characteristics depending on the road surface and speed of three different passenger cars, while the second involves a detailed study of a passenger car to assess the impact of summer and winter tires on braking characteristics.

The experimental setup includes the examination of three vehicle models under realistic simulations of emergency braking on dry, wet, and sand-dusted road surfaces. The study incorporates precise measurements using a contactless measurement system, allowing for accurate tracking of dynamic parameters such as braking distance, stopping time, and braking deceleration. A key element of the research is the parallel examination of the system under normal operation and with the forced deactivation of ABS, which facilitates an objective comparative analysis and evaluation of the role of ABS in enhancing braking efficiency and dynamic stability of vehicles in critical situations.

The theoretical comparison of experimental results was realized through mathematical modeling based on the formulas presented in Chapter II of the dissertation. This approach enables the identification of statistically significant deviations and in-depth analysis of the factors influencing braking efficiency under various conditions.

To record the parameters being studied in the vehicles, modern and precise equipment is essential to ensure accurate results. In this study, a contactless system for measuring speed and distance of moving vehicles, EnergoSM 4.0, was used, which is described in detail in Chapter II of the dissertation.

III.1. Experimental investigation of the effect of road surface type on braking deceleration and braking distance

III.1.1. Examination of the condition of the surface and the speed of the vehicle on braking deceleration

The factors investigated include:

- Three conditions of the road surface: dry, wet, and sandy;
- Three vehicle speeds: 40, 50, and 60 km/h;
- Three vehicles: A1 (BMW 318i), A2 (Seat Leon), A3 (Opel Astra);
- ABS system activated and deactivated.

Figures 3.1, 3.2, and 3.3 show the graphical diagrams of braking deceleration under different road surface conditions and varying speeds, with and without the ABS system for the three vehicles.

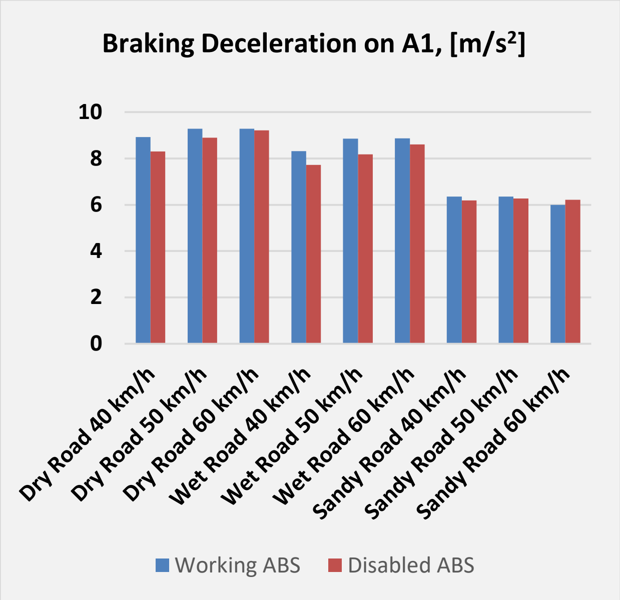

Fig.3.1. Results of Braking Deceleration on A1 with Working ABS and Disabled ABS

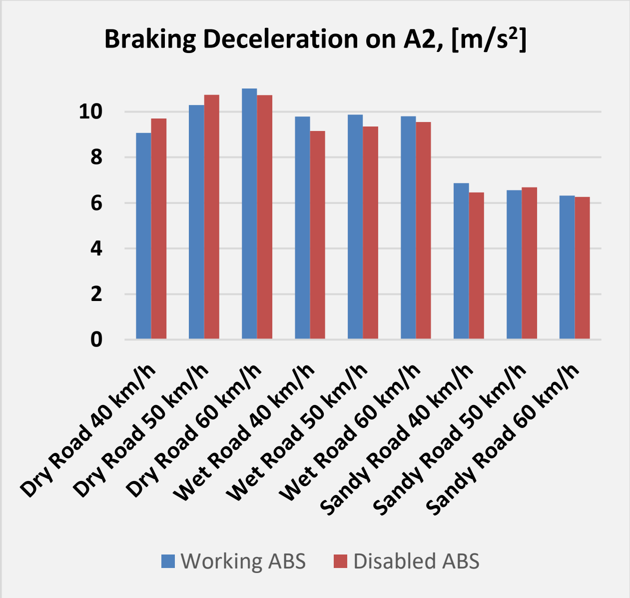

Fig.3.2. Results of Braking Deceleration on A2 with Working ABS and Disabled ABS

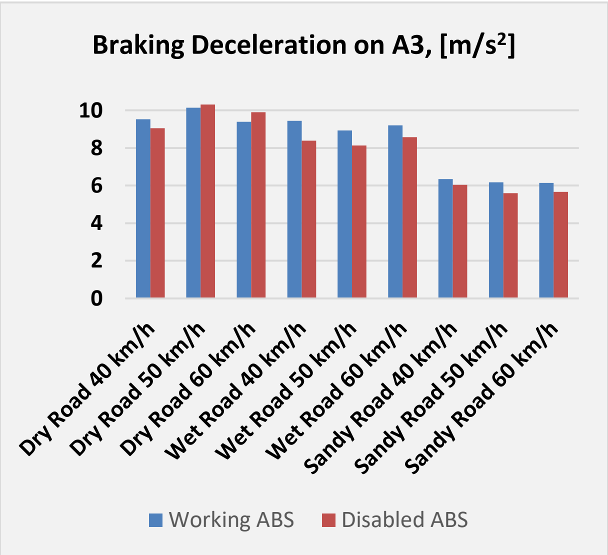

Fig.3.3. Results of Braking Deceleration on A1 with Working ABS and Disabled ABS

Conclusions:

1. For vehicles equipped with the ABS system, the highest values of braking deceleration are observed on dry surfaces. With changes in the condition of the road surface (wet and sandy), braking deceleration significantly decreases.

2. For vehicles with the ABS system deactivated, braking deceleration is lowest on sandy surfaces. This is attributed to wheel lock-up and loss of traction due to decreased friction, resulting in greater instability of the vehicle and an increased risk of loss of control.

3. The average values of braking deceleration for vehicles equipped with the ABS system are higher than those for vehicles with the system deactivated under adverse

road conditions (wet and sandy). This indicates that the ABS system prevents wheel lock-up and provides better control of the vehicle.

III.1.3. Examination of the condition of the surface and the speed of the vehicle on braking distance

Figures 3.7, 3.8, and 3.9 show the graphical diagrams of stopping time with and without the ABS system for the three vehicles.

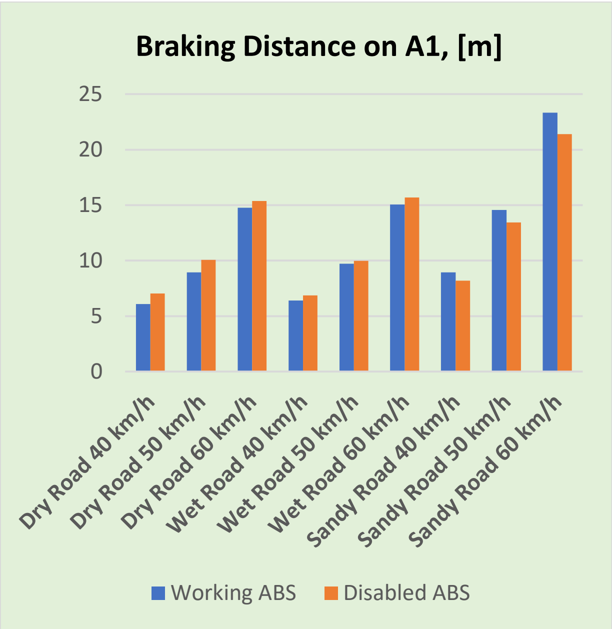

Fig.3.7. Results of Braking Distance on A1 with Working ABS and Disabled ABS

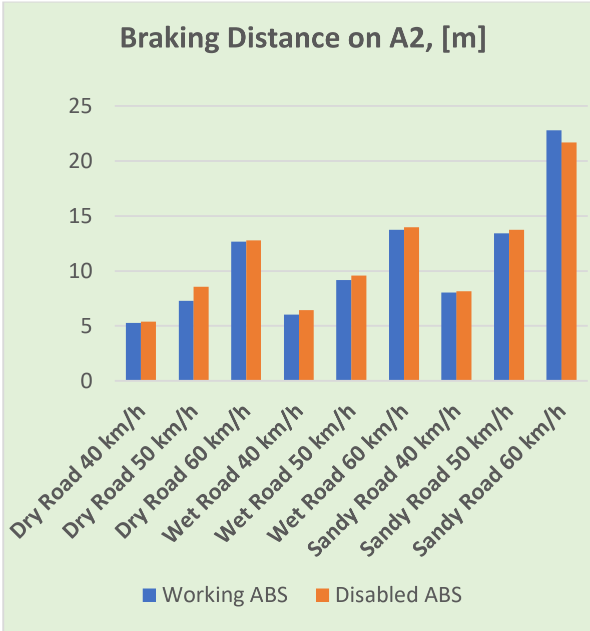

Fig.3.8. Results of Braking Distance on A2 with Working ABS and Disabled ABS

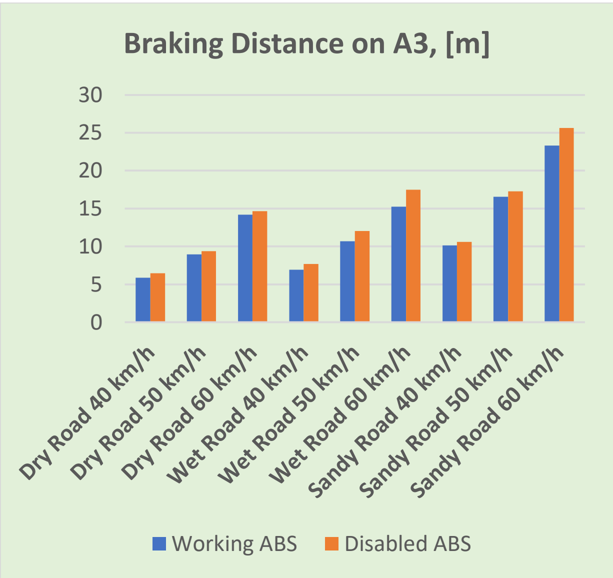

Fig.3.9. Results of Braking Distance on A3 with Working ABS and Disabled ABS

Conclusions:

1. The braking distance on dry surfaces is the shortest, as the coefficient of friction is the highest. On wet and sandy surfaces, the braking distance increases due to reduced traction between the tires and the surface.

