

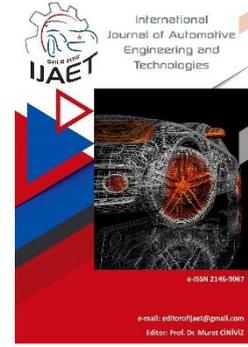


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Original Research Article

### The effects of load distribution and hitch position on driving dynamics in towed vehicles



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#### ABSTRACT

Car-trailer systems, consisting of a towing vehicle (tractor) and one or more towed vehicles (trailers), are widely used today. The widespread use of these vehicle systems in traffic also brings with it increased accident risks. Sometimes the aim is to transport more cargo and goods at a lower cost, while other times it's for recreational and hobby purposes. Regardless of the purpose, there are several important vehicle parameters that significantly affect driving dynamics in such vehicle combinations. While it's possible to prevent accidents by using expensive control systems and vehicle equipment, it's also possible to prevent accidents simply by understanding and paying attention to the effects of important vehicle parameters. In this study, the effects of the trailer's load distribution, i.e., its center of gravity position on the vehicle's longitudinal axis, and the hitch distance of towing vehicle from the rear axle center of the vehicle on the driving dynamics of both vehicles were investigated. It was found that both of these variables have a significant impact on the lateral dynamics of the car-trailer combination. It was observed that the trailer's load distribution and the hitch distance of towing vehicle from the rear axle center of the vehicle can trigger undesirable jackknifing and snaking behaviors, thus increasing the tendency of the vehicles to roll over. Therefore, it is believed that many potential accidents can be prevented simply by paying attention to the positioning of the loads during trailer loading and the hitch position of the towing vehicle.

**Keywords:** Towed vehicles, load distribution, hitch position, trailer stability.

#### 1. Introduction

The increasing need to transport both people and more goods with the same vehicle has led to the widespread use of trailers. A car-trailer system consists of a vehicle that performs the towing operation and a unit that is towed. The towing and towed vehicles are connected to each other via an articulated hitch. The

flexibility in connecting and disconnecting vehicle units offers advantages such as lower transportation costs due to high fuel economy and reduced greenhouse gas emissions. In addition to these advantages, vehicles towing trailers or other units can be particularly sensitive to steering, braking, or road quality. Changes in load, load position, and the position

of the trailer's center of gravity significantly affect the lateral stability of the car-trailer system at high speeds. Various load distributions on the trailer can cause center of gravity to change, increasing the risk of the trailer sliding or detaching from the towing vehicle [1]. Therefore, car-trailer systems bring with them accident risks in addition to the advantages. Car-trailer systems frequently exhibit significant motion instability, which often leads to fatal traffic accidents. As shown in Figures 1b and 1c, a serious accident of jackknifing for a towing vehicle-semi-trailer can result from non-periodic deviation of towing vehicle swing or trailer swing, respectively. As shown in Figure 1a, the dynamic instability of the towing vehicle/semi-trailer usually manifests itself as a yaw response with increasing amplitude, which is known as trailer snaking [2]. All of these situations also apply to car-trailer systems [3]. Many approaches to controlling the lateral stability of car-trailers exist in the literature. In addition, a literature review was conducted covering the effects of external factors such as tire forces, aerodynamic forces, and road/climate conditions [4]. To address the effects of these factors, researchers have previously investigated numerous passive and active safety control techniques.

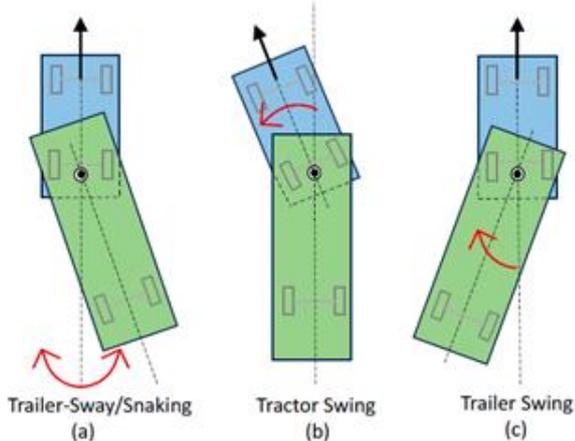


Figure 1. Schematic representation of three different unstable yaw-motion modes of a towing vehicle/semi-trailer: (a) trailer sway/snaking; (b) towing vehicle swing; (c) trailer swing [2].

