International Journal of Research in Science & Engineering
ISSN: 2394-8299
Vol: 03, No. 04, June-July 2023
http://journal.hmjournals.com/index.php/IJRISE
DOI: https://doi.org/10.55529/ijrise.34.1.13

Improving the Stability of Semi Trailer Articulated Vehicles

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Received: 09 February 2023 **Accepted:** 30 April 2023 **Published:** 17 June 2023

Abstract: The transportation of industrial products is an important function of every industry involved in mass production. This is mostly done with the use of semi trailer articulated vehicles. The dynamics characteristic of these vehicles differs from those of other vehicles, and their accidents are fatal and destructive leading to lost of lives and valuable properties. Therefore, there is a need for continuous research and improvement of the stability of these vehicles. This paper aimed at reviewing literatures on improvement of stability of this vehicle in order to ensure safety of lives and properties. Driver Assistance Systems (DAS) such as Semitrailer Differential Braking Technique (SDBT), Roll Stability Control (RSC) system, Electronic Stability Control (ESC) system, Active Yaw Control (AYC) system, Linear Quadratic Regulator (LQR) controller, Robust LQR (RLQR), were noted as an efficient method for combating the vehicle instability and loss of control. It was noted that the RWA is an important parameter for determining the rollover propensity of this vehicle., while a driver model would be of great important to investigate the interaction between the driver and Driver Assistance Systems (DAS).

Keywords: Yaw, Rollover, and Electronic Stability Control.

1. INTRODUCTION

In contrast to earlier work done by Bako et. al., [1] on stability analysis of semi trailer articulated vehicles; this paper presents a literature review on improvements and stability control of the vehicles. The vehicle consists of two or more sections called a trailer and a tractor. These sections are connected to each other through the use of couplings known as hitch points or fifth wheel couplings. Fig. 1 shows a common type of these vehicles used in many countries of the world. The size of the vehicles can lead to instability; thereby reducing

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the visibility of the driver, which can lead to road accidents. Compared with rigid vehicles, these vehicles have complex dynamics and often have unstable motions even at lower driving speeds [2-3]. Unlike passenger car crashes, trailer related crashes are destructive and results in high casualties, properties damage, and traffic congestion [4]. About 1.3 million people die in road traffic accidents worldwide every year, and about 400,000 to 50 million people are injured as the result of this vehicle accident. However, in Nigeria, approximately 624 and 308 people were involved in the accidents in the past few decades, resulting in a total of 3359 deaths [5, 6]. This has become an important topic of concern for academia, industry, and policy makers to improve safety of lives and properties.

Rollover accidents are one of the dangerous types of road traffic accidents that are associated with these vehicles. In most cases, such accidents occur with such vehicles that have high center of gravity (CG) position [7-8]. If these vehicles are not properly designed, handled or built, they can become unstable. It may also be due to factors such as the geometry of the fifth wheel [9], vehicle configuration, vehicle payload, vehicle stiffness, vehicle speed limits, steering geometry, suspension and road tire adhesion [6]. In addition, in the semi trailer articulated tanker, the lateral slosh of the fluid in the tanker affect the degree of the rollover torque and reduce its roll stability [10]. This condition is severe when the tank is partially filled with fluid. This is because the roll stability of the vehicle can be significantly reduced during certain maneuvers [11].

Due to the instability of these vehicles, this paper came up as a measure to reduce the instability conditions of these vehicles, and its mortality rate as a result of road accidents. The purpose of this paper is to provide a literature review for improving the stability of the semi trailer articulated vehicles to improve the safety of the vehicles, and also the safety of lives and properties.

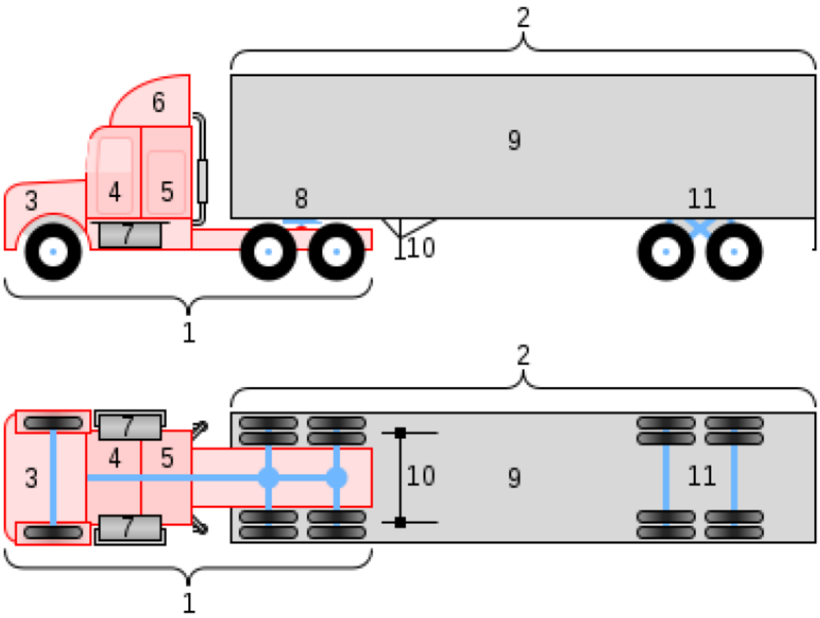

Fig. 1 Schematic diagram of semi-trailer articulated vehicle

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2. STABILITY IMPROVEMENT

Automotive researchers and designers are interested in the development and improvement of vehicle control systems and safety such as, autonomous vehicles and advanced driver assistance systems (ADAS) to improve vehicle stability and safety. In addition, Driver Assistance Systems (DAS) such as Anti-Lock Braking System (ABS), Cruise Control (CC) and Electronic Stability control (ESC) are used in the automotive industries to improve vehicle stability and safety. Automotive safety and vehicle stability have become an important research areas of interest to researchers in both academia and industry. Over the past 30 years, this has become an important area of automotive research, making significant contributions to the automotive industries [11-21]. These vehicles control systems help to ensure good driver control for safe driving. Furthermore, whenever a new vehicle is introduced into the automotive market, countermeasures are introduced for proper orientation and enlightens. These include safety orientations and introduction of control equipment and other measures such as onboard weight control, improved ESP, stability control systems, and driver training to ensure good vehicle handling [7].

2.1 Roll Stability Control

The degree of rollover of a semi trailer articulated vehicle is defined by its rollover index. The rollover index of the vehicle is the real-time difference between the vertical loads of the left and right tires of the vehicle. Fig. 2 shows a schematic diagram of the roll center and roll angle of the vehicle. The rollover index R_{in} is expressed as the difference between the normal reaction force and the tire (F_{z1}, F_{z2}), which is due to the rolling motion of the semi trailer. The roll index is equal to zero (R_{in}=0), when the load on both sides of the vehicle are equal. In this case, there is no rollover hazard or danger. In a severe rollover situation, the load is fully transferred to one side of the vehicle and the rollover index becomes R=±1. This is a clear indication that one side of the tire has lifted from the road level. This means that tendency of rollover will increase if the value of R_{in} is closer to ±1 [6].

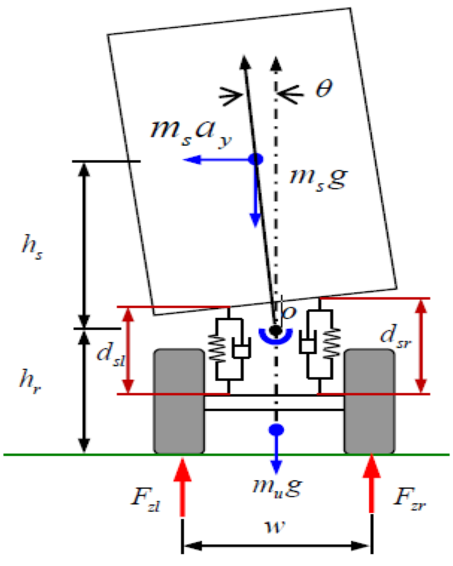

Fig. 2 Rollover Motion of a Semi Trailer Articulated Vehicle [6]

The controllability of a semi trailer articulated vehicle was analysed by Sampson [22] to investigate the fundamental limitations of achieving vehicle roll stability using an active roll control system. The study showed that it is not possible to control load transfer and roll angles of all axles simultaneously and independently. It is worth noting that the best feasible way to minimize roll instability is to set the normalized load transfer equal for all critical axles while considering the highest inward suspension roll angle as the maximum allowable roll angle. It was also noted that the vehicle's rollover stability can be improved by 30% to 40% for both steady-state and transient maneuvers. It is recommended that the rollover instability of the vehicle can be minimized by using the following methods;

i. By ensuring that the normalized load transfers on all critical axles are balanced when setting the maximum inboard angle of the sprung mass to the maximum allowable angle.
ii. By ensuring the sprung mass has maximum inward roll angle.

Yunbo [4] studied the role of active safety systems, namely; Roll Stability Control (RSC) for trailers and Electronic Stability Control (ESC) for tractors, respectively. The Roll Stability Control (RSC) system is a less complex version of the ESC system and is used on semi trailer articulated vehicles. The RSC system senses the vehicle's lateral acceleration and yaw rate and compares them with the obtained thresholds. Whenever a higher value is obtained, the RSC system will selectively slow one or both of the trailer axles to reduce vehicle speed and then reduce the intensity of the rollover. The combination of the ESC system of the tractor and the RSC system of the trailer significantly improve the rollover stability of the vehicle, but it also caused a certain degree of under-steering condition to the trailer. The results of the study shows that, the RSC system has reduced the risk of rollover at high speeds, while the combination of ESC (on the tractor) and RSC (on the trailer) reduces the risk of rollover.

2.2 Yaw Control

To improve vehicle stability, different approaches have been used for yaw stability control of semi trailer articulated vehicles. These methods include differential braking, active suspension systems, steering and differential braking [23]. These approaches have been used on light and semi trailer articulated vehicles to control yaw and roll stability. However, to improve the yaw stability of semi trailer articulated vehicles, Mobini et. al.. [24] proposed an improved method using active braking with nonlinear optimal control. Other researchers [25-29] have carried out studies on yaw stability control. Their main areas of interest were the reduction of off-tracking and obtaining a desired path in line with vehicle characteristics during low-speed and high-speed maneuvering conditions, respectively.
An Active Yaw Control (AYC) system is to maintain a minimum sideslip angle under all driving conditions. This analysis was performed during braking in “J” turn, at double lane changes and worst case maneuvering. It is worth noting that vehicles without AYC lost control when the steering direction was reversed. Whereas the vehicle with AYC maintains its stability [30]. One of the methods used by Anwar [31] to control yaw motion is a model predictive controller, which was another optimization technique demonstrated by Eslamian [32]. This optimization method uses a nonlinear model for sideslip control. The Sliding Mode

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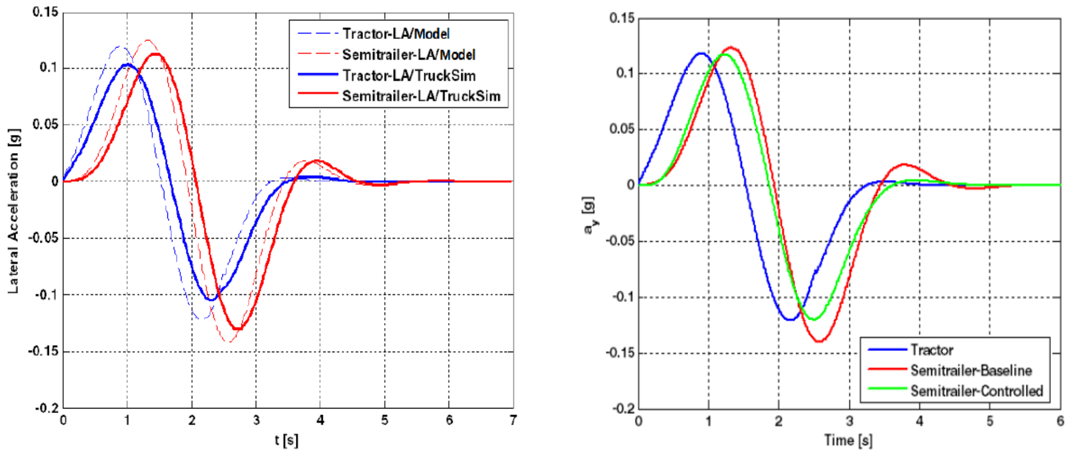
Control (SMC) is also another method used to solve the instability problem of the semi trailer articulated vehicles [33-35].

2.3 Steering Control

Researchers [36, 37, 38, 39] investigated the effect of the articulation angle of a semi-trailer articulated vehicles with the aim of improving the vehicle's maneuverability by off-tracking. Lajos and Janos [40] studied the characteristics of this vehicle from the perspective of the vehicle steering. This work involves improving the lateral stability of a vehicle with the help of controlled elements on the vehicle chassis. The results of the study suggested that the steering should be placed at the rear wheels of the tractor according to the control of the sideslip angle of the vehicle. In both cases, a new approach called Robust LQR (RLQR) was utilized. To improve the high-speed directional stability of these vehicles, Palkovics and El-Gindy [41] also introduced a Linear Quadratic Regulator (LQR) controller. This was achieved by reducing parameters such as articulation angle, tractor yaw rate, articulation speed and tractor sideslip angle. This concept was exploited by El Gindy et. al., [42] and Hac et. al., [43]. However, the concept reflects more on vehicle stability than vehicle maneuverability.

Wang et. al., [44] proposed an adaptive steering controller. In this case, the vehicle articulation angle was developed based on its geometry. In contrast to Wang et al. , [44]; Milani [45] studied the tendency of Active Steering Control (ASC) to improve vehicle maneuverability and stability. The results showed that the vehicle with ASC combination has a significant improvement compared to the value of the baseline vehicle. From the lateral acceleration results shown in Fig. 3(a), it can be seen that both vehicles exhibit similar lateral and yaw motion characteristics, which were affected by the lateral acceleration of the vehicle. A small difference was noted due to small change in initial trajectories and vehicle modeling parameters. It was also noted that the lateral acceleration of the vehicle has been reduced and damped by the active steering control compared to the reference vehicle. Therefore, the Reverse Amplification (RA) ratio has been reduced to 1.0, as expected for a Linear Quadratic Regulator (LQR) design.



(a) (b)

Fig. 3 (a) Lateral Acceleration, (b) Maneuvering Lateral Acceleration - Baseline vs. ASC [45]

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2.4 Electronic Stability Control

One of the key functions of the Electronic Control Unit (ECU) on a semi-articulated vehicle is to detect and sense vehicle speed, lateral acceleration, and yaw suspension system by using electronic sensors and mechanical actuators. The vehicle rollover index is also assessed using these sensors. Whenever the calculated value of the rollover index is greater than the value specified in the ESU, the differential braking system will be activated with the help of mechanical actuators in response to the corresponding wheels of the vehicle. This system is used to describe the stability of the vehicle. However, the system automatically provides roll and yaw stability based on lateral acceleration, wheel speed, steering angle, yaw rate, vehicle mass. [46]. The ESC system works by using differential brakes on the wheels and assists in keeping the vehicle in the desired direction requested by the driver . However, keeping the vehicle on the road prevents off-road accidents, which is one of the main factors that cause most vehicles to roll over [47].

Oreh et. al., [48] investigated **a** new approach to improve directional control of semi trailer articulated vehicle. Initially, linear and nonlinear models of the vehicle were developed. The linear models were used to develop controllers and generate reference responses. On the other hand, the nonlinear models were used to study system response. The results showed that the proposed method has a significant effect on improving the handling performance of the vehicle.

Table 1. Some literatures Summary

Author	Research Description	Control Method	Results/Improvements
Mohamed et, al., [49]	This study aims to improve the stability of a semi-trailer articulated vehicle performance using multi-leaf springs and semi-active suspension of the driver's seat. This analysis describes the effect of a vehicle suspension on its performance metrics under different load conditions using MATLAB Simulink.	Skyhook strategy, power spectral density and root mean square.	The results showed that the acceleration of the cab, tractor and trailer was increased by 22%, 21% and 28% respectively, which provides comfort during long-distance travel.
Milani[46]	The potential of Active Steering Control (ASC) for semi trailer articulated vehicles in improving the maneuverability and stability of vehicle combinations was investigated.	Linear Quadratic Regulator. Quantum particle swarm optimization technology	The study showed that the combination of ASC shows a significant improvement compared to the baseline vehicle.
Elheml et. al., [45]	A new control strategy called "Semi-Trailer Differential	Differential Braking	The results of the analysis showed an

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	Braking Technique (SDBT)" was proposed using MATLAB Simulink to investigate and improve the dynamic stability of a semi trailer articulated vehicle equipped with a standard Anti-Lock Braking System during high-speed evasive maneuvers.	Technology (SDBT)	improvement in handling performance against rollover and jackknifing during evasive maneuver at high speed.
Yang [26]	A reconfiguration control approach based on Control Allocation (CA) was proposed to improve the yaw dynamics of the semi trailer articulated vehicle. Optimal braking force distribution and reconfigurable control were transformed into error minimization and control minimization problems, which were further solved using algorithm	Sliding mode yaw moment controller and lower optimal brake force distributor.	The results showed that the CA technique-based optimal reconfigurable control was rather effective for semi trailer articulated vehicle to improve the yaw stability and the reliability in case of actuator failure.
Oreh et. al., [48]	To improve the stability and maneuverability of a semi-trailer articulated vehicle, a steering control referenced model was proposed. Linear and nonlinear models of the vehicle were developed. Linear models were used to design controllers and generate reference response, while the nonlinear models were used to evaluate the system responses.	A linear Controller Based on Optimal Control Theory	The results showed that the articulation angle of the vehicle should be controlled when driving at full speed. Under different driving conditions, the proposed reference articulation angle shows superior performance in reducing track deviation compared with the steady-state articulation angle.
Juinovich et. al., [29]	An active steering controller was developed for a semi trailer articulated vehicles. It was designed to improve perfect path-following under all driving conditions.	Passive command steer steering strategy, and a conventional trailer With a fixed	The results showed reduction of cut-in (79%), tail swing (100%), exit settling distance of 97% and a lateral tire force of 83% relative to the unsteered