2. As the vehicle speed increases, the braking distance grows under all road conditions, which is attributed to greater inertial forces and kinetic energy of the vehicle.

III.1.4. Summary data from the investigation of braking deceleration and braking distance of the three passenger cars

Tables 3.1 and 3.2 present the results of the measurements of braking deceleration for the three vehicles under different conditions of the road surface, vehicle speeds, and the state of the ABS system. The tables also include the tread height of the tires on the three vehicles.

Table 3.1. Results of measured braking deceleration for the three vehicles with normally operating ABS system

Pavement condition	Initial speed, km/h	Measured braking deceleration, m/s^2		
		A1 (BMW 318i) Tread Depth: 6 mm	A2 (Seat Leon) Tread Depth: 8 mm	A3 (Opel Astra) Tread Depth: 7 mm
dry	40	8.92	9.07	9.53
dry	50	9.29	10.3	10.15
dry	60	9.28	11.09	9.4
wet	40	8.32	9.79	9.45
wet	50	8.86	9.87	8.94
wet	60	8.87	9.8	9.21
sand	40	6.36	6.87	6.35
sand	50	6.36	6.56	6.17
sand	60	6.00	6.32	6.14

Influence of the ABS system on braking deceleration

With a normally functioning ABS system in all vehicles, ABS provides more stable and predictable braking deceleration, especially on dry and wet surfaces.

On a dry surface at 60 km/h, A2 demonstrates the highest deceleration (11.09 m/s^2), while the lowest value (9.28 m/s^2) was measured for vehicle A1.

On a wet surface at 50 km/h, A2 again shows the highest braking deceleration (9.87 m/s^2), while the lowest value (8.32 m/s^2) was recorded for vehicle A1 at 40 km/h.

On a sandy surface at 40 km/h, A2 again demonstrates the highest deceleration (6.87 m/s^2), with the lowest (6.00 m/s^2) measured for vehicle A1.

Table 3.2. Results of measured braking deceleration for the three vehicles with ABS system forcefully disabled

Pavement condition	Initial speed, km/h	Measured braking deceleration, m/s^2		
		A1	A2	A3
dry	40	8.3	9.71	9.05
dry	50	8.89	10.74	10.32
dry	60	9.21	10.73	9.9
wet	40	7.72	9.16	8.39
wet	50	8.18	9.35	8.13
wet	60	8.6	9.55	8.57
sand	40	6.19	6.46	6.04
sand	50	6.27	6.69	5.59
sand	60	6.22	6.27	5.66

With the ABS system deactivated, braking deceleration is higher, particularly on dry surfaces, but it is more unstable on wet and sandy surfaces. This is due to wheel lock-up and loss of traction, which increases the risk of losing control.

The comparison graph of braking deceleration is presented in Figure 3.10.

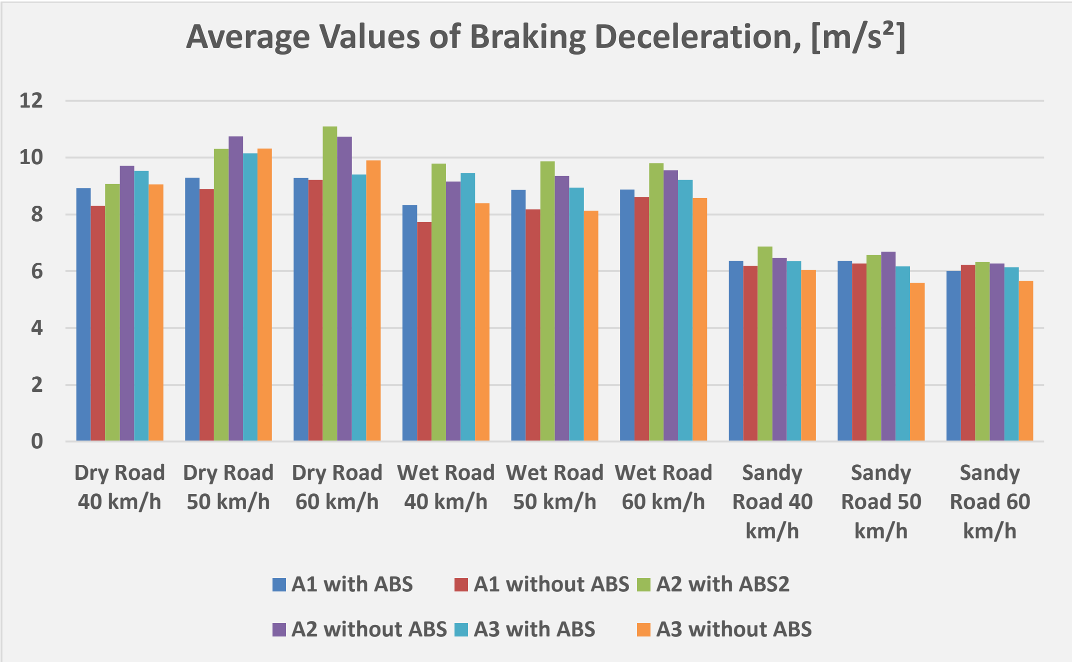

Fig.3.10. Results of braking deceleration for the three vehicles with ABS enabled and ABS disabled

The data show that on dry surfaces, braking deceleration is higher with the ABS system deactivated (for example, A1 and A2 at 40 km/h, all three vehicles at 50 km/h, and A1 and A3 at 60 km/h). This is due to the wheel lock-up during conventional braking, which creates a higher peak coefficient of friction at the beginning of braking. On wet surfaces, the functioning ABS demonstrates an advantage in almost all conditions. On sandy surfaces, the differences are minimal, indicating the limits of the system's effectiveness during extreme braking under reduced traction.

Tables 3.5 and 3.6 present the results of the measured braking distances for the three test vehicles under different road surface conditions, vehicle speeds, and the state of the ABS system. The tables also include a column with the average values of the measured braking deceleration for the three vehicles.

Table 3.5. Results of measured braking distance for the three vehicles with normally operating ABS system

Pavement condition	Speed, km/h	Measured braking distance, m		
		A1	A2	A3
dry	40	6.09	5.27	5.86
dry	50	8.95	7.29	8.97
dry	60	14.78	12.66	14.2
wet	40	6.42	6.04	6.95
wet	50	9.73	9.18	10.7
wet	60	15.07	13.73	15.25
sand	40	8.95	8.05	10.15
sand	50	14.57	13.42	16.57
sand	60	23.32	22.78	23.33

Table 3.6. Results of measured braking distance for the three vehicles with ABS system forcefully disabled

Pavement condition	Speed, km/h	Measured braking distance, m		
		A1	A2	A3
dry	40	7.05	5.39	6.47
dry	50	10.08	8.57	9.39
dry	60	15.36	12.77	14.64
wet	40	6.88	6.45	7.7
wet	50	9.99	9.58	12.03
wet	60	15.68	13.96	17.49
sand	40	8.2	8.16	10.6
sand	50	13.44	13.75	17.26
sand	60	21.41	21.68	25.65

Influence of the ABS system on braking distance

With a normally functioning ABS system, the braking distance is significantly reduced, especially on dry and wet surfaces. This is particularly important at high speeds, where ABS prevents wheel lock-up and provides better control over the vehicle.

With the ABS system deactivated, the braking distance is considerably longer, especially on wet and sandy surfaces, where the absence of ABS leads to wheel lock-up and loss of traction.

The comparison graph of braking distance is presented in Figure 3.12, where the values illustrate the differences in braking distance with the ABS system active and deactivated. The most significant parameter from a practical standpoint shows that ABS reduces the braking distance on dry and wet surfaces at high speeds (for example, 15.25 m versus 17.49 m on wet surfaces at 60 km/h). Interestingly, on sandy surfaces, the trend reverses, and ABS increases the braking distance (22.78 m versus 21.68 m at 60 km/h)—a phenomenon attributed to wheel lock-up and "digging in" into the loose surface.

