

## Stability Analysis of a Semi-Trailer Articulated Vehicle: A Review

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### Abstract

Semi-trailer articulated vehicles are mainly used for transportation of goods and industrial products. The vehicles are made of two or more vehicular units that are coupled by a mechanical device called, hitch point. The static and dynamic behavior of these vehicles differs from those of other vehicles, while accidents on these vehicles are fatal and disastrous. Therefore, there is need to know more about the static and dynamic characteristic of these vehicle, in order to ensure safety of lives and properties. This paper provides literature review on the aforementioned vehicle in order to have more insight on how to improve its stability. It was observed from the literatures review that, the higher the weight on this vehicle, the farther the distance of centre of gravity (CG) from the hitch point. This affects the safety margin against rollover stability of these vehicles. The fifth wheel lead, and the distance between the tractor, and the trailer CG were also found to play a vital role in influencing the stability of these vehicles. However, it was observed that, it would of great important for a tractor unit with one rear axle, to have the fifth wheel lead, to be as large as possible in order to control the vehicle instability. Therefore, due to the unusual behavior of these vehicles, more research works are needed in order to have more insight on the static and dynamic characteristic of these vehicles as to improve the safety of lives and properties.

**Keywords:** Dynamic stability; Lateral stability; Rollover stability; Yaw stability.

### Review Article

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## 1. Introduction

The stability of a semi-trailer articulated vehicle is an important research area for automotive engineers. This is in order to enhance good road and passengers' safety. While large weight on this vehicle affects traffic safety, stability and safety of the vehicle [1]. According to the data from the Global Road Safety Partnership, about 1.3 million people are killed while about 40 to 50 million people are injured every year in road accidents [2, 3]. While According to Nigerian Federal Road Safety of Corps (FRSC) road Crash data, 624 and 308 people were involved in trailers and road tanker accident with the total of 3359 casualties in the past three years, and the country has recorded several cases of road traffic crashes involving semi articulated trailers and tankers [4]. Unlike passenger's car crashes, trailer-related crashes always have greater exposure, due to the high fatality and injury rates, as well as excess property damage and traffic congestion [5].

## 2. Semi-trailer articulated vehicle

A fundamental understanding of the stability concept of this vehicle is highly required so as to ensure safety of goods and passengers. The semi-trailer articulated vehicle has a maximum of 16.5m admissible length, while the vehicle combination has a maximum of 18.75m length [6]. This can lead to dynamic stability problem on a steep road because of its weight; and length, thereby by reducing the visibility of driver which may lead to road crashes [3]. Figure 1 and 2, shows the schematic view of a semi-trailer articulated vehicle. The dynamics of this vehicle are significantly different from those vehicles with single chassis. Some characteristics of the semi articulated vehicle are stated below [7].

- The vehicle has small stability region in yaw and roll modes at high speed
- It is prone to Jackknifing and trailer swing conditions
- It is subjected to lateral trailer oscillation and self-excited
- It has phase lag between vehicle and trailer motions

- v. It has rearward amplification and high peak lateral acceleration at the rearmost
- vi. It is unstable during reverse motion

Winkler et al. [8-10] analyzed US accident statistics, and showed the relationship between the steady state roll stability phenomena and the likelihood in a rollover accident. The studies showed that, an increase of 0.1g static rollover threshold in the range 0.4–0.7, leads to 50% reduction in the frequency of rollover accidents for a semi-trailer articulated vehicle. The rollover accident is one to the most dangerous type of road crashes leading to loss of lives and properties. In most cases, vehicles with high situated centre of gravity position are subjected to this type of road accident [11]. Aerodynamics forces also affect the drag force on the vehicle, thereby affecting its velocity, and acceleration as well as the fuel consumption [12]. The lift forces at the sides of the vehicle can lead to instabilities and improper handling circumstance. The vehicle can fall into instability, if it is not correctly designed, handled or rebuilt. This phenomenon is affected by several factors such as; the geometric position of the fifth wheel [13], vehicle configuration, vehicle stiffness, vehicle speed limit, steering geometry, and vehicle payload, the centre

of gravity of the payload, suspensions and the road surfaces tire adhesive coefficient [2]. Also, in semi-tractor articulated tanker, the lateral sloshing of the fluid acting at the wall of the tanker, also increases the intensity of the rollover torque and decreases its roll stability [14]. This situation is critical when the tank is partially filled with fluid; this is because the vehicle would experience a significant reduction in roll stability during certain maneuvers [15].