In their study, He and Ren developed linear and nonlinear car-trailer vehicle dynamic models with different degrees of freedom and compared them with a car-trailer model they developed using the CarSim software package. They performed the comparison of the models

with fishhook and single lane change maneuver tests. While making the comparison, they focused particularly on the change in the articulation angle between the car and the trailer. Car-trailer models were evaluated in terms of accuracy, applicability and complexity for active safety system design through comparative evaluation [5].

Shamim et al. stated that there are three typical unstable motion modes for car-trailer systems: trailer swing, jackknifing, and rollover, which cause potential hazards. They proposed various active control techniques to improve the stability and handling of a car-trailer systems, not limiting themselves to passive parameters such as the trailer's center of gravity. They indicated that applicable control methods include active trailer steering control, active trailer braking, and a variable geometry approach that actively controls the lateral displacement of the car-trailer hitch. They introduced the relevant yaw plane models for deriving these three controllers. Through comparative evaluations, they identified the characteristics of different control strategies and discussed their applicability [6].

Darling et al. experimentally investigated the effects of different trailer parameters on the high-speed stability of the car-trailer system by varying the dimensions, mass, and inertial characteristics of an adjustable trailer. They stated that the dominant factors affecting stability were the trailer's load distribution, yaw inertia, and trailer axle position, with tire pressure having a lesser effect. As a result of their experimental tests, they suggested that the use of a friction balancer and the car's electronic stability program (ESP) improved high-speed stability and helped delay the onset of snaking motion [7].

In another study on snaking motion, experiments and simulations showed that a passenger car and a cargo trailer system can become unstable at highway speeds when the trailer is improperly loaded. Principles and apparatus were developed to measure the steering angle, the articulation angle, and the lateral force of the trailer's tow bar. The study also stated that measuring the lateral force of the trailer's tow bar made it possible to determine the trailer's yaw inertia instantaneously. This was stated to be one of

the most effective parameters of snaking motion [8].

In another study, it was reported that a direct yaw moment was created in the towing vehicle by torque vectoring to control the yaw rate and articulation angle of the towed vehicle. When the initial imbalance of the trailer was detected by an articulation angle sensor, the reference yaw rate for the vehicle was changed. According to the experimental results, it was shown that the torque vectoring control device based on the yaw rate and articulation angle measurement of the vehicle ensures the safe behavior of the trailer during extensive maneuvers [9].

Studies aimed at predicting the jackknifing behavior seen in articulated vehicles in the event of loss of yaw stability are also available in the literature. Jackknifing most often occurs when the trailer is empty. In their study, Bouteldja and Cerezo developed an intelligent jackknifing safety system. They designed a new system for jackknifing detection and prediction for articulated vehicles. This system, on the one hand, uses a model of the articulated vehicle, which makes it possible to determine the dynamic state of the vehicle, such as the relative yaw angle. On the other hand, the detection algorithm is based on the jackknifing criterion and the jackknifing prediction function to estimate the jackknifing time [10].

The load distribution of a trailer is one of the key factors affecting the driving characteristics of a car-trailer combination in terms of vehicle stability. Dižo et al. presented a study on how the load distribution on a trailer affects the driving stability of a car-trailer combination. They stated that the results presented were obtained for a specific car-trailer combination and a specific set of driving conditions. However, they suggested that it could also be valid for load distributions corresponding to different car-trailer combinations [11].

Li et al. represented the load on the towball of the towing vehicle with the position of the trailer's center of gravity and investigated its effects on the stability of the towing and towed vehicles. They also optimized the load on the towball (tongue weight) for the models they used and offered improvement suggestions.

They argued that this load value should be within a reasonable range that can prevent the towing vehicle from understeer and maintain the lateral stability of the caravan [12].

This study investigated the effects of the load distribution of the towed vehicle (trailer) on the driving dynamics of both the towing and towed vehicles. Modifying the trailer's load distribution was achieved by shifting the trailer's center of gravity along the longitudinal axis to both in front of and behind the axle center. Furthermore, the effects of the distance from the towing vehicle's hitch to the rear axle center on the driving dynamics of both vehicles were also determined. It was found that both of these variables have a significant impact on the lateral dynamics of car-trailer combination vehicles. In contrast to the literature, it clearly revealed the general trend of the effects of trailer load distribution and towing vehicle hitch position on driving dynamics.