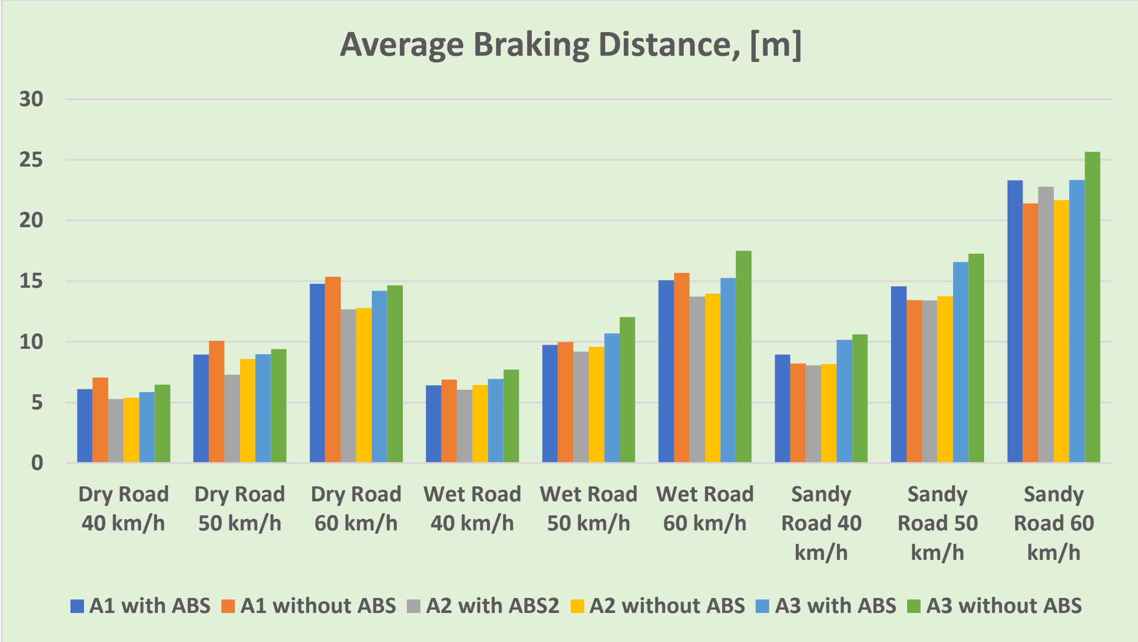

Fig.3.12. Results of braking distance for the three vehicles with ABS enabled and ABS disabled

From these summarized data from the experimental studies, the following conclusions can be drawn:

1. The height of the tire tread significantly influences the braking characteristics of a vehicle on all types of road surfaces. As the tread height decreases, the braking deceleration decreases, and the stopping time and braking distance increase.
2. The road surface has a significant impact on the braking effectiveness of vehicles. On wet surfaces, the braking deceleration decreases, which leads to an increase in stopping time and braking distance compared to the same indicators on dry surfaces.
3. A functioning anti-lock braking system (ABS) improves braking performance by providing better traction and control while braking, especially in adverse weather conditions.

III.2. Investigation of braking deceleration and braking distance with the ABS active safety system on a passenger car equipped with summer and winter tires

The present study aims to analyze the braking deceleration and braking distance of a passenger car, equipped successively with summer and winter tires under various road conditions (dry and wet road surfaces). It is important to determine how the presence of ABS with different types of tires affects braking effectiveness under different road conditions

III.2.1. Investigation of braking deceleration and braking distance of a passenger car equipped with summer tires

The comparison graph of braking deceleration is presented in Figure 3.13, which clearly shows the differences between the functioning and deactivated ABS systems.

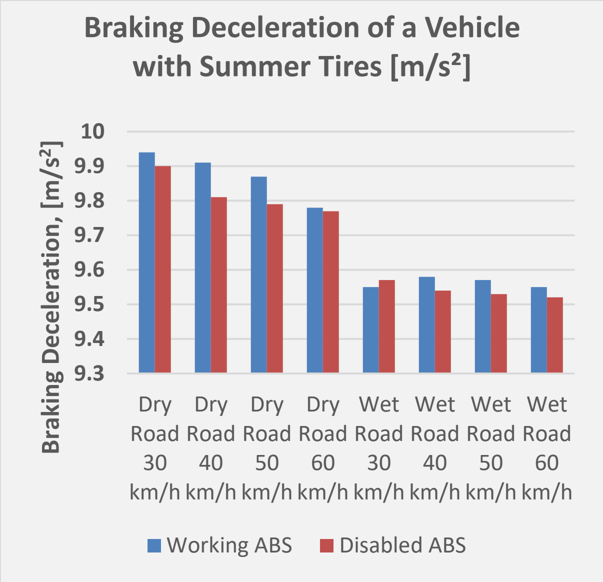

Fig.3.13. Results of braking deceleration for a vehicle equipped with summer tires with ABS enabled and ABS disabled

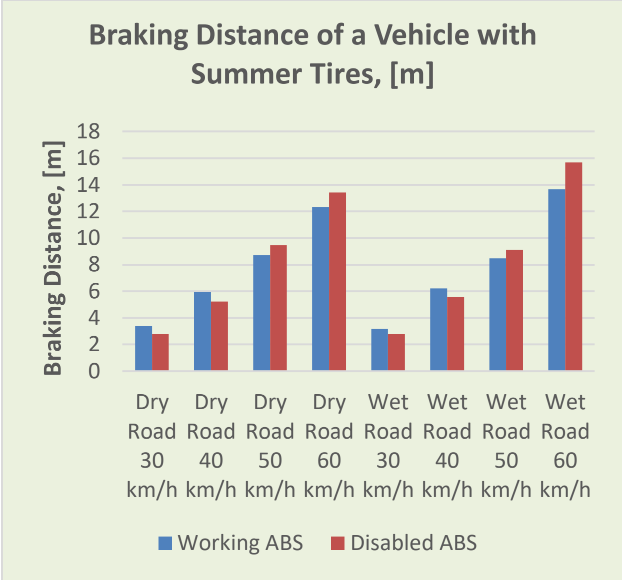

Fig.3.15. Results of measured braking distance for a vehicle equipped with summer tires with ABS enabled and ABS disabled

In Figure 3.15, the differences in braking distance with the ABS system active and deactivated are demonstrated. The graph highlights the negative impact of the absence of the ABS system on the vehicle's braking distance, especially in wet conditions. As speed increases, there are significant increases in braking distance, which underscores the need for active safety systems like ABS to ensure quicker and safer stopping. This data is crucial for drivers to understand the risks associated with operating vehicles without active control measures in conditions of variable traction.

III.2.2. Investigation of braking deceleration and braking distance of a passenger car equipped with winter tires

The comparison graph of braking deceleration is presented in Figure 3.16, which clearly shows the differences between the functioning and deactivated ABS systems.

Figure 3.18 shows the results of the measured braking distance of a passenger car equipped with winter tires, under conditions with and without ABS. The graph provides a clear visualization of the differences in braking performance depending on the functioning of the ABS.

The graph highlights the negative impact of the lack of ABS on a vehicle's braking distance, especially in wet conditions. Increasing speed leads to significant increases in braking distance, proving the need for active safety systems such as ABS to ensure shorter braking distances.

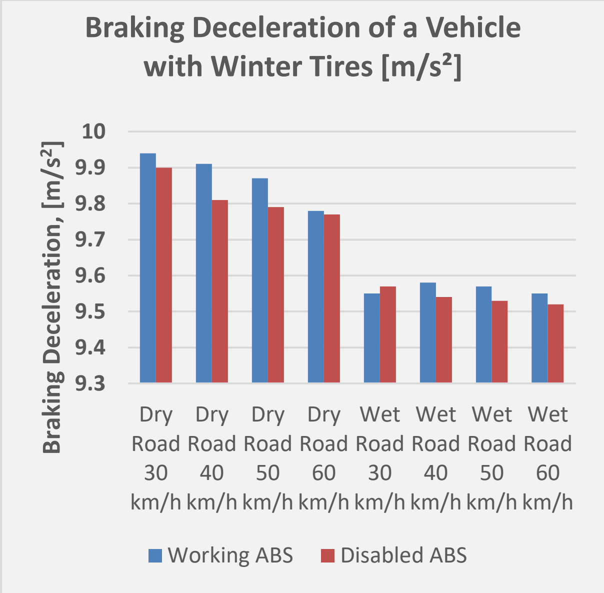

Fig. 3.16. Results of braking deceleration for a passenger car equipped with winter tires with ABS enabled and ABS disabled

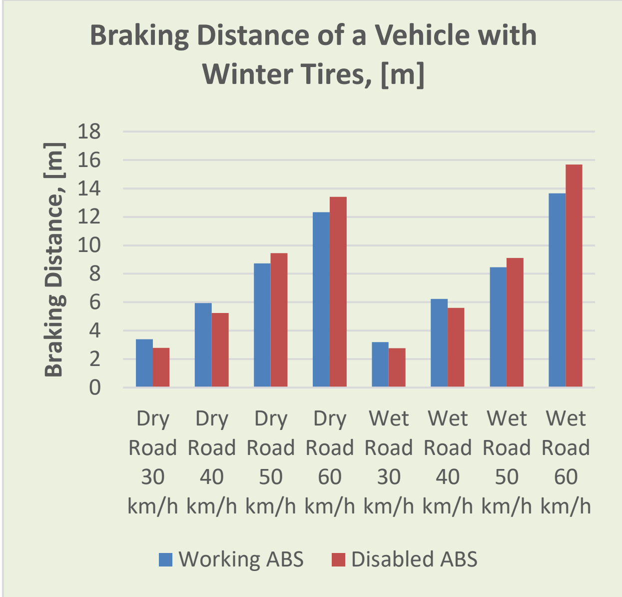

Fig.3.18. Results of measured braking distance for a passenger car equipped with winter tires with ABS enabled and ABS disabled

III.2.3. Summary of the investigation of braking deceleration and braking distance of a passenger car equipped with summer and winter tires

The conducted study analyzed the influence of tires designed for different seasons and the anti-lock braking system (ABS) on the braking deceleration and braking distance of a passenger car, equipped successively with summer and winter tires. The results emphasize the significant role of tires depending on the season, particularly regarding traction and safety during braking.