Semi-trailer articulated vehicle snaking and jackknifing, are conditions that required well trained driver. The untrained drivers cannot control such situations [7] which may result to loss of stability of the vehicle, thereby leading to loss of lives and properties. For this reason, some researchers have studied the static and dynamic characteristics of this vehicle and have proposed measures to enhance the vehicle stability [16]. This is because detail analysis of vehicle stability provides essential evidence for dynamics control [17] in order to enhance vehicle safety. This can help to eliminate instability and to improve good road and passengers' safety. This article tends to review literatures on the stability of this vehicle in order to serve as measure for combating the vehicle instability.

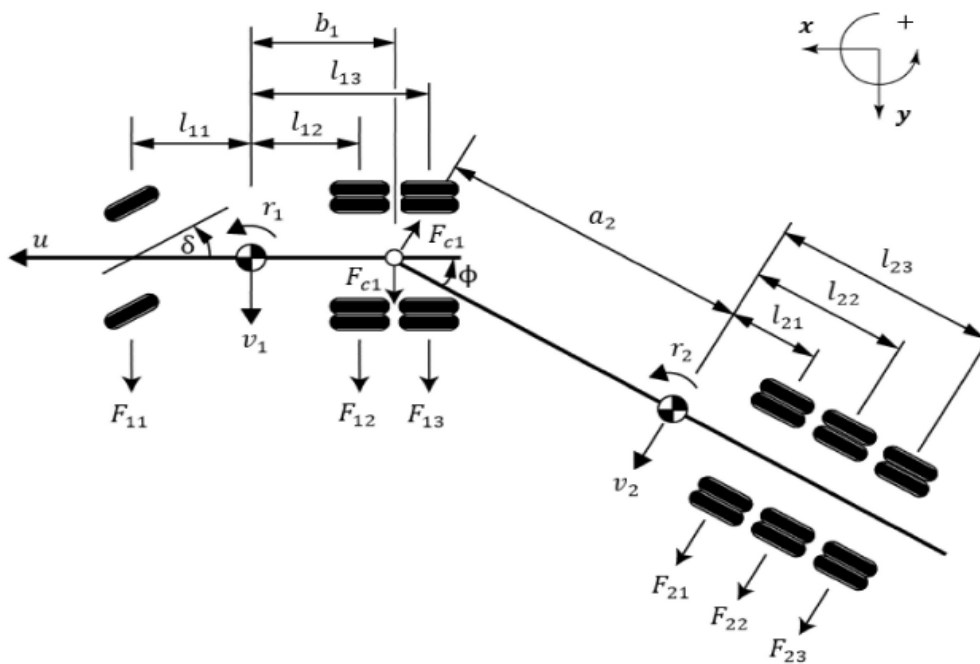


Fig. 1. The articulated vehicle free body diagram [8]

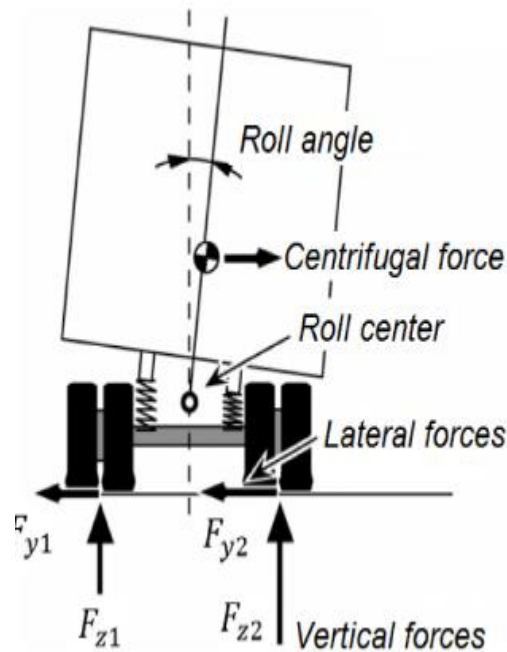


Fig. 2. The articulated roll model [18]