## 2. Materials and Methods

A tow or trailer hitch refers to a mechanical fastening element used to enable vehicles to safely tow trailers or semi-trailers. Wired electrical connections are required between the vehicle and the trailer for brake lights, turn signals, and stop lights. For larger trailers, braking system assemblies can also be added to the trailer. The vehicle can trigger the trailer brake to increase safety. There are various types of tow bars available, including fixed, detachable, and swivel types that can be concealed under the vehicle. A tow bar allows a vehicle to tow a trailer, providing additional load-carrying capacity. However, it also significantly impacts driving safety.

A series of tests were conducted in the CarSim simulation environment to investigate the effects of the center of gravity positions of both the towing and towed vehicles on the dynamic behavior of both vehicles in a car-trailer system. CarSim is a commercially available computer-based simulation software with important features for modeling vehicle dynamics. The technical specifications of the combined vehicle system used in the simulations are shown in Table 1.

The car (D-SUV) used in the simulation tests has independent suspension at the front and

Table 1. Key technical parameters of the car-trailer combination

Vehicle	D-Class SUV, 150kW, 6-spd Front-wheel drive and Left- hand drive
Vehicle mass	1800 kg
Axle load ratio	50:50 %
Wheelbase	2800 mm
Track width	1590 mm
Ground clearance	190 mm
Center of gravity height	600 mm
Height of hitch	500 mm
Distance of the hitch from rear axle	400 mm
<b>Trailer</b>	<b>1-Axle Trailer</b>
Trailer mass	500 kg
Center of gravity (CoG) height	600 mm
Track width	1800 mm
Height of hitch	500 mm
Distance of the hitch from axle	3000 mm
Distance of the hitch from CoG	3000 mm



Figure 2. The appearance of the car-trailer combination in the simulation environment.

rigid axle suspension at the rear. The suspension of the single-axle trailer is also rigid axle. The car has a front shock absorber stroke of 120 mm and a rear shock absorber stroke of 180 mm. The trailer's shock absorber stroke is also 180 mm. The front and rear suspension spring coefficients of the car are 130 kN/m and 40 kN/m respectively. The trailer's suspension spring coefficient is also 40 kN/m. The car-trailer system used in the CarSim simulation environment has a total of 21 degrees of freedom. These are translational movements along the x and y axes, rotation (yaw) around the z axis, and rolling movements around the longitudinal axis for both vehicles. Both vehicles have vertical wheel movement due to their suspension systems and also wheel rotational movement. Finally, there is an articulated angle between the two vehicles. The Magic Formula is used to model the tire/road forces. The appearance of the vehicles in the simulation environment

is given in Figure 2. Furthermore, Figure 3 shows the geometric parameters of the car-trailer configuration in the simulation environment.

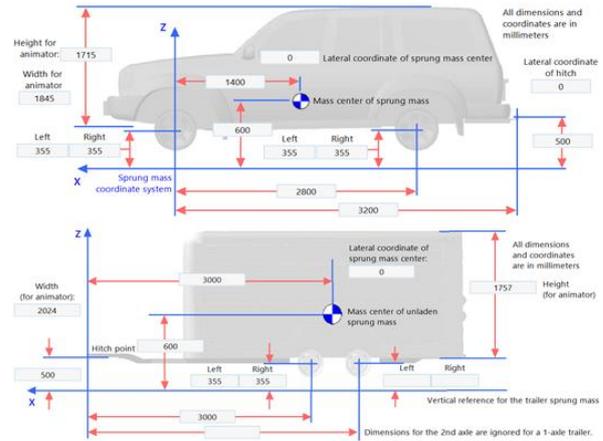


Figure 3. Geometrical parameters of car-trailer configuration in the simulation environment

The National Highway Transport Safety Administration (NHTSA) is constantly researching rollover-related issues and publishing a series of dynamic rollover tests. Open-loop maneuver tests, described as the "J-Turn" maneuver and the "Fishhook" maneuver, performed using an automated steering control device, have been shown to yield better results than other maneuver tests [13]. The fishhook maneuver uses steering inputs that approximately mimic the steering movements a panicked driver might use to regain lane position after two wheels have gone off the road [14]. In this study, the Fishhook maneuver was used in the simulation tests. Figure 4 shows the Fishhook maneuver description illustrating the steering movements, and Figure 5 schematically shows the Fishhook test course.