Specifically for the summer period, the study showed that summer tires provide good braking performance on dry surfaces, but their effectiveness decreases under wet conditions. With the ABS activated, the vehicle demonstrates shorter braking distances and increased controllability, as the functioning ABS system reduces the risk of wheel lock-up and loss of traction.

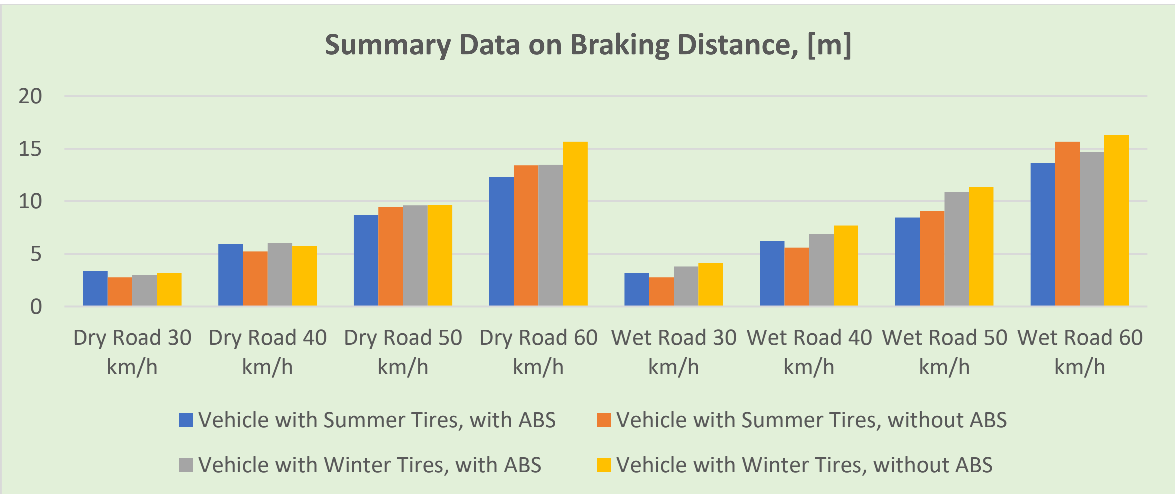

Fig.3.19. Results of the measured braking distance of a vehicle equipped with summer and winter tires, with ABS enabled and with ABS disabled

In the tests with winter tires, the results for braking distance show that in almost all trials, the braking distance is longer compared to summer tires. This is because winter tires are designed to perform under lower temperatures and on variable road surfaces.

III.3. Mathematical modeling and theoretical analysis of experimental results.

The purpose of this mathematical modeling is to identify statistically significant deviations and to conduct an in-depth analysis of the factors affecting braking efficiency under various conditions.

III.3.1. Mathematical modeling and theoretical analysis of experimental results from three different models of passenger cars subjected to testing under three differentiated types of road conditions

Figure 3.20 presents a comparison between the measured braking distance and the theoretically calculated braking distance for the averaged values from the results of vehicle A1 with an active and inactive anti-lock braking system (ABS).

Figure 3.21 presents a comparison between the measured braking distance and the theoretically calculated braking distance for the averaged values from the results of vehicle A2 with an active and inactive ABS.

Figure 3.22 presents a comparison between the measured braking distance and the theoretically calculated braking distance for the averaged values from the results of vehicle A3 with an active and inactive anti-lock braking system (ABS).

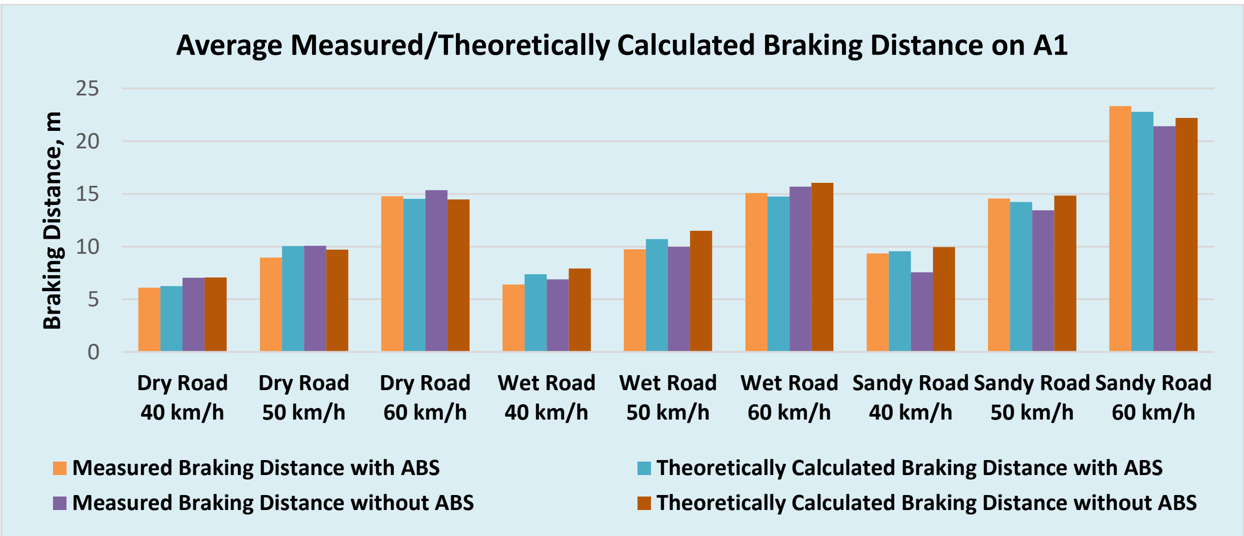

Fig.3.20. The differences between the measured braking distance and the theoretically calculated braking distance of A1 with ABS enabled and ABS disabled

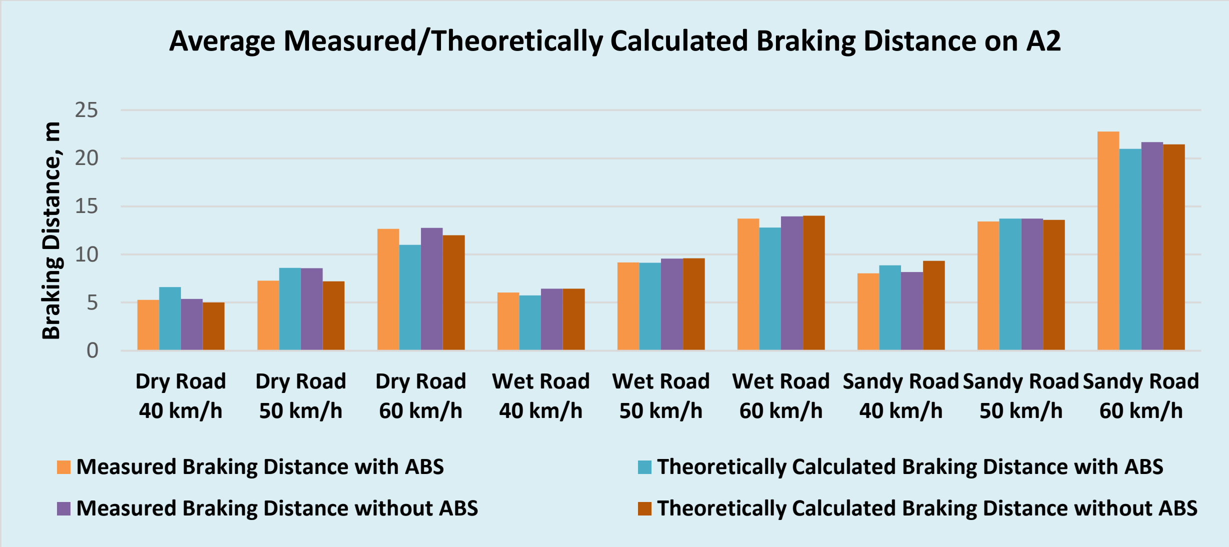

Fig.3.21. The differences between the measured braking distance and the theoretically calculated braking distance of A2 with ABS enabled and ABS disabled

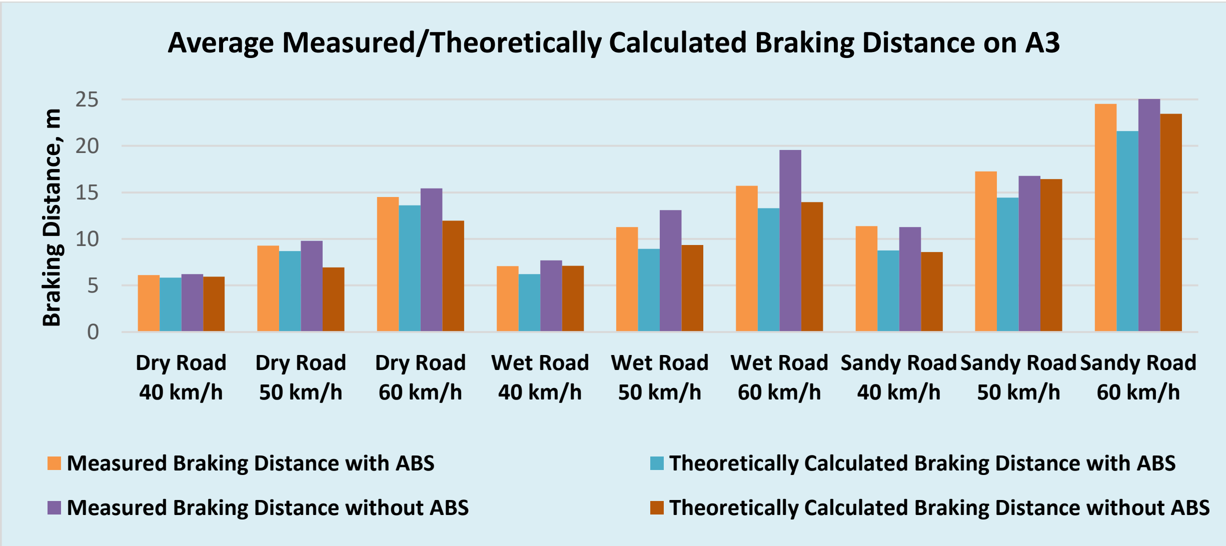

Fig.3.22. The differences between the measured braking distance and the theoretically calculated braking distance of A3 with ABS enabled and ABS disabled

The mathematical model demonstrates the highest accuracy in relation to the experiments when the ABS system is active and the surface is dry, especially for vehicle A3, where the deviations are minimal (1-3%).