### 3. Stability

Some researchers [19, 20, 21, 22, 23, 24], have studied the stability of a semi-trailer articulated vehicle. Ellis [19] and Pauwelussen [20] developed an equation for evaluating the stability boundary as function of the vehicle parameters. Pacejka [21] and Andrzejewski [23] employed numerical approach to investigate the effect of these parameters on the vehicle's stability. It was noted by Mattia et al. [16] that, the stability of a semi-trailer articulated vehicle depends on some certain parameters such as; the vehicle's mass, yaw, dimensions, mass of moment inertia, and its coupling (hitch) point. Literatures [19, 21, 24] showed that trailer snaking and jackknifing are the common types of instability on these vehicles. A jackknife can occur when the yaw angle of the tractor unit is greater than the angle desired by the driver. This results in high tractor sideslip and also high trailer articulation angle. This can lead to instability and loss of control of this vehicle [25, 26]. Snaking takes place when the trailer oscillates in a self-amplifying condition [27]. This occurs when the parameters on the trailer unit lead to system instability from the control point of view [16].

#### 3.1 Dynamic stability

In vehicle dynamics, rollover is treated as one of the major problems while the vehicle is in motion. The loss of stability involves deviation of vehicle from its desired direction. It is disastrous, as it can lead to departure of the vehicle from the road, rollover and collision with other vehicles, thereby causing loss of lives and properties. This loss can occur during cornering of the vehicle at high velocity [6]. Chieh and Tomizuka [28] worked on the dynamic modeling of a semi-trailer articulated

vehicle for Automated Highway Systems (AHS). A system was utilized to analyze the translational and rotational behavior of the articulated vehicle. A linear model, with lateral and yaw motions was developed in line with the assumptions that, the longitudinal velocity is constant and the lateral and yaw motions of the vehicle are minimal. The vehicle damping was found to be inversely proportional to the vehicle longitudinal speed, while the gyroscopic forces were found to be proportional to the product of trailer mass and the longitudinal speed.

Ellis [19] and Fancher et al., [29] worked on the dynamic stability of an articulated vehicle with two articulations. In contrast to the semi-trailer articulated vehicle, there was no weight transfer between the articulated units. The hitch point effectively decouples the towing vehicle at a small articulation angle, with respect to the lateral dynamics, since the hitch point transmits side forces [39]. One of the methods to investigate the lateral dynamics of the articulated vehicle is to develop a handling diagram with consideration to the tire non-linearity [30]. Lateral force is one of the crucial parameters in dynamic simulation. At large slip angle, force generated on the road interface by the tire, would no longer be linear. It will increase proportionally less than the increase in the slip angle. This non-linearity effect is commonly modeled with the magic formula [31].

#### 3.2 Yaw stability

Yaw instability is an unstable behavior of a semi-trailer articulated vehicle during a sudden change in road lane or at an excessive speed in a given curve or while driving in a straight trajectory [17]. Whenever the lateral acceleration of the vehicle exceeds the vehicle's roll or yaw stability level during a steering

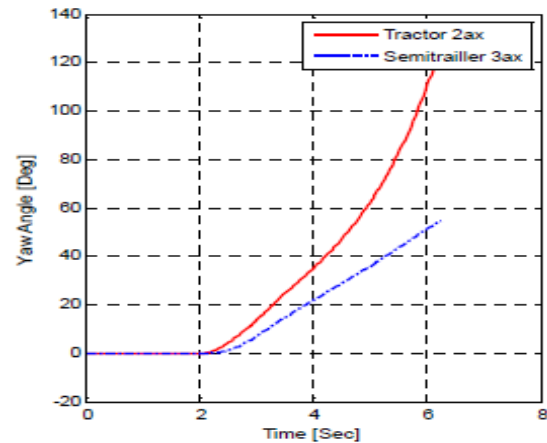
maneuver; the rollover or loss of control is initiated by the vehicle. An abrupt steering maneuver by drivers, such as a single or double lane change maneuver, or an attempt to perform an off-road recovery maneuver; results to lateral acceleration that is significantly high to cause a rollover and to create yaw instability [15].