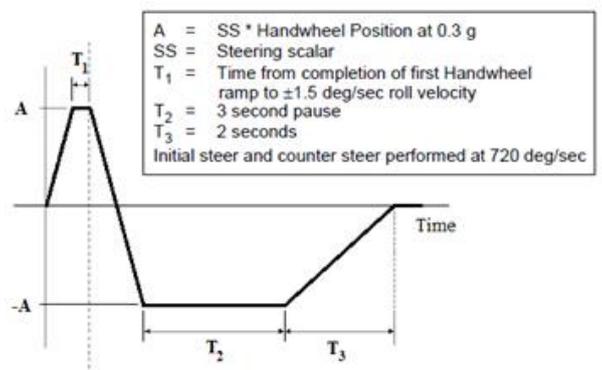


Figure 4. NHTSA Fishhook Maneuver Description [13,14]

To investigate the effects of load distribution and center of gravity on driving dynamics, the

car-trailer system was subjected to Fishhook

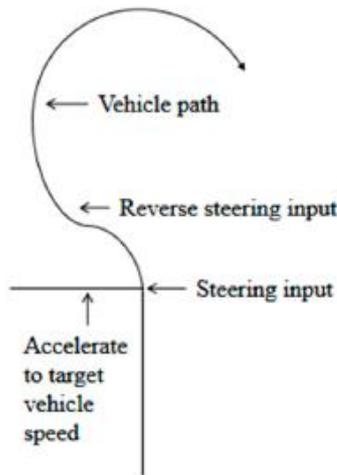


Figure 5. Schematic diagram of the Fishhook test course [15]

maneuver tests in the CarSim environment. The coefficient of friction was assumed to be 0.85. The tests were conducted at a constant start speed of 60 km/h, without braking, using only steering movements, in a windless environment. The results obtained are shown graphically below for both vehicles (towing vehicle and trailer). The test conditions in the simulation environment were given in Table 2.

Table 2. The test conditions in the simulation environment

Test Parameter	Description
Vehicle speed at the start of the test	60 km/h
The road surface friction coefficient	0.85
Vehicle driving conditions at the time of testing	Driving only steering movements without braking
Test track slope	Flat road without incline
Test environment wind conditions	Windless environment
Condition of the test road surface	Dry road surface
Tire contact with the ground during testing	The tires remained on the ground without lifting.

The correct range for the tongue weight is generally recommended in the literature to be around 10-15% of the total trailer weight. Shifting the trailer's center of gravity before or behind the axle center changes the tongue weight. When shifting the trailer's center of gravity, a distance of 500 mm was chosen to exceed this tongue weight value. Choosing this

value deviates from the ideal conditions. This allows the effects of the trailer's center of gravity being in front of or behind the axle center to be more clearly demonstrated. In the car-trailer combination, the minimum and maximum hitch distance values of 400 mm and 1200 mm were selected according to the dimensions of vehicles used in real-world. Furthermore, according to the NHTSA's fishhook test procedure, the test must be completed without the vehicle's wheels lifting off the ground. According to the test procedure, the vehicle speed can be selected between 55-80 km/h. In this study, 60 km/h was chosen because it was the speed at which the vehicle's wheels could be tested without lifting off the ground. The results obtained in this study reflect a general trend and are not limited to the car-trailer system in this study alone, due to the wide range of simulation parameters selected.

### 3. Results and Discussion

The trailer's center of gravity was first shifted relative to the vehicle's longitudinal axis, to observe the effects of the towed vehicle's load distribution on driving dynamics. Tests were conducted in three different positions: with the trailer's center of gravity at the axle center, 500 mm in front of the axle center, and 500 mm behind the axle center. By shifting the center of gravity forward and backward relative to the axle center, the trailer's load distribution was altered. Figure 6 shows the vehicles in a simulation environment for the three different load distribution scenarios. Here, the yellow arrows indicate the vertical wheel load on each wheel.