In wet and sandy conditions, as well as with the ABS deactivated, the discrepancies between the theoretical and measured values increase significantly for all models, with vehicle A1 reaching over 17% under certain conditions (sand, without ABS).

Each of the three vehicles (A1, A2, A3) exhibits specific differences and trends in deviations, highlighting that, in addition to road conditions, the structural features and settings of vehicle A1 also significantly influence the correspondence between the model and the actual results.

III.3.2. Mathematical modeling and theoretical analysis of the results of a passenger car equipped with summer tires and winter tires

Figure 3.23 presents a comparison between the measured braking distance and the theoretically calculated braking distance for the results of the vehicle with summer tires, with the anti-lock braking system (ABS) active and deactivated.

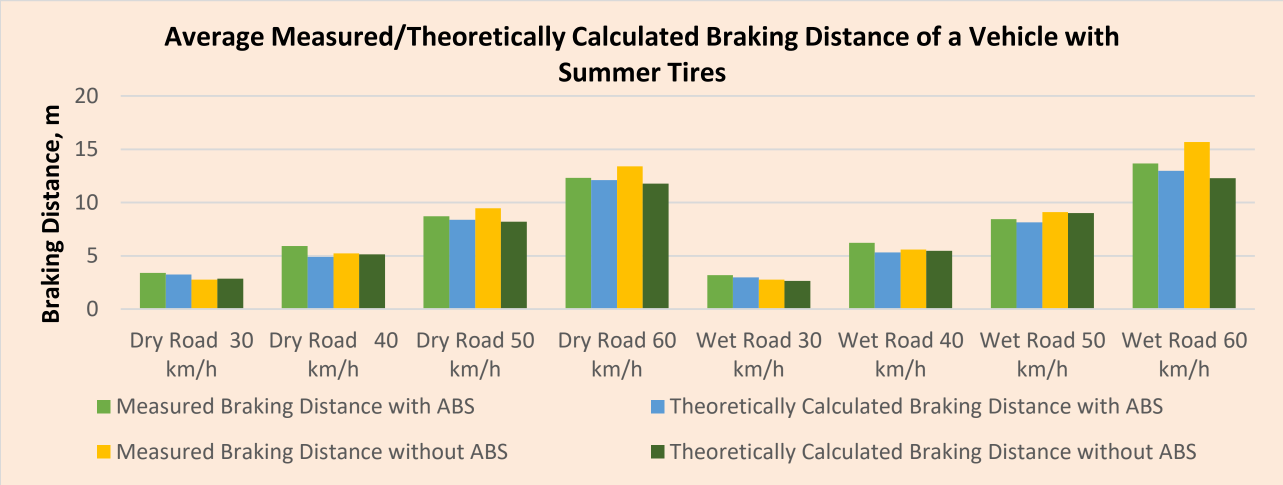

Fig.3.23. The differences between the measured braking distance and the theoretically calculated braking distance of a passenger car equipped with summer tires, both with and without ABS

Figure 3.24 presents a comparison of the results for the vehicle equipped with winter tires, with the anti-lock braking system (ABS) active and deactivated.

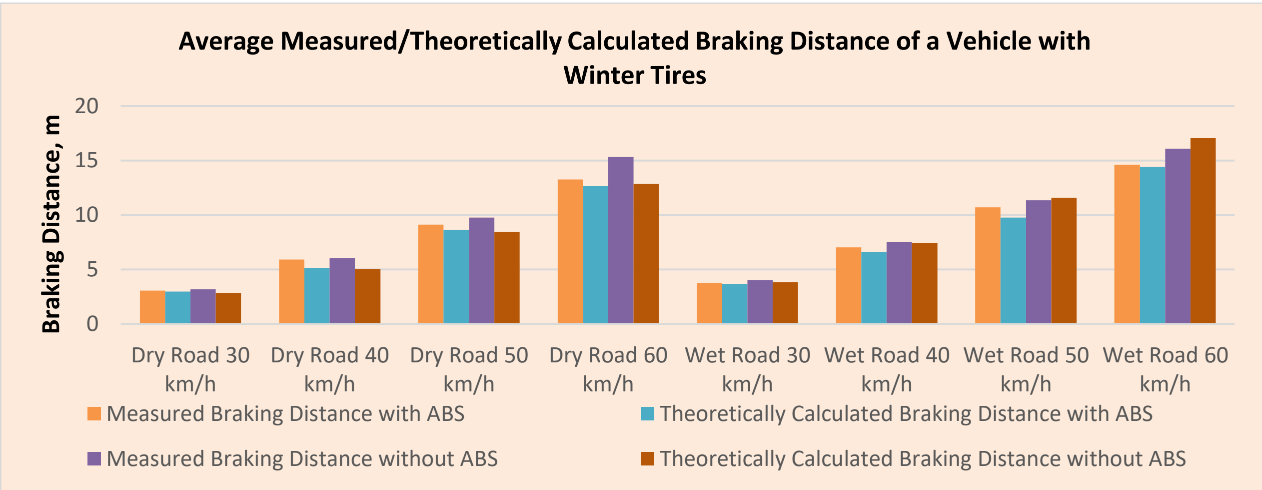

Fig.3.24. The differences between the measured braking distance and the theoretically calculated braking distance of a passenger car equipped with winter tires, both with and without ABS

When the ABS system is functioning, the braking distance is longer compared to the theoretically calculated values across all road surfaces. This results from additional factors not accounted for by the mathematical model.

The mathematical model demonstrates relatively good accuracy compared to the experimental data for both summer and winter tires, with most deviations being relatively small.

The activated ABS system provides more predictable braking behavior for both types of tires, while significant fluctuations are observed with the system deactivated, especially at high speeds and on dry surfaces.

CHAPTER IV. STUDY OF THE EFFECTIVENESS OF THE AUTOMATED EMERGENCY BRAKING (AEB) SYSTEM

In this chapter of the dissertation, the primary task of the experimental research is to evaluate the effectiveness of the Automated Emergency Braking (AEB) system in detecting potential hazards on the road and taking appropriate measures to prevent a collision. The main braking characteristics are: stopping time, braking deceleration, and the distance of the stopped vehicle to an oncoming obstacle at various initial speeds.

IV.1. Methodology and tools for the experiment on the effectiveness of the automated emergency braking (AEB) system

The methodology of the experimental research has been developed to assess the effectiveness and reliability of the Automated Emergency Braking (AEB) system under real conditions. This includes detailed planning of the experiments, selection of appropriate equipment, and analysis of the results.

The methodology includes measuring the probability of system activation, the deceleration during braking, the stopping time, and the distance of the already stopped vehicle to the obstacle while varying the vehicle's speed. The scheme of the experimental research is shown in Figure 4.1.

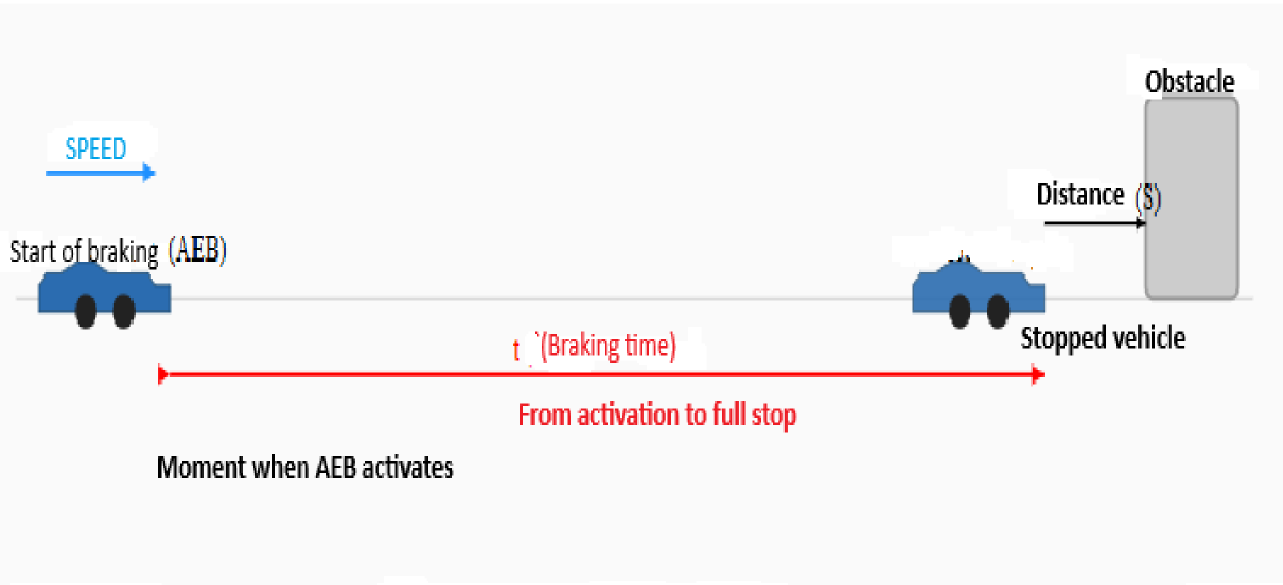

Fig. 4.1. Schematic representation of the experiment

IV.1.1. Experimental setup

The experimental research was conducted using a vehicle equipped with a contactless speed and deceleration measurement system, EnergoSM 4.0, which provides accurate data on the dynamic characteristics of the vehicle.