Aleksander et al. [32] studied the dynamic stability of a semi-trailer articulated vehicle in the yaw plane. A linear model demonstrating the lateral and yaw motion of a semi-trailer articulated vehicle was developed to investigate the impact of the vehicle parameters on its dynamic stability, and the effects of various control approaches. The results of the analysis were validated using a vehicle with different trailer configurations. The trailer design made it possible to input many parameters on the trailer. The results were utilized to compare the non-linear model of the trailer vehicle combinations. The models were also utilized to investigate the effects and the constraints of the two models with the active brake control.

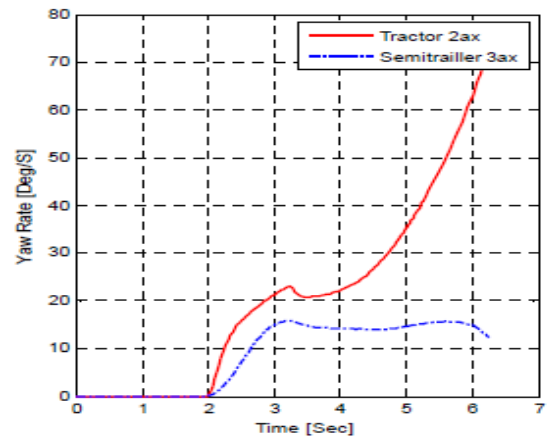
Jackknifing was demonstrated by Bouteldja and Cerezo [33] as a loss of vehicle stability in yaw motion on a semi-trailer articulated vehicle. Mokhiamar and Abe [34] proposed two sliding models for direct yaw control. One of the models was based on the yaw rate of the towing articulated vehicle while the other one was based on side slipping angle. Mokhiamar [35] developed a feedback control model that gave the required lateral force and yaw moment that were converted into braking force for towing an articulated vehicle. The control models were found to be inefficient at low friction state. The feedback model to obtain the required steering condition at the rear wheels of the towing vehicle was validated by Deng and Kang in [7], to study the situation based on the lateral velocity and yaw rate of the hitch angle and hitch rate. The analysis showed that, the operating point of the model linearization has little effect on the vehicle stability [16].

Barickman et al. [11] emphasized that, lateral acceleration contributes significantly to both yaw and roll stability, despite the differences governing the mechanics of the phenomena. Wesemeier et al., [36] studied the input-output relationships between yaw rate and lateral acceleration of a semi-trailer articulated vehicle at a given steering angle. The advantage of the approach was that, the cornering stiffness can be estimated without knowing the vehicle's moment of inertia. In line with work done by Wessmeier et al. [36], Baffet et al. [37] developed a model that estimated tyre cornering stiffness of a semi-trailer articulated vehicle based on: yaw rate, lateral acceleration, steering angle, and wheel angular velocities. While You et al., [38] described a model that identifies cornering stiffness based on extant signals and also produced an estimate of road bank angle. An analysis was done by Elhemly, Zeyada and Fayed [39] to improve semi-trailer articulated vehicle stability during intensive maneuver at high driving speed. It was shown that the yaw rate of the tractor unit increased drastically to 95 deg/sec. while the yaw rate of the semi-trailer unit was 20 deg/sec. resulting to a high articulation rate as shown in Figure 3. The yaw damping

of the tractor and the semi-trailer combination was obtained by the distance between the hitch point and the trailer axle.



(a)



(b)

Fig. 3. Semi-trailer articulated vehicle (a) yaw angle (b) yaw rate [39]

### 3.3 Lateral stability

Lateral force is one of the most important parameter in vehicle dynamics. At higher slip angle, the forces at the tyre are not linear, but increase in proportion less than the tyre's slip angle. This can be analyzed with the help of the magic formula [31]. As earlier stated, one of the methods to investigate the lateral dynamics of a vehicle, is to develop a handling diagram where the non-linearity of the tyre is taken into consideration [30, 31]. The vehicle speed and the nature of the road have a significant impact on vehicle dynamics since the response increase linearly with respect to the increment in velocity and the nature of the road surface [40].

Appropriate tyre inflation pressure plays a vital role in ensuring driving safety and economic [41]. Sebaaly and Tabatabae [42] found that tyre contact area between the road surface

on a semi-trailer articulated vehicle, depends on the tyre inflation pressure. This inflation pressure has impact on the dynamic and static characteristic of these vehicles. This inflation pressure can be monitored by using Artificial Neural Network (ANN) for predicting power required for inflating different tyres [43]. Because of the successful application of Fuzzy logic and Artificial Neural Networks in Vehicle handling, Azidi et al. [44] proposed an Adaptive-Network-based Fuzzy Inference System (ANFIS) approach, for automatic parking of a semi-trailer articulated vehicles because of their nonlinear and sophistic kinematic motion.