Figure 6. Appearance of vehicles in the simulation environment

Figure 7 graphically shows the effects of the trailer's load distribution on the yaw angles of the vehicles. As the trailer's load distribution, i.e., the position of its center of gravity, shifts towards the rear, i.e., away from the hitch, the

yaw angles of both vehicles increase. When the trailer's load distribution is shifted 500 mm in front of the axle center, the yaw angle of the trailer is around  $50^\circ$ , while when it is shifted 500 mm behind the axle center, the yaw angle reaches  $65^\circ$ . As the yaw angle increases, the steering stability of the vehicles is negatively affected. Similar studies in the literature have emphasized that the trailer's load distribution also affects the dynamics of the towing vehicle. It has been stated that when the load is at the rear, it leads to an excessive reduction in the load on the rear axle of the towing vehicle and a risk of detachment from the trailer. When the load is at the front, it has been emphasized that it causes the towing vehicle to exceed its permitted load capacity many times over and, in a front-wheel-drive vehicle, to cause an excessive reduction in the load on the drive axle [1]. If the trailer's center of gravity shifts backward, a reverse moment occurs, resulting in yaw instability in the vehicle.

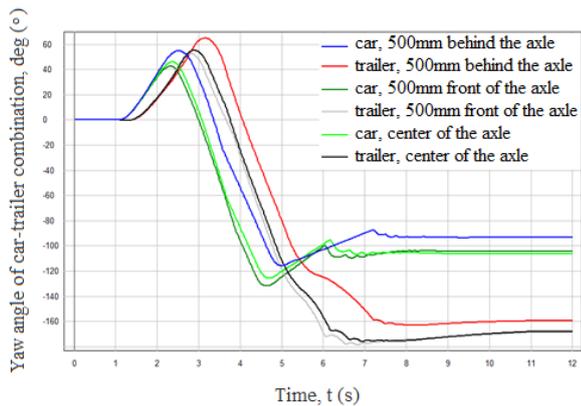


Figure 7. Time-dependent variation of yaw angle of car-trailer combination

Figure 8 graphically illustrates the effects of trailer load distribution on the roll angles of the vehicles. It also shows the time-dependent changes in the roll angles of both vehicle bodies for three different trailer load distribution scenarios. The largest roll angle of  $3.6^\circ$  occurs when the trailer load distribution is concentrated 500 mm behind the axle center, while the smallest roll angle of  $2.8^\circ$  occurs when the load distribution is concentrated 500 mm in front of the axle center. As the trailer load distribution shifts from front to back, the roll angle of the trailer body increases. This impairs lateral stability and increases the tendency to roll over. Although there are no very large changes in the roll angles of the

towing vehicle, the roll angle of the towing vehicle body increases as the trailer load distribution shifts from rear to front. As the trailer load distribution shifts towards the front of the axle center, it applies extra load to the towing vehicle, thus increasing the roll angle of the towing vehicle. Since jackknifing behavior occurs around the 5th second in the graph, subsequent changes in roll angle are not significant. The same applies to the graph in Figure 7. Here, changes in the vehicles' yaw angles after the 5th second are insignificant.

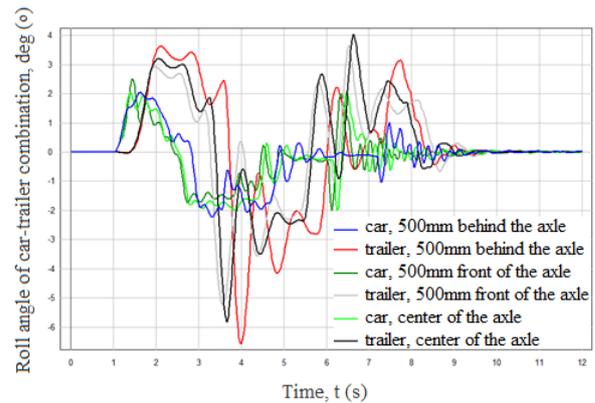


Figure 8. Time-dependent variation of roll angle of car-trailer combination

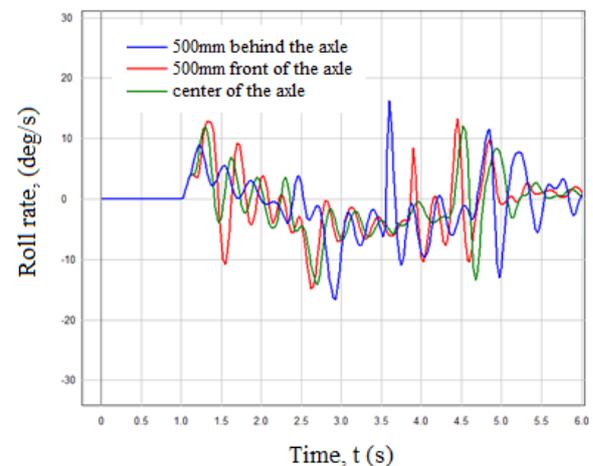


Figure 9. Time-dependent variation of roll rate of the towing vehicle

Figure 9 shows the changes in the roll rate of the towing vehicle over time according to three different load distribution scenarios of the trailer. In the first few seconds of the graph, it seems advantageous that the load distribution of the trailer is concentrated behind the axle center, but as time progresses, it is seen that it increases the roll rate of the towing vehicle even more. In the graph, it is seen that the roll rate of the towing vehicle reaches higher values after 2.5 seconds when the load