The experiments took place on a dry, flat, and horizontal road surface with a high coefficient of friction. During the experiments, the vehicle's movement was simulated relative to an obstacle that imitated a stopped car. The Automated Emergency Braking (AEB) system detects the potential hazard (the obstacle) and emits an audible warning signal to the driver. If there is no adequate response from the driver, the AEB autonomously activates the vehicle's brakes, distributing the braking force effectively to prevent the anticipated collision with the obstacle.

A Toyota C-HR passenger car, manufactured in 2022, was chosen for the experiment. This vehicle is standardly equipped by the manufacturer with Toyota Safety Sense™ 2.5 (TSS 2.5), which includes a suite of driver assistance technologies such as: forward automatic emergency braking, adaptive cruise control, blind-spot monitoring, lane departure warning, collision warning, and a rearview camera.

An artificial obstacle (Figure 2.2) was used in the experimental setup, designed to simulate a stopped vehicle.

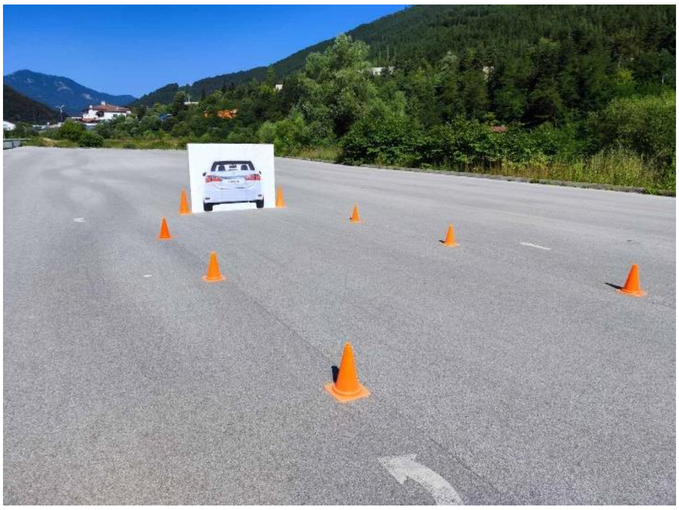

Fig.4.2. Artificial obstacle

The artificial obstacle is made of Styrofoam with a thickness of 10 mm and has the following dimensions: a width of 2 meters and a height of 1.5 meters. It is shaped at a 1:1 scale to resemble the rear of a car, which is essential for the realism of the tests. For added authenticity, it features illuminated brake lights that simulate the activated rear lights of a vehicle.

IV.1.3. Conducting the experiments

The experimental part of the research includes a total of 27 trials, with 9 trials conducted at each stage, carried out at different vehicle speeds. Each experiment was conducted under controlled conditions to ensure accuracy and repeatability of the results.

The main measured parameters are speed; braking deceleration (measured deceleration of the vehicle after AEB activation); stopping time (the time required for the vehicle to come to a complete stop after the AEB system is activated); and the distance to the obstacle (the distance of the already stopped vehicle to the obstacle).

IV.2. Experimental research

The results of the conducted experiments cover two aspects:

1. Probability of AEB Activation.

This part of the study focuses on evaluating the effectiveness of the Automated Emergency Braking (AEB) system under various conditions.

2. Measurement of Key Dynamic Parameters

These include braking deceleration, stopping time, and distance to the obstacle.

IV.2.1. Experimental research on the probability of AEB activation

A total of 27 trials were conducted, where the vehicle was driven towards the artificial obstacle without the driver intervening in the braking process. Each trial had a different initial speed according to the specified stages: the vehicle first moves at a low speed (11-20 km/h), then at a moderate speed (21-35 km/h), and finally at a high speed (36-46 km/h).

The results from the experimental investigations regarding the effectiveness of the system to activate automatically without driver intervention are presented in Table 4.1.

Out of a total of 27 trials conducted, the system activated automatically without driver intervention 21 times, resulting in approximately 78% overall success rate.

Table 4.1. Success results from all experiments with automatic AEB activation

No.	Speed, (km/h)	result	No.	Speed, (km/h)	Result
1	12	Successful	15	28	Successful
2	15	Successful	16	27	Failed
3	11	Successful	17	34	Successful
4	10	Successful	18	23	Successful
5	13	Successful	19	39	Successful
6	18	Successful	20	42	Successful
7	20	Successful	21	40	Failed
8	12	Successful	22	46	Successful
9	14	Successful	23	36	Successful
10	24	Successful	24	39	Failed
11	25	Failed	25	45	Successful
12	28	Successful	26	41	Failed
13	25	Successful	27	38	Successful
14	29	Failed			

The conducted tests provide grounds to assert that the AEB active safety system has high reliability in critical situations, which creates potential for significantly reducing the risk of road traffic accidents.

A detailed analysis by speed ranges has been performed in Table 4.2.

Table 4.2.- Probability of activating the AEB system at different speeds

Speed range	Number of experiments	Successful activations	Probability of Activation
11-20 km/h	9	9	100%
21-35 km/h	9	6	66.67%
36-46 km/h	9	6	66.67%
Total	27	21	77.78%

Conclusions:

- The system demonstrates exceptional effectiveness at speeds up to 20 km/h, making it ideal for use in urban conditions where speeds are generally low.
- At higher speeds, the system maintains its functionality, but with a slight declining trend. This underscores the need for additional optimizations of the algorithms and sensors to enhance responsiveness in more dynamic situations.
- The overall success rate of activations (77.78%) is statistically significant and indicates that the AEB system is a reliable tool for improving road safety.

IV.2.2. Experimental research on braking characteristics

The braking characteristics used to evaluate the effectiveness of the AEB system include: braking deceleration, stopping time, and the distance to the artificial obstacle. These parameters were studied at various speeds, allowing for an analysis of the dynamic characteristics of the system under realistic conditions. The results provide information about the AEB system's ability to respond appropriately in critical situations, delivering data on vehicle deceleration and the distance needed for safe stopping.

The diagrams generated by the Energo-SM 4.0 decelerometer and processed with the software "ESM2: EnergoSM decelerometer windows software" Ver. 2.0.5 show real indicators for speed (in km/h), acceleration (in m/s^2), and stopping time (in seconds).

The obtained results are summarized in Table 4.3, which contains the values for braking deceleration, stopping time, and distance to the obstacle—key aspects for assessing the reliability and safety of the system.

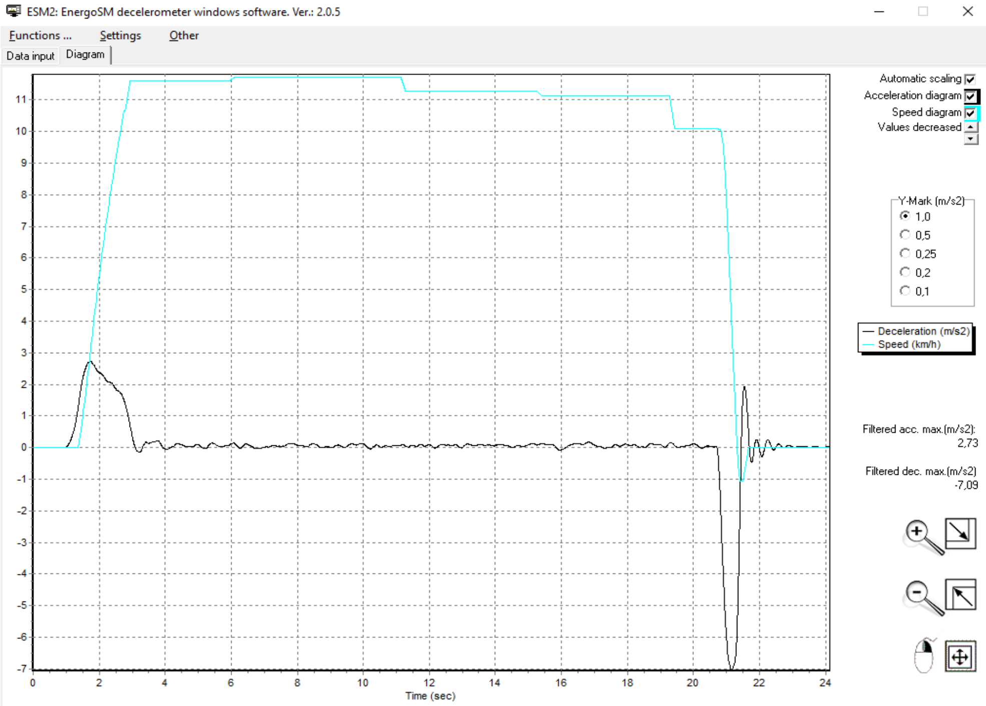

Fig.4.3. Diagram of deceleration and speed curves over the full range, measured at a speed of 10 km/h