Zhu and Li [45], developed a new extended planar model of a multi-axle articulated vehicle with nonlinear tyre model. The model was specifically intended to improve performance in regimes where tyre lateral force approaches the point of saturation. The nonlinear tyre model was used in conjunction with the 6-axle planar articulated vehicle model to extend the ranges of the original linear model into the nonlinear regimes of operation. The performance analysis of the proposed nonlinear of the semi-trailer articulated vehicle model was verified using the double lane change maneuver on different road adhesion coefficients using TruckSim software. The simulation results showed that, the proposed vehicle model has high accuracy, which provides accurate results of the vehicle states at different road adhesion coefficient.

David [46] studied the lateral dynamics of a vehicle articulated in a windy environment. The study showed that the lateral displacement of the vehicle has reduced by increasing the side-force coefficient of the trailer units relative to the tractor unit. The clockwise yaw displacement of each unit of the vehicle increased with the trailer side-force coefficient ( $C_y$ ). The same configurations from the previous section were tested with random crosswind acting from right to left. The random cross winds were of the same average velocities as the steady crosswind. One additional configuration was added, which consisted of a standard tractor, trailer 1 with  $C_y=2.00$  and trailers 2 and 3 with  $C_y=1.50$ . The trend of the lateral displacement results with respect to side-force coefficient were the same as observed during the steady crosswind test. Increasing  $C_y$  reduced the vehicle maximum lateral displacement. Reducing the lateral  $C_y$  for the last two trailers further reduced the maximum vehicle lateral displacement. This reinforces the tractor-trailer relationship observed during the steady crosswind simulations. As with the steady wind simulations, the tractor yaw response increased with trailer  $C_y$ . The additional configuration (trailer 1:  $C_y=2.00$ , trailers 2 and 3:  $C_y=1.50$ ) had no noticeable effect on the tractor yaw response.

Tankut and Umit [47] noted that semi-trailer articulated vehicle exhibits an unstable condition at a lateral acceleration of 0.3 g to 0.4 g, during the application of brakes and during steering. It was also found in [8], that a vehicle would be unstable at certain lateral acceleration. Jackknife instability can also be described as a form of lateral instability where the tractor hitch point move backward toward the trailer unit. This can be caused by slippery road surface, hard brake application and shifting loads at the trailer unit [26].

### 3.4 Rollover stability

Rollover of a semi-trailer articulated vehicle is one of the dangerous vehicle accidents leading to high fatality rate than other forms of accident [48]. Rollover analysis using quasi-static model shows that, the tankers articulated vehicles' rollover condition declined significantly with respect to the normal semi-trailer articulated vehicles. The tank articulated vehicle's rollover angle is higher than those of normal semi-trailer articulated vehicle under the same driving conditions [49]. Vehicle rollover is defined as the movement or rotation of the vehicle at its longitudinal axis. It occurs when roll moment during cornering cannot be counter balanced by the action of the vehicle weight [11]. Rollover is sometimes categorized in two classes namely: tripped rollover and untripped rollover. The tripped rollover takes place during sideway sliding of the vehicle, and when the vehicle digs its tyres into a soft road surface. The untripped situation takes place during typical driving condition, such as at intensive speed while cornering, severe lane change during maneuver, and avoiding obstacles during driving [50].

Yunbo [5] studied rollover and yaw stability of a semi articulated vehicle with single and double trailers at low, and high speed. The study offered two distinct evaluations of commercial vehicles: 1) low speed driving in tight turns, representative of city driving; and 2) high speed lane change and evasive maneuvers, typical of highway driving. Specifically, for city driving, the geometric parameters of the roadway in places where tight turns occur such as in roundabouts were closely examined in the study, in order to evaluate the elements that could cause high rollover index. The results showed that, when the rear axles of the trailer encounter the trailer apron in the roundabout, the climbing and disembarking action could cause wheel unloading on the opposite side, thereby, increasing the risk of rollover condition. In contrast to most high speed rollovers that happen with fully-loaded trailers at low speeds, the highest risks are associated with lightly loaded or unloaded trucks.

When driving a semi-trailer articulated vehicle up a curved grade, at a minimum ultimate radius of 250m combined with a upgrades of 3% to 5%, at the driving speed of 70 km/h, the vehicle was found to be at a safe driving condition. But at the speed of 75 km/h or more, the vehicle remained at the warning state of rollover. Also, at the upgrade of 6%, the vehicle was still at the warning state of rollover within the speed of 80 km/h to 90 km/h. When driving down a curved grade of 3% and 4%, the vehicle was in the warning condition of rollover within the speed of 70 km/h to 80 km/h and at a dangerous state of rollover instability within the speed of 85 km/h to 90 km/h. while driving down curved grades of 5% and 6%, the vehicle was still at the warning state of rollover within the driving speed of 70 km/h to 75 km/h and at dangerous state of rollover instability at the speed of 80 km/h to 90 km/h [51].

#### 4. Centre of Gravity (CG) Position

The centre of gravity (CG) position of a vehicle determines its stability [52]. Semi-trailer articulated vehicles are subjected to wide range of loading, and the weight distribution on this vehicle have a vital role in influencing its height of centre of gravity (CG) [2]. The rollover stability of any vehicle is affected by its loads and C.G. height. For the same weight, an increase in the C.G. height would result to decrease in the vehicle's roll stability [53]. Roland et al. [54] noted that, with less than a full load of livestock on a semi-trailer articulated vehicle, the movement of the livestock, caused unsafe handling of the vehicle. Thereby it is affecting the position of centre of gravity, and making rollover more likely to take place. During high speed turning or sharp maneuvers, the lateral acceleration created large forces at the vehicle C.G. When these lateral forces overcome the balancing effect of the tyre-road friction forces, the wheels at the inside of the vehicle will tend to lift off the road surface eventually leading to a rollover [55]. Literature showed that, the position of centre gravity height significantly affects the rollover stability [56]. Yubiao [17] mentioned that, the closer distance of CG from the articulation point (hitch point), the higher risk of jackknifing. In addition, a trailer sway is more likely to occur when the CG location is around the trailer axle or in the back of the axle. [17]. Yaw motion occurring as a result of oversteering, mostly take place when a vehicle is lightly loaded, and has a low position of centre of gravity height. Rollover of a semi-trailer articulated vehicle mostly take place when the vehicle is fully loaded, due to high position centre of gravity height [15]. The height of the centre of gravity from the road surface affects the left and right load transfer of vehicle, which also affects the ability to generate lateral forces at the tyres [57]. The centre of sprung mass of the vehicle shifts outward from its centre-line and this would lead to a condition that will reduce the vehicle rollover stability. The aim of stabilizing the vehicle active rollover control system, is in order to lean the vehicle into corners so that the centre of sprung mass of the vehicle shifts inward of the vehicle centre-line. This is in order to enhance a stabilized roll moment [58].

During high lateral accelerations, semi-trailer articulated vehicles are subjected to rollover while passenger's vehicles are always likely to spin or plow out. This is as the result of high position of centre of gravity relative to the track width of the vehicle. Rollover of heavy vehicles usually occur at highway exit, at entrance ramps, on curve segments of roads where the vehicle tilts sideways due to the CG rotating, around the opposite side to the turning radius direction, due to the centrifugal force opposing the lateral acceleration pointing towards the centre of the turn. The critical point that indicates the beginning of rollover, is when the weight shifts to the outer wheels, so that the normal force at the inner wheels is zero. The main measurement tool used for determining rollover, is the static rollover stability (SRS), which is a relation between the track width and the height of centre of gravity [43]. Therefore, the increase in CG

height affects the vehicle static stability factor and decreases its rollover stability.

Kenneth et al. [59] showed that, as the weight on a vehicle increases, the position of the CG moves in rearward direction. While the rollover stability of vehicles decreases with increase in C.G height [53]. In line with work done by Kenneth et al., [60], Bako et al. [60] showed that, as the position of CG moved rearward direction, the height of the CG from the road surface also increases. It is justified because the longitudinal distance of CG tends to move rearward from the coupling (hitch) point. This is justified in Table 1. For a semi-trailer articulated vehicle, the yaw moment is mostly obtained as the distance between the hitch point and the axle of the trailer unit [6].

Static Rollover Threshold (SRT) also known as Static Stability Factor (SSF), is one of the most important tool used to determine the stability of a vehicles. it highly depends on the position of the centre of gravity (CG) of the vehicle, and it represents the maximum lateral acceleration before one tyre of the vehicle would loses contact with the road surface [61,62,63]. Gonzalo et al. [64] studied the influence of load distribution on the stability of a semi articulated vehicles. In their study, Davies's method was used to investigate the longitudinal, lateral and vertical displacements of the centre of gravity (CG) of a semi-trailer articulated vehicle. The results of the study showed that, the longitudinal displacement of CG of the vehicle leads to an increase in SRT factor; but the overweight on the front axle produces understeering of the vehicle, while the overweight on the rear axle produces the oversteering on the vehicle.

#### 5. Speed and Stability

An increase in forward velocity results in less vehicle stability [26]. Analysis by Ren, Zheng and Li [59] showed that, when a vehicle was loaded with 30,000 kg and was driving at the speed of 20 m/s, 25 m/s and 30 m/s, respectively. The increase in the vehicle speed would reduced the vehicle stability and eventually lead to road accident during rollover thresholds. The vehicles were subjected to rollover accidents at low driving speeds and were also subjected to instability at high driving speeds, even if the vehicle turning radius is 177m.

The speed characteristic of an under steered vehicle, is the speed at which the angle of the steering wheel is twice the angle of the Ackermann. The critical speed of an over steered vehicle is defined as, the speed at which the angle of the steering wheel is zero. In this case, the drivers have to counter steer for further increase in speed. The gain in yaw velocity during under steering is limited, and can reach its maximum level at its characteristic speed. Therefore, a vehicle in an under steered condition is directionally stable at any given speed. The gain in yaw velocity of a vehicle at neutral steering condition increases linearly with respect to its speed. The gain in yaw velocity of a vehicle in an over steering condition goes to infinity at the critical speed since the vehicle will not be stable beyond this driving velocity [14].

Table 1. The novelty of some selected studies on stability of semi-trailer articulated vehicle

Weight of Tractor (kg)	Weight of Trailer (kg)	Longitudinal Distance of Trailer CG from Hitch Point (m)	Longitudinal Distance Between CGs (m)	Novelty/Contribution	Reference
8268	27562.1	3.5	4.72	Designed an anti-jackknifing device with a semi-active control at the switchable damper.	Laszlo et al. [65]
7500	6000	4.77	7.16	The analysis showed that, the stability of a semi-trailer articulated vehicle with a non-steering rear axle, are more effected, when the tractor unit has only one non-steering axle at the rear. The fifth Wheel was found to influence the vehicle stability.	Ren et al. [66]
7269.2	26018	4.20	7,26	Demonstrated detail stability analysis of a semi-trailer articulated vehicle	Taheri et al. [67]
7449	32551	4.98	7.47	The work showed the concept of the stability boundaries of a semi-trailer articulated vehicle.	Luijten [6]
6525	33221	5.65	7,61	The study proposed a method for enhancing the handling behavior of a semi-trailer articulated vehicle.	Oreh et al. [68]
6525	33221	5.65	7.61	Developed and proposed a roll over control system for articulated vehicles carrying liquids	Saedi et al. [69]
7000	44000	7,50	8.10	The analysis showed an improvement in handling performance of a semi-trailer articulated against rollover and jackknifing during evasive maneuver at high speed.	Elhemly et al. [39]
7500	29800	3.62	8.42	The analysis showed the effects of tractor coupling position on a semitrailer articulated vehicle stability.	Erik and Johan [13]
7495	27325	7.24	9.92	The analysis uses adjustable suspension parameters to enhance the characteristics of unladed vehicle. The result shows an improvement of the vehicle acceleration.	Mohamed et al. [70]
8812	16484	7.48	10.02	Worked on the relationship between steering inputs and the behavior of the semi-trailer articulated vehicle.	Maas [27]
6980	9767	1.46	2.81	A linearised stability analysis model was developed to study the factors influencing the stability of articulated vehicles.	Lei et al. [71]
8305	11540	6.07	6.39	The study developed a multi-objective stability control algorithm which improved the stability of a semi-trailer articulated vehicle by using differential braking. A vehicle controller was designed to minimize the likelihood of rollover and jack-knifing.	Zong et al. [72]
7677	25323	4,90	7,01	Studied yaw stability of articulated vehicle using the phase trajectory method which consist of a nonlinear tyre model and a nonlinear articulated bicycle model with four degrees of freedom. The study showed the convergence regions of equilibrium through numerical integration of equations of motion. The changes in the obtained regions were expressed as a function of the tractor speed and the position of the hitch point.	Andrede et al. [73]
1521	2000	6.00	8.94	The study presents nonlinear bifurcation stability analysis of an articulated vehicles using active trailer differential braking (ATDB) The bifurcation analysis was based on phase-plane method while the Lyapunov analysis theory was employed to evaluate the lateral stability of the vehicle. It was found that, the ATDB system has significantly improved the yaw and roll stability of the vehicle	Tao et.al. [74]
8305	11540	4.07	6.49	A new model of a multi-axle articulated vehicle with non-linear tyre model was developed and compared with the conventional linear articulated vehicle model; this new model has several advantages.	Zhu and Li [45]

