

INVESTIGATION OF ELECTRONIC STABILITY CONTROL PERFORMANCE IN EXTREME CONDITIONS OF TIRE INFLATION, SPEED AND WEIGHT DISTRIBUTION

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Abstract

Electronic Stability Control (ESC) is one of the crucial safety features designed to assist drivers in maintaining control of their vehicles during dynamic driving situations. Enhancing vehicle safety in a variety of driving situations requires an understanding of how these elements affect ESC's function. There are a lot of variables that might affect how effective ESC is, however, in this study tire inflation pressure, vehicle speed, and weight distribution are considered. An investigation has been carried out to simulate the functioning of ESC and evaluate its performance under these parameters in a Double Lane Change test (DLC). DLC was chosen as it replicates a real-world scenario that is ideal for assessing the effectiveness of an electronic stability control system. The results revealed that ESC performance was significantly impacted by tire pressure, speed, and weight distribution of the vehicle. Underinflated tires provide increased grip in certain situations, but the investigation reveals ESC finds it hard to predict the vehicle's response. ESC also finds it challenging to precisely identify and address loss of traction because of the increased body roll and greater slip angles brought on by load fluctuations, which may result in a delayed or less successful intervention. In conditions where tire pressure and speed were suboptimal ESC effectiveness was notably compromised, posing a risk of dangerous accidents, and Loading the vehicle with weight distributed on a single side was found to be not recommended.

Keywords: Double Lane Change Test; Electronic Stability Control; Tire Inflation; Vehicle Dynamics; Vehicle Safety

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Introduction

Electronic Stability Control plays a vital role in enhancing vehicle safety by preventing skidding and loss of traction, particularly on slippery or uneven road surfaces. It improves cornering stability by selectively applying brakes to individual wheels, thereby reducing the risk of understeer or oversteer. ESC provides critical support during emergency situations, such as sudden lane changes or obstacle avoidance, helping drivers maintain control and minimize accident risks. It significantly reduces rollover risks by controlling excessive body roll, especially in high-center-of-gravity vehicles like SUVs.

This system in vehicles use feedback control along with active front or rear steering, or by braking individual wheels to keep the vehicle stable. When the actual yaw rate (the rotation around the vertical axis) differs too much from the desired rate, the ESC is activated. Based on the vehicle's model, ESC determines the appropriate yaw rate by using signals including vehicle speed and the steering wheel angle. In order to accommodate the driver's preferences, ESC also determines the ideal yaw rate.

ESP recognizes critical driving conditions, such as panic reactions of driver in dangerous situations, and stabilizes the vehicle by wheel-individual braking and engine control intervention. The sensors, the electronic control unit, and the actuators are the three main components that make up ESC. Wheel-individual braking and engine control intervention are two ways that ESC stabilizes the car when it detects critical driving conditions, such as drivers' panic reactions in hazardous scenarios. Active yaw control stabilizes the vehicle about its vertical axis, while the ABS/TCS function primarily interferes with the longitudinal dynamics of the vehicle by controlling wheel slip during braking and acceleration. Without requiