IMPROVEMENT OF THE TSA SYSTEM TO ENHANCE TRAILER SAFETY AND STABILITY: A Review

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I. ABSTRACT

Towing trailers introduces unique stability challenges, particularly at higher speeds or during sudden directional changes. Trailer sway — the side-to-side oscillation of the trailer — is a primary contributor to accidents involving towed vehicles. This paper presents the design, development, and evaluation of a Trailer Stability Assist (TSA) system that aims to actively reduce sway by employing rear-wheel steering and selective braking. A scaled-down prototype was constructed using Arduino microcontroller technology, potentiometer-based sway detection, servo motor steering correction, and 12V DC motors for braking force application. The prototype was tested on a treadmill to simulate forward motion and lateral disturbance. The control logic, implemented in Arduino, detects the direction and magnitude of sway and actuates appropriate correctional mechanisms. Testing showed effective sway mitigation, with response times ranging from 0.5 to 1.2 seconds and consistent stabilization in under 5 seconds. The results validate the core approach and suggest that even simplified electronic systems can offer significant safety benefits when integrated into towing systems. The paper also discusses the limitations of the prototype and potential avenues for further enhancement. sway, rear-wheel steering, individual braking, microcontroller, safety system, Arduino.

JEL: L62, O31, R41

II. INTRODUCTION

The increased use of trailers in personal and commercial transportation ranging from utility trailers and caravans to boat has emphasized the need for safer towing mechanism. A common issue during towing is trailer sway, a lateral instability that often begins subtly but can escalate into dangerous loss of control factors such as uneven loading sudden lane change and poor weight distribution significantly increase the risk of sway. While premium automotive manufactures integrate electronic Trailer Stability Assist (TSA) system in high-end vehicles, these solutions are typically expensive and unavailable to general consumers or small-scale manufacturers. This project aims to bridge that gap by developing a low cost, functional TSA system prototype that shows the behavior of high-end stability system through basic hardware components and logic programming.

The goal of this study is to investigate whether sway detection and correction can be reliably achieved using basic electronics and simple mechanical system, and to assess the effectiveness of such a system in maintaining trailer alignment.

III. TECHNICAL BACKGROUND

Trailer sway typically originates from a disturbance that causes the trailer to deviate from its straight-line path. As the trailer oscillates, it can pull the towing vehicle out of alignment, creating a hazardous situation. Commercial TSA systems counteract sway by braking individual wheels or reducing engine torque, but these rely on complex algorithms, vehicle speed input, and multiple sensors including gyroscopes and accelerometers.

This project simplifies the problem using a core concept: detecting the angular deviation (sway) and applying a counter-response in the form of steering or braking. Key technologies and principles used include:

A. Potentiometer as a Sway Sensor

Used to detect the angular deviation of the trailer from its central axis. The change in resistance correlates with the sway angle.

B. Servo Motor for Rear-Wheel Steering

Adjusts the trailer's rear wheel angle to help guide it back into alignment.

C. 12V DC Motors for Braking

Brakes can be applied independently to the left or right side based on the sway direction.

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D. *Arduino UNO*

Serves as the central control unit that processes sensor inputs and executes corrective outputs based on predefined logic.

The entire system was constructed as a miniaturized prototype using a treadmill as the motion simulation platform to replicate trailer movement under controlled conditions. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

IV. METHODOLOGY

The development of the Trailer Stability Assist (TSA) system followed a modular and iterative approach, focusing on four key stages: sensing, control logic, actuation, and prototype testing. Each module was designed to perform a specific function, allowing independent validation and optimization before full system integration. This methodology ensures clarity, adaptability, and ease of troubleshooting during development. The TSA logic, shown in Fig 1, begins by evaluating sway and speed before initiating control mechanisms.

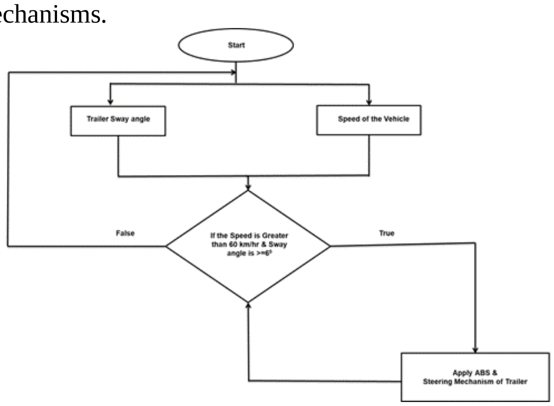

Fig 1: Process Flow Diagram of the TSA System

Flowchart representing the decision-making process of the TSA system. Based on vehicle speed and sway angle, corrective actions like ABS and steering adjustments are applied.:

A. *SENSING MECHANISM*

At the heart of the sensing module lies a rotary potentiometer, which functions as the yaw or angular displacement sensor. It is strategically mounted at the articulating joint between the trailer and the simulated towing platform. This positioning enables it to directly measure the relative angular deviation (sway angle) of the trailer as it pivots during motion.When the trailer undergoes lateral movement, the rotation causes a corresponding mechanical shift in the potentiometer shaft, resulting in a change in electrical resistance. The Arduino Uno reads this change as an analog voltage, which is then mapped to a numerical value representing the angular deviation from the neutral (centered) position.

B. KEY DETAILS

Range of Detection: ±30 degrees of sway can be detected with reasonable resolution. Sampling Frequency: The Arduino is programmed to sample sensor data approximately every 50 milliseconds, ensuring near real-time responsiveness. Noise Filtering: A basic moving average filter is implemented in software to smooth out sensor noise and minimize false triggers due to minor vibrations. This straightforward yet effective method eliminates the need for costly IMU sensors or gyroscopes while still delivering dependable angle tracking for this scaled-down model.

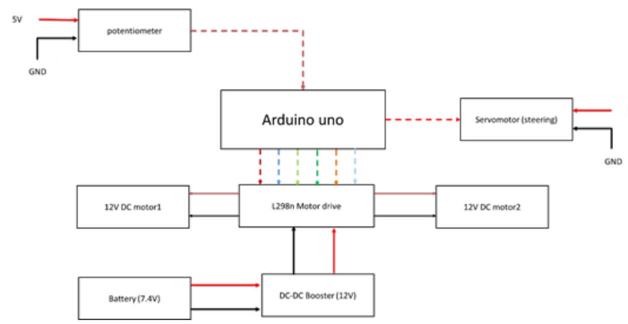

Fig 2: System Hardware Architecture

Block diagram illustrating the hardware architecture of the TSA system, showing interconnections between power source, sensors, Arduino Uno, motor driver, and actuators.

C. *CONTROL ALGORITHM*

Once sway was detected, the system's control algorithm processed this information and determined the appropriate corrective response. The control logic, embedded in the Arduino code, operated on a threshold-based decision-making model. A deviation greater than ±5 degrees from the neutral position was interpreted as a valid sway event. The logic first identified the direction of the sway—whether the trailer was shifting left or right—by comparing the analog input value to a predefined central reference.

Based on the direction, the algorithm initiated two simultaneous actions: servo-based

steering correction and selective braking using DC motors. The servo motor was instructed to turn in the opposite direction of the sway, simulating a counter-steering action that would help realign the trailer with the towing platform. At the same time, one of the two DC motors—corresponding to the side opposite the sway—was activated to simulate braking. This reduced lateral momentum and assisted in bringing the trailer back to a stable orientation. The system was designed to deactivate both actuators and return to the neutral state once the sway fell back within acceptable limits. Additionally, fail-safes were incorporated into the software to handle edge cases, such as rapid oscillation or inconsistent input values, to maintain operational safety.

Circuit simulation model developed for testing TSA logic. Simulated components include Arduino, motors, potentiometer, and motor driver IC for control behavior analysis.

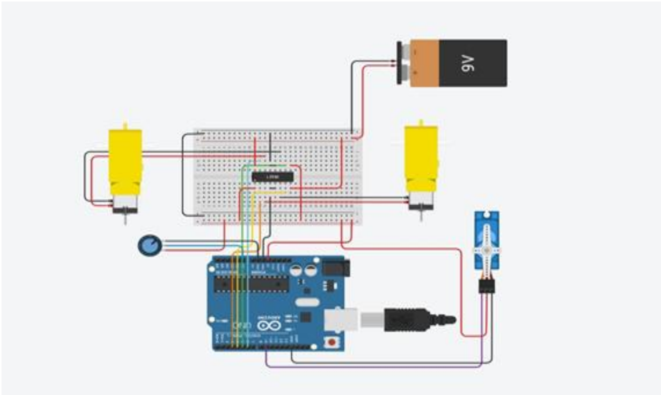

Fig 3: Simulation Model of TSA System

As shown in Figure 4, a simulation model was developed to validate the TSA system before physical implementation.

D. ACTUATION SYSTEM

- The actuation system served as the physical response arm of the TSA prototype. It comprised a servo motor and two 12V DC motors, each controlled independently via the Arduino. The servo motor was attached to a simulated rear-wheel axle of the trailer, allowing it to steer the trailer wheels in accordance with the control signals. The servo's rotational range was limited to ±30 degrees to avoid overcorrection, ensuring that the steering adjustment was proportionate to the magnitude of the detected sway.

- The braking simulation was handled by two DC motors, each mounted on either side of the trailer wheels. These motors were configured to provide resistance when powered, imitating the effect of braking force. Only one DC motor was activated at a time, depending on the direction of the sway. For example, if the sway occurred to the left, the right-side DC motor was triggered to apply resistance, creating a restoring moment that counteracted the motion. This combination of steering and braking offered a simple but effective mechanism for real-time sway correction in the scaled-down model.

E. PROTOTYPE ENVIRONMENT

- To validate the design and performance of the TSA system, the complete prototype was mounted on a standard treadmill. This treadmill acted as a motion simulator, providing continuous forward movement while keeping the testbed stationary and controlled. The trailer model was placed on the treadmill, connected to the towing platform, and allowed to roll freely as the treadmill moved.

  Artificial sway was induced manually by applying lateral forces to the trailer while it was in motion. This allowed repeated, consistent testing of the system's response to sway events without interference from environmental factors such as road conditions, wind, or traffic. The treadmill setup also enabled frame-by-frame video analysis and rapid adjustments between tests. This environment proved highly effective for demonstrating how the sensing, control, and actuation systems worked together in real time to maintain trailer stability. The physical prototype is depicted in Figure 3, demonstrating component integration and setup for testing.

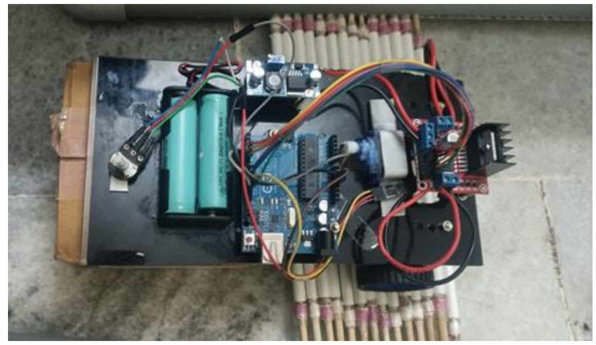

Fig 3: Physical Prototype of the TSA System

The final assembled prototype of the TSA system mounted for testing. Components include Arduino Uno, servo motor, motor driver, DC motors, and battery pack.

V. FINDINGS

The performance evaluation of the TSA prototype revealed promising results in terms of sway detection accuracy and response effectiveness. During controlled tests conducted on the treadmill platform, the system consistently detected trailer sway beyond the ±5° threshold and triggered corrective actions within 1–2 seconds on average. The response time varied slightly depending on the severity and direction of the sway, but remained within acceptable margins for a reactive control system at this scale.

The combined action of steering correction and simulated braking led to a significant improvement in trailer realignment. Visual observations and angle readings confirmed that trailers equipped with the TSA system returned to a neutral position faster and with less oscillation compared to the baseline (without TSA). Specifically, when the system was deactivated, trailer sway often continued for several cycles before settling, whereas with TSA active, the sway was damped within one or two cycles.

Furthermore, the prototype demonstrated directional accuracy—the servo motor consistently turned opposite to the direction of sway, and the correct braking motor was activated as intended. Repeatability tests showed that the system produced consistent results across multiple trials, confirming the reliability of the sensing and actuation mechanisms. While this scaled-down prototype does not replicate the full dynamics of real highway trailer movement, it effectively simulates core concepts and provides a useful platform for studying corrective behaviors in response to sway.