Lei et al. [71] developed a nonlinear dynamic model of a semi-trailer articulated vehicles with a hydraulic steering system. The causes of the snake oscillation and relevant indicators for evaluating snake instability were analyzed using several parameters. The equations of state required for nonlinear dynamic analysis, and the corresponding eigenvalue analysis, were obtained from Newtonian mechanical equilibrium equations. The analysis showed that, the stability of an articulated vehicles decreases with increasing speed. Among the vehicle parameters, centre of mass position and hydraulic system were observed to have significant influence on the stability of the vehicles than the other parameters.

## 6. Conclusions

This paper presents a literature review on stability analysis of a semi-trailer articulated vehicle in order to analyze the static and dynamic characteristics as to ensure good road and passengers' safety. This paper shows that, the higher the weight of trailer and the tractor unit, the farther the distance of the centre of gravity (CG) from the hitch point of the semi trawler articulated vehicle. This reduce the safety margin against rollover stability of the vehicles. It was also observed that, the increase in CG height affects the vehicle Static Stability Factor (SSF) thereby decreasing its rollover stability. The fifth wheel lead and the distance between the tractor and the trailer CG were found to play a vital role in influencing the stability of the vehicle. However, it was observed that, it would be of great importance for a tractor unit with one rear axle, to have the fifth wheel lead, to be as large as possible in order to control the vehicle instability.

Further researches are hereby needed on the instability of the vehicle so as to provide a medium for improving its static and dynamic stability. Constant training and enlightenment of the vehicle users are hereby recommended to educate them on any change in behavior or design of these vehicles. This would help to monitor the static and dynamic characteristics of these vehicles, thereby ensuring good road and passengers' safety.

## Nomenclatures

$\delta$	: steering angle ( $^{\circ}$ )
$\varphi$	: articulation angle ( $^{\circ}$ )
$u$	: longitudinal velocity (m/s)
$v_1$	: tractor lateral velocity (m/s)
$v_2$	: trailer lateral velocity (m/s)
$r_1$	: tractor yaw velocity (m/s)
$r_2$	: trailer yaw velocity (m/s)
$b_2$	: tractor cg from hitch point (m)
$a_1$	: trailer cg from hitch point (m)
$F_{c1}, F_{c2}$	: forces at hitch point (N)
$F_{11}, F_{12}, F_{13}$	: tractor lateral forces (N)
$F_{21}, F_{22}, F_{23}$	: trailer lateral forces (N)
$l_{11}, l_{12}, l_{13}$	: distance of tractor cg from tractor wheels (m)
$l_{21}, l_{22}, l_{23}$	: distance of trailer cg from trailer wheels (m)

## Conflict of Interest Statement

The Authors declared that there is no conflict of interest in this study

## CRedit Author Statement

**Sunday Bako:** Conceptualization, Writing-Original Drafting, Analysis, Editing:

**Bori Ige:** Literature Research, Refining, Review:

**Abdulkarim Nasir:** Literature Research, review, Refining:

**Nicholas A. Musa:** Literature Research, Review, Analysis, Editing.

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