distribution of the trailer is 500 mm behind the axle center. This indicates that snaking behavior can be more easily triggered when the load distribution of the trailer is behind the axle center.

Tongue weight is defined as the vertical force applied by the trailer to the tow hitch. Maintaining the correct range (generally around 10-15% of the total trailer weight is recommended) is critical for system stability. Negative tow weight (the load that lifts the tow point) can increase vehicle stability problems. The load shifted to the rear of the trailer reduces the towing capacity, increasing the trailer's tendency to sway during braking, which impairs the vehicle's ability to brake evenly. An adequate and balanced tongue weight maintains steering stability and improves the vehicle's cornering handling. When the tongue weight is too low (especially when the load shifts to the rear), the vehicle-trailer system becomes more prone to swaying; the trailer's oscillation can impair the towing vehicle's steering response. This is known as trailer oscillation/sway and makes steering control more difficult. It can also cause the towing vehicle to oversteer in corners [12].

Furthermore, the effects of the distance of the hitch point on the towing vehicle to the rear axle center of the towing vehicle on the driving dynamics of the car-trailer system were also investigated. In these simulation tests, the characteristics of both the towing and towed vehicles remained the same. The center of gravity of the trailer was assumed to be at the axle center, and only the distance of the hitch on the towing vehicle to the rear axle center of the towing vehicle was selected at three different values. Figure 10 shows the time-dependent changes in the yaw angle of both vehicles for different positions of the hitch on the towing vehicle. As the hitch distance increased, the yaw angles of both the towing vehicle and the trailer increased. In particular, the increase in the yaw angle of the trailer was greater. At a hitch distance of 1200 mm, the highest yaw angle value of 79° was observed for the trailer. The lowest yaw angle value of the trailer was 54° at a hitch distance of 400 mm. Lateral forces on the tires create yaw moment and increase the yaw angle.

Additionally, axle load distribution affects the yaw angle because it alters the moment balance. An increase in yaw angle indicates a change in the vehicle's direction.

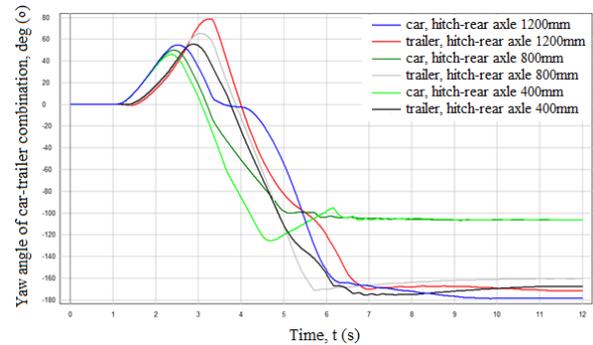


Figure 10. Time-dependent variation of yaw angle of car-trailer combination

Figure 11 shows the time-dependent changes in the roll angle of both the towing and towed vehicles for different hitch distances on the towing vehicle. This angle, which occurs when the vehicle's center of gravity shifts to the outside of a curve during driving, is directly related to lateral forces and load transfer. As the roll angle increases, the vehicle's stability and handling characteristics change negatively [16,17]. As the hitch distance increases, the roll angles of both the towing and towed vehicles increase. In particular, the changes in roll angle around the 3rd second are dramatic for both vehicles.