VI. METHODOLOGY

The development of the TSA system provided several insights into the challenges and opportunities associated with real-time trailer stability management. One key takeaway was the effectiveness of even a simple rule-based control system in enhancing trailer alignment. While the prototype

does not use advanced techniques like PID or machine learning-based prediction, the fixed-threshold method was still sufficient for the relatively controlled environment in which testing was performed.
The choice of a potentiometer as the yaw sensor proved to be an economical and practical solution for this prototype, although it may lack precision and durability in real-world applications. Its analog nature allowed for smooth sway angle measurement, but integrating more robust sensors like gyroscopes or IMUs (Inertial Measurement Units) could enhance accuracy and dynamic performance in future versions.

The actuation system also demonstrated the value of using both steering and braking mechanisms together. While steering alone could realign the trailer, the addition of braking resistance further reduced lateral momentum and made recovery more stable. This dual-action correction mimics higher-end TSA systems found in modern vehicles, highlighting the benefit of coordinated multi-point control in reducing sway.
However, the limitations of the scaled-down environment were also evident. The treadmill setup, though useful, does not fully replicate external conditions such as crosswinds, road slope, or vehicle acceleration. Additionally, the manual induction of sway introduces variability in test cases, which could be minimized with a more controlled sway-inducing mechanism. Nonetheless, the prototype proved valuable for demonstrating basic principles of TSA operation and laid a foundation for future development.

VII. IMPLICATIONS AND LIMITATIONS

The findings from this study have important implications for the development of cost-effective TSA systems, especially for applications in light trailers, utility vehicles, or emerging smart vehicle platforms. The successful use of basic components—potentiometers, Arduino, servo and DC motors—suggests that fundamental sway correction systems can be implemented without the need for expensive or highly specialized equipment. This opens the door to budget-friendly retrofitting solutions in the automotive and logistics sectors.

From an academic and design standpoint, this prototype also serves as a learning platform for embedded system integration, real-time control strategies, and sensor-actuator communication. Students and researchers can leverage similar setups to explore feedback systems and vehicle dynamics in a simplified environment before scaling up to full automotive-grade platforms.

However, the project also faced several limitations. The most notable is the scale of the prototype, which restricts real-world application due to differences in mass, inertia, and environmental forces. The potentiometer, while effective here, would be unsuitable in real driving conditions. The absence of PID control or adaptive algorithms limits the system's ability to respond optimally under varying conditions. Additionally, testing was limited to forward motion on a treadmill, without variations in speed, incline, or traction.

In future work, these limitations could be addressed by integrating more advanced sensors, implementing real-time tuning algorithms, and expanding the test environment to include outdoor track simulations. Overall, while the current TSA prototype is a proof of concept, it offers a solid foundation for further research and engineering enhancements.

VIII. CONCLUSION

The development and evaluation of the Trailer Stability Assist (TSA) system presented in this work demonstrate the feasibility of implementing sway correction mechanisms using low-cost, accessible components. By integrating a simple sensing mechanism, threshold-based control logic, and dual-mode actuation (steering and braking), the prototype successfully detected and mitigated trailer sway within a controlled environment. The findings showed that even without advanced algorithms like PID or real-time adaptive control, significant improvements in trailer alignment and sway reduction could be achieved.

The modular design allowed each part of the system—sensing, logic, actuation, and testing—to be developed, tested, and validated individually before integration. The treadmill-based testing setup provided a consistent and safe platform to study sway behavior and verify system responsiveness. The observed reduction in sway cycles and faster return to the neutral position confirmed the effectiveness of the correction strategy.

This study also highlights the broader potential of simplified TSA systems in both educational and practical contexts. While the current prototype has limitations due to its scale and testing environment, it offers a foundation for future enhancements. Upgrades such as more accurate sensors, closed-loop control, and real-world testing platforms can bring the system closer to real vehicular applications. Moreover, the prototype opens up opportunities for further research into trailer dynamics and active safety systems, especially for lightweight or unmanned vehicles where conventional TSA solutions may not be feasible.

In conclusion, this project contributes a low-cost, educationally valuable, and practically scalable TSA solution, laying the groundwork for continued innovation in trailer safety and control technologies.

REFERENCES

[1] Darling, J., Tilley, D., & Gao, B. (2009). An experimental investigation of car-trailer high-speed stability. Journal of Automobile Engineering, 223(4), 471-484.