Table 4.3. Results of experiments established with EnergoSM 4.0

No.	Speed at Braking (km/h)	Deceleration (m/s²)	Stopping Time (s)	Distance to Obstacle (m)
1.	10	7.09	0.7	0.95
2.	11	7.77	0.8	1.11
3.	12	7.60	0.7	1.02
4.	12	7.64	0.8	1.08
5.	13	7.85	0.8	1.07
6.	14	7.44	0.8	0.98
7.	15	10.24	0.7	1.09
8.	18	8.35	1.1	0.98
9.	20	10.48	1.1	0.91
10.	23	6.40	1.6	1.08
11.	24	10.34	1.0	0.90
12.	25	5.86	1.7	1.09
13.	28	5.49	2.0	1.10
14.	28	6.05	1.9	1.02
15.	34	5.90	2.1	0.96
16.	36	6.48	2.4	0.93
17.	38	8.41	2.1	0.97
18.	39	6.32	2.8	1.04
19.	42	7.89	2.2	1.02
20.	45	9.22	1.9	1.07
21.	46	6.66	1.3	0.99

IV.2.3. Analysis of effectiveness

The results obtained (Table 4.3) provide a detailed analysis of the braking characteristics of the AEB system at different speeds. Braking deceleration varies depending on the speed, being higher at lower speeds. Stopping time also changes; at higher speeds, more time is needed to stop. The distance to the obstacle remains relatively constant, indicating that the system maintains a safe distance regardless of speed.

Figure 4.23 illustrates a graph showing the relationship between the measured braking deceleration and the initial speed at which the automatic AEB system is activated.

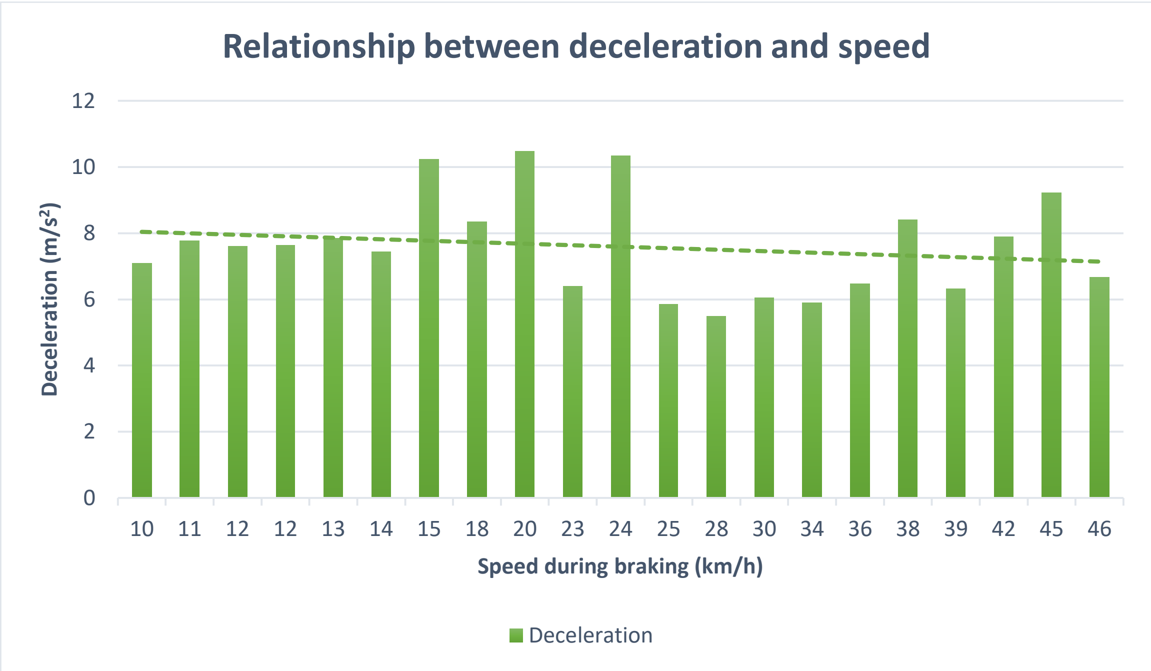

Fig.4.23. Graph showing the relationship between deceleration and speed during braking

The graph reveals that the braking deceleration of the AEB system varies with the vehicle's speed. The following dependencies can be noted:

- A nonlinear relationship is observed. At lower speeds (10-20 km/h), braking deceleration is relatively high (about 7-10 m/s^2). This indicates that the AEB system is very effective in urban conditions.
- As speed increases, braking deceleration tends to decrease, especially in the range of 20-39 km/h, which is expected since higher speeds require greater distance and time to stop.
- There are peaks in braking deceleration at certain speeds (e.g., around 15, 20, and 24 km/h), which may be attributed to specific settings of the AEB system's algorithm or peculiarities in the functioning of the sensors at these speeds.

At the highest speeds (over 40 km/h), there is again an increase in braking deceleration, indicating that the system attempts to compensate for the higher speed with more intensive braking.

Figure 4.24 illustrates a graph showing the relationship between the measured stopping time of the vehicle and the initial speed at which the automatic AEB system is activated.

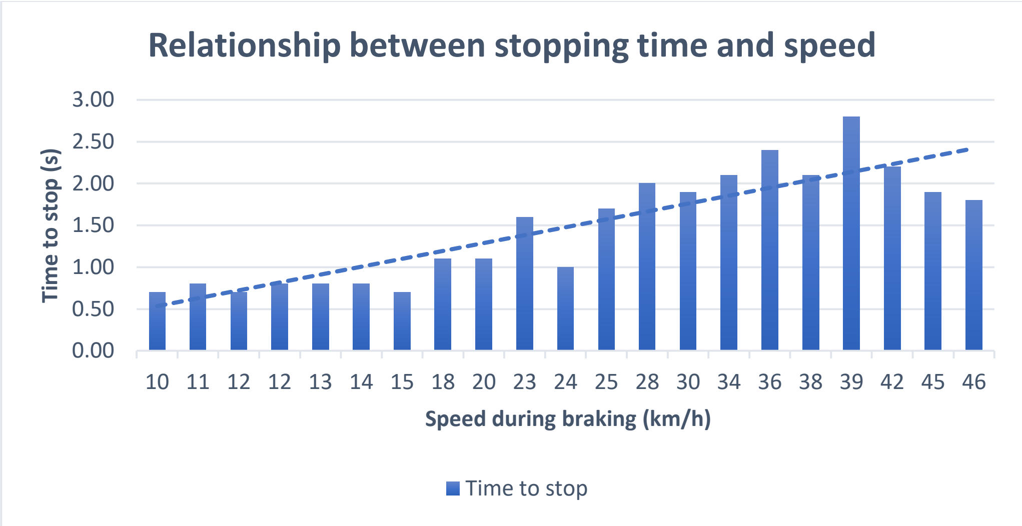

Fig.4.24. Graph showing the relationship between stopping time and speed during braking

The graph illustrates that the stopping time of the vehicle increases with an increase in speed.

Conclusions:

- At lower speeds, the stopping time is relatively short (0.7-1.1 seconds).
- At higher speeds (over 30 km/h), the stopping time reaches up to 2.8 seconds. This relationship underscores that at higher speeds, the AEB system requires more time for a complete stop.
- Stopping time increases with the increase in speed.

Figure 4.25 illustrates a graph showing the relationship between the measured distance from the already stopped test vehicle to the artificial obstacle and the initial speed at which the automatic AEB system is activated.

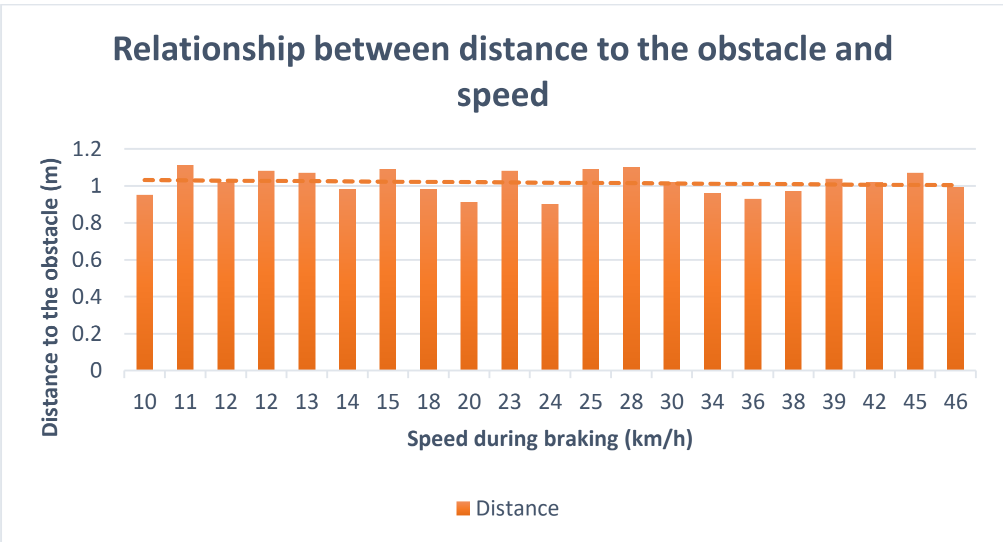

Fig.4.25. Graph showing the relationship between the distance from the stopped vehicle to the obstacle and speed during braking

The graph shows that the distance to the obstacle remains relatively constant, regardless of speed.