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		axles.	condition.
Behrooz et. al., [50]	The concept of using an active auxiliary axle to improve lateral stability of semi-trailer was introduced. Co-simulation was carried out by integrating MATLAB/Simulink software with the vehicle simulation environment.	Rule-based control	It was shown that active auxiliary tag axle can control lateral instability of a semi trailer articulated vehicle and also reduce the risk of traffic catastrophes effectively.
Sampson [22]	The analysis was performed to investigate the fundamental limitations of achieving roll stability of a semi trailer articulated vehicles with active roll control systems.	All axles load transfers and body roll angles.	The results showed that the steady-state and transient stability of the vehicle has improved between 30% and 40%, and the handling performance has also significantly improved. It is worth noting that it is not possible to control all axles load transfers and body roll angles simultaneously and independently. The best control approach for improving roll stability was noted as setting of the normalized load transfer on all critical axles to be equal, while taking the maximum inward suspension roll angles as the maximum allowable angle.
Shuwen and Siqi [6]	A rollover prevention control method using real-time calculation of rollover Index was proposed in this study	Real time calculation of rollover index.	The results show that the proposed rollover control can stabilize the semi trailer articulated vehicle, and prevent it from rolling over when driving on a curve road and at a high speed.
Esmail et. al., [51]	The objective of this analysis was to design an adaptive	Adaptive Sliding Mode	The sliding mode controller improved the

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	sliding mode controller that resists the change of load on semi trailer articulated vehicle.	Control	vehicle performance at both high-speed and low-speed maneuvers and on wet and dry roads compared to conventional sliding-mode and linear controllers.
Saidi et. al., [52]	An active roll control system using Truck Sim software was proposed to limit the effects of liquid sloshing on the lateral dynamics of semi articulated vehicles carrying liquid substances.	Sliding mode control.	The results of the analysis showed that the proposed roll control system operates efficiently with a significantly reduction in lateral load transfer ratio.
Yi et. al., [53]	A differential braking strategy for stability control of a semi trailer articulated vehicle was presented. The brake control inputs were derived from the sliding control principle for a 3DOF yaw plane vehicle model.	The sliding control law based on 3DOF Direct Yaw Moment Controller (DYC)	The results showed that the proposed controller can provide a superior performance with regards to brake actuation, system smoothness, and can minimize the vehicle acceleration and jerk without affecting its stability at high driving speed and large steering angle.

3. CONCLUSION

This paper presents a literature review on improving the stability of semi trailer articulated vehicles as to improve vehicle safety, as well as the safety of lives and properties. Driver Assistance Systems (DAS), such as Differential Braking Technology (SDBT), Roll Stability Control (RSC), Active Yaw Control (AYC), Electronic Stability Control (ESC), and Linear Quadratic Regulation (LQR) has been found to be an effective measure to improve the stability and loss of control of these vehicles.

Research should also be done to develop algorithms for Electronic Stability Control (ESC) systems. Driver's models and closed-loop simulations are important to demonstrate the drivability of the proposed models, and to determine the interaction between the driver and Driver Assistance Systems (DAS) in order to modify the vehicle design, road design, traffic signs, and driver orientation.

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Nomenclatures

1	Trailer	2	Semi Trailer
3	Engine	4	Cabin/Tanker
5	Sleeper	6	Air Dam
7	Fuel Tank	8	Hitch Point/Fifth Wheel Coupling
9	Enclose Cargo/Tank Space	10	Landing Gear Legs
11	Tandem Axles	a_y	Lateral Acceleration
F_{2l}	Normal Reaction at Left Tire	F_{2r}	Normal Reaction at Right Tire
d_{sl}	Suspension Deflection at Left Tyre	d_{sr}	Suspension Deflection at Right Tyre
R_{in}	Roll Index	m_s	Sprung Mass
m_u	Unsprung Mass	θ	Sprung Mass Roll Angle
h_r	Height of Roll Center	h_s	Sprung Mass CG Height
g	Acceleration due to Gravity	w	Track Width

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International Journal of Research in Science & Engineering
ISSN: 2394-8299
Vol: 03, No. 04, June-July 2023
http://journal.hmjournals.com/index.php/IJRISE
DOI: https://doi.org/10.55529/ijrise.34.1.13

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