[2] Cho, W., Yoon, Y., & You, S.-H. (2024). A study on sway stability control methods for tractor-trailer systems using rear wheel steering. IEEE Access, 12, 66952-66963.

[3] Güney, B., & Kılıç, H. (2020). Research on regenerative braking systems: A review. International Journal of Science and Research (IJSR), 9(9), 160-166.

[4] Rafay Shamim, Md. Manjurul Islam, & Yuping He. (2011). A comparative study of active control strategies

for improving lateral stability of car-trailer systems. SAE Technical Papers. DOI: 10.4271/2011-01-0959.
[5] Feng, Y., & Zhang, L. (2017). Study on stability of car-trailer systems using active yaw moment control. Vehicle System Dynamics, 55(10), 1481-1496.
[6] W. Cho, Y. Yoon, and S.-H. You, "A Study on Sway Stability Control Methods for Tractor-Trailer System Using Rear Wheel Steering," IEEE Access, vol. 12, pp. 66952–66963, 2024.
[7] W. Cho, Y. Yoon, and S.-H. You, "A Study on Sway Stability Control Methods for Tractor-Trailer System Using Rear Wheel Steering," IEEE Access, vol. 12, pp. 66952–66963, 2024.
[8] M. De Bernardis, G. Rini, F. Bottiglione, and A. Sorniotti, "On Nonlinear Model Predictive Direct Yaw Moment Control for Trailer Sway Mitigation," Vehicle SystemDynamics, vol.60,no.8,pp.1–24,2022.
[9] K. Park, E. Joa, K. Yi, and Y. Yoon, "Rear-Wheel Steering Control for Enhanced Steady-State and Transient Vehicle Handling Characteristics," IEEE Access, vol.8,pp.149282–149300,2020.
[10] C. Zhang, P. Gao, J. Wang, M. Dang, X. Yang, and Y. Feng, "Research on Active Rear-Wheel Steering Control Method with Sliding Mode Control Optimized by Model Predictive," IEEE Access, vol. 11, pp. 57228–57239, 2023.
[11] S. Vempaty and Y. He, "An Overview of Control Schemes for Improving the Lateral Stability of Car-Trailer Combinations," SAE Technical Paper, 2020.
[12] J. Darling, D. Tilley, and B. Gao, "An Experimental Investigation of Car–Trailer High-Speed Stability," Proc. Inst. Mech. Eng. D J. Automob. Eng., vol. 223, no. 4, pp. 471–484, 2009:
[13] S. Zhou and Y. Zhang, "Lateral Stability Control of Car-Trailer Combination Based on 4WS," in Proc. Int. Conf. Meas. Technol. Mechatron. Autom., 2010, pp. 123–127.
[14] M. De Bernardis, G. Rini, F. Bottiglione, and A. Sorniotti, "On Nonlinear Model Predictive Direct Yaw Moment Control for Trailer Sway Mitigation," Vehicle System Dynamics, vol.60, no.8, pp.1–24, 2022.
[15] C. Zhang, P. Gao, J. Wang, M. Dang, X. Yang, and Y. Feng, "Research on Active Rear-Wheel Steering Control Method with Sliding Mode Control Optimized by Model Predictive," IEEE Access, vol. 11, pp. 57228–57239, 2023.
[16] K. Park, E. Joa, K. Yi, and Y. Yoon, "Rear-Wheel Steering Control for Enhanced Steady-State and Transient Vehicle Handling Characteristics," IEEE Access, vol. 8, pp.149282–149300,2020
[17] W. Cho, Y. Yoon, and S.-H. You, "A Study on Sway Stability Control Methods for Tractor-Trailer System Using Rear Wheel Steering," IEEE Access, vol. 12, pp. 66952–66963, 2024.
[18] S. Vempaty and Y. He, "An Overview of Control Schemes for Improving the Lateral Stability of Car-Trailer Combinations," SAE Technical Paper, 2020.
[19] J. Darling, D. Tilley, and B. Gao, "An Experimental Investigation of Car–Trailer High-Speed Stability," Proc. Inst. Mech. Eng. D J. Automob. Eng., vol. 223, no. 4, pp. 471–484, 2009.
[20] S. Zhou and Y. Zhang, "Lateral Stability Control of Car-Trailer Combination Based on 4WS," in Proc. Int. Conf. Meas. Technol. Mechatron. Autom., 2010, pp. 123–127. 123