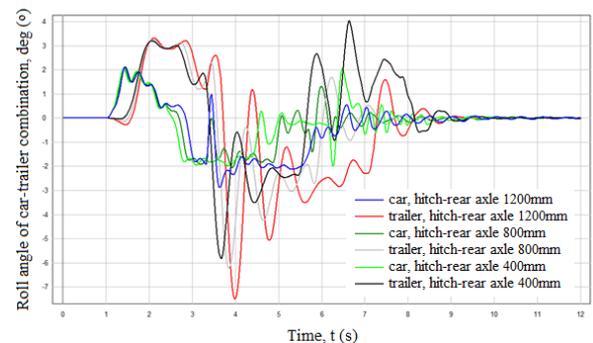


Figure 11. Time-dependent variation of roll angle of car-trailer combination

Figure 12 shows the time-dependent changes in the roll rate of the towing vehicle for different hitch positions on the towing vehicle. While the graph initially shows no effect of different hitch positions on the towing vehicle's roll rate, around 3.5 seconds, an increase in hitch distance dramatically increases the roll rate. The towing vehicle's body roll rate momentarily reaches 40 deg/s. Changes in the roll rate of the vehicle body

increase lateral load transfer and rolling moment [18]. It also increases lateral force generation by altering tire load distribution. This indicates that the vehicle's lateral stability could be significantly compromised.

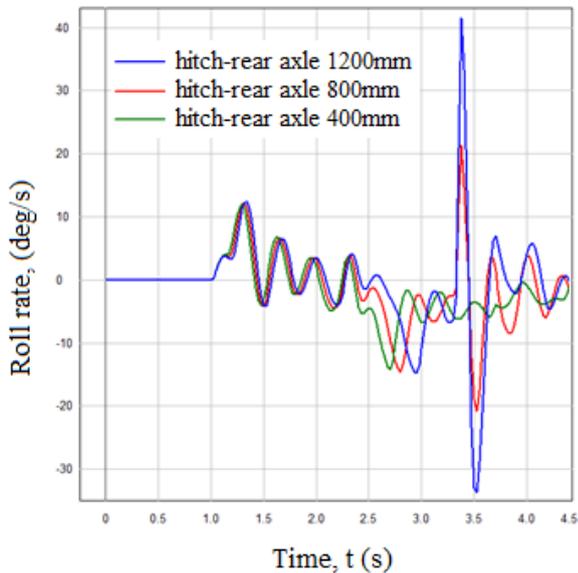


Figure 12. Time-dependent variation of roll rate of the towing vehicle

#### 4. Conclusions

This study investigates the effects of varying the load distribution of the trailer and the hitch distance of the towing vehicle from the rear axle center on the driving dynamics of a car-trailer system. First, to observe the effects of the trailer's load distribution, the trailer's center of gravity was shifted 500 mm forward and backward relative to the axle center. As the trailer's center of gravity shifted backward, i.e., further away from the hitch, the yaw angles of both vehicles increased. When the center of gravity was 500 mm rearward compared to 500 mm forward, the yaw angle of the trailer body increased by 30%. As the yaw angle increased, the steering stability of the vehicles was negatively affected. Under the same conditions, the roll angle of the trailer increased by 28.5%. This disrupts the lateral stability of the trailer and increases its tendency to roll over. Although there were no significant changes in the roll angles of the towing vehicle, as the trailer's load distribution shifted forward of the axle center, the towed vehicle applied extra load to towing vehicle, thus increasing its roll angle. When the trailer's load distribution is behind the axle center, the roll rate of the towing vehicle body increases,

which means that snaking behavior can be triggered more easily.

As the distance from the hitch on the towing vehicle to the rear axle center of the towing vehicle increased, the yaw angles of both the towing vehicle and the trailer increased. The increase in yaw angles of the trailer was particularly significant. Increasing the hitch distance resulted in a 46% increase in the yaw angle of the trailer. As the hitch distance increased, the roll angles of both the towing vehicle and the towed vehicle also increased. Furthermore, the increased hitch distance also increased the roll rate of the towing vehicle. This indicates that increasing the hitch distance can cause the roll rate of the towing vehicle to reach levels that can significantly impair the lateral stability of the vehicle.

In conclusion, it has been observed that the load distribution of the trailer and the hitch distance of the towing vehicle from the rear axle center can trigger undesirable jackknifing and snaking behaviors, thus increasing the tendency of vehicles to roll over. Therefore, it has been shown that the positioning of the loads during trailer loading and the hitch distance of the towing vehicle have a significant impact on driving dynamics. In this way, it is thought that accident prevention can be largely achieved by knowing and paying attention to the effects of important vehicle parameters, instead of using costly control systems and vehicle equipment.

#### CRedit authorship contribution statement

The author confirms sole responsibility for all aspects of this work. The author contributed to the conception, design and simulation of the study, analysis and interpretation of results, and manuscript preparation. The author reviewed and approved the final version of the manuscript.

#### Declaration of Competing Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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