Conclusions:

- The distance to the obstacle remains relatively stable in the range of 0.9-1.1 meters, irrespective of speed. This indicates that the system is designed to maintain a safe distance from the obstacle, regardless of dynamic conditions.
- At low speeds (10-20 km/h), the distance is approximately 0.95-1.1 meters, which is optimal for preventing a collision.
- At higher speeds (36-46 km/h), the distance remains within the same range, demonstrating that the system is reliable and consistent in maintaining a safe distance.

CONCLUSION

This dissertation is related to the study of active safety systems in vehicles, focusing on their role in reducing the risk of road traffic accidents.

In the first chapter, an extensive literature review of contemporary active safety systems is presented, discussing the technical advancements of these systems. The importance of active safety in the context of reducing road incidents is emphasized. An analysis of the results from various experimental studies conducted in different countries, including Bulgaria, is carried out, focusing on stopping dynamics and vehicle behavior in extreme conditions.

Summarizing the literature review, we can conclude that the automotive industry continuously seeks new approaches to enhance active safety. Despite the availability of numerous systems and technologies aimed at reducing the risk of incidents, the results highlight the particularly important roles of the anti-lock braking system (ABS) and automatic emergency braking (AEB).

Studies show that ABS stabilizes the vehicle and shortens the stopping distance, especially on slippery surfaces and during emergency maneuvers. AEB automates critical intervention in the event of a collision threat, providing a quick response in situations where the driver cannot react adequately. These two systems demonstrate significant contributions to enhancing safety under various road conditions while simultaneously reducing the likelihood of accidents and their consequences.

The second chapter emphasizes the methodology and tools used for the experimental research. A methodology was developed to examine the impact of active safety provided by the anti-lock braking system (ABS) under various driving conditions. The methodology includes conducting experiments with ABS in two modes: normal operation and forced deactivation. This approach aims to objectively establish the influence of ABS on the dynamic braking characteristics of the vehicle.

The experimental studies on the capabilities of ABS were conducted in two directions: First, to determine braking deceleration with the ABS active safety system across three different models of passenger cars under three differentiated types of road conditions. Second, to conduct a comparative evaluation of braking deceleration with the ABS active safety system on a passenger car equipped with summer and winter tires.

Measurements were conducted using the non-contact system Energo-SM 4.0, which ensures high precision and reliability of the data. The research focused on the braking deceleration of vehicles during emergency braking on various road surfaces, analyzing the influence of ABS on braking effectiveness.

In the study of the first direction, three main factors were examined: the condition of the road surface (dry, wet, and sandy), the speed of the vehicle (40, 50, and 60 km/h), and different car models. In the second direction, the following were studied: the condition of the road surface (dry and wet), the speed of the vehicle (30, 40, 50, and 60 km/h), and a vehicle equipped with summer and winter tires.

A methodology for theoretically calculating the braking distance is presented, which describes the relationship between initial speed, stopping time, and braking deceleration. This methodology allows for theoretical modeling of the braking process and comparison with experimental data obtained from the conducted tests. The objective is to calculate the theoretical values of the braking distance under various conditions, which will help evaluate the accuracy and reliability of the model, as well as identify potential deviations related to real road conditions and vehicle characteristics.

As formulated, the methodology provides a foundation for in-depth investigation of the ABS factor and its application in the context of active safety.

Chapter three presents the results of the experimental studies aimed at analyzing the influence of road surface, speed, and different vehicles on braking deceleration and braking distance.

The results indicate that the type of road surface has a significant impact on the braking characteristics of the vehicle. On dry surfaces, the highest value of braking deceleration, the shortest stopping time, and the smallest braking distance are observed. Meanwhile, on wet and sandy surfaces, the coefficient and force of friction decrease, which leads to a reduction in braking deceleration, an increase in stopping time, and an extension of the braking distance.

It has been established that as the speed of the vehicle increases, the coefficient of friction decreases for all types of surfaces. As a result, braking deceleration diminishes, stopping time increases, and braking distance lengthens.

The implementation of an ABS system improves the braking characteristics of the vehicle under almost all types of surfaces and speeds. When the ABS system is turned off, the braking characteristics of the vehicle significantly deteriorate, especially on wet and sandy surfaces, as wheel lock leads to a loss of traction between the tires and the road.

The research shows that, in addition to the aforementioned factors, the tread height of the tires significantly affects the braking characteristics of the vehicle on all types of road surfaces. When the tread height decreases, the braking deceleration increases, the stopping time lengthens, and the stopping distance also extends.

The conducted mathematical modeling establishes that the difference between the theoretically calculated and the obtained experimental results is within small margins.

The comparative analysis demonstrates that the proposed methodology is effective and can successfully predict the braking behavior of the vehicle under various conditions.

In conclusion, the conducted experiments have established that the combination of optimal road surface conditions, suitable vehicle speed, and the presence of an ABS system significantly influences braking characteristics, confirming the necessity of integrating active safety systems in the automotive industry.

Chapter four focuses on experiments conducted to investigate the effectiveness of the automatic emergency braking (AEB) system. The experimental research aims to assess the probability of system activation and analyze dynamic parameters, including braking deceleration and stopping time, with regard to differences in system performance under real conditions.

The experiments show that the studied automatic emergency braking (AEB) system demonstrates good efficiency in preventing collisions within the tested speed range of 10 to 46 km/h. The AEB system exhibits high effectiveness at low and medium speeds, ensuring rapid deceleration and maintaining a safe distance from obstacles.

At higher speeds, the effectiveness of the system slightly decreases, highlighting the need for further optimizations to improve response in dynamic conditions. Nevertheless, the system demonstrates reliability and consistency, making it a key element in enhancing road safety.

The results from the experiments confirmed that AEB is capable of significantly reducing the risk of incidents, especially in situations where the driver cannot react in time. The conclusions emphasize the importance of integrating AEB into vehicles as a means of further increasing road safety and reducing road traffic accidents, in the context of modern requirements for active safety.

The proposed methodology for assessing the effectiveness of active safety systems, based on empirical data and theoretical analysis, stands as a valuable resource for training drivers, automotive engineers, and transportation sector specialists. The integration of results into educational programs and practical training will enhance participants' competencies and facilitate the mastery of safe road behavior principles.

The obtained data and validated models can be employed for driver training and for evaluating the performance of these systems under various road conditions, which will contribute to a reduction in traffic accidents and an improvement in driving culture.

The established database, comprising results from experimental investigations, serves as a valuable resource for automotive technical expertise. Through this database, specialists will be able to analyze the braking characteristics of various vehicle models under different road conditions, contributing to a better understanding of automobile safety and the advancement of active safety technologies. The data collected will support the assessment of the effectiveness of these systems and will expand knowledge in the field of automotive safety.

CONTRIBUTIONS OF THE DISSERTATION WORK

Scientific and applied contributions:

1. A methodology for the experimental investigation of the braking characteristics of vehicles has been proposed, ensuring both efficiency and accuracy of results.
2. A method for evaluating the effectiveness of Automatic Emergency Braking (AEB) systems has been introduced, allowing for the determination of activation probability and an analysis of its braking characteristics under various conditions.
3. The potential for precise forecasting of the braking process under different driving modes and types of road surfaces has been established by comparing the theoretical model of braking characteristics with experimental investigations.

Applied contributions:

1. The influence of road surface type on the braking characteristics of vehicles has been identified, taking into account the coefficient of friction between the road surface and the vehicle tires.
2. The impact of vehicle speed on braking characteristics has been validated, considering the diminishing nature of frictional force with increasing speed.
3. The statistically significant effect of a functioning Anti-lock Braking System (ABS) on improving vehicle braking characteristics across all road surfaces and speeds has been demonstrated.
4. A statistically significant relationship has been established between tire tread depth and braking characteristics, highlighting that the appropriate selection of tires, corresponding to seasonal conditions and road types, significantly affects traffic safety.
5. A comprehensive knowledge base and practical methodologies concerning active safety systems in vehicles have been presented, which can be effectively utilized in educational programs for training students, drivers, engineers, and traffic safety specialists.
6. The resultant database of experimental findings on braking characteristics provides valuable information for automotive technical expertise in analyzing and assessing the condition of vehicle braking systems.

LIST OF PUBLICATIONS RELATED TO THE DISSERTATION WORK

1. **N. Toshev,** H. Kanevski, S. Asenov, and A. Parushev (2024). "Study of the Automatic Emergency Braking Active Safety System of a Passenger Car." 2024 XXXIII International Scientific Conference Electronics (ET), Sozopol, Bulgaria, pp. 1-4; DOI: 10.1109/ET63133.2024.10721506. [Scopus]

2. **Toshev, N. (2022).** Modern Active Safety Systems in Automobiles. Proceedings of the Third National Scientific Conference "Man and the Universe," Smolyan 2021, SUB – Smolyan, Scientific Papers, Volume 3, Part 3, pp. 454-464, Smolyan, 2021; ISSN: 1314-9490 (online).

3. **Toshev, N.**, Kanevski, H. (2024). Experimental Determination of the Passenger Car Deceleration under Different Road Conditions. Science Series "Innovative STEM Education," Volume 06, pp. 129-139; ISSN: 2683-1333, Institute of Mathematics and Informatics – Bulgarian Academy of Sciences; DOI: https://doi.org/10.55630/STEM.2024.0615.

4. **N. Toshev (2024).** "Research on the Braking Deceleration of a Passenger Car Equipped with Tires for Different Weather Conditions Under Various Road States." 2024 II National Scientific Conference Physics-Engineering-Technology, November 27-28, 2024, Plovdiv, Bulgaria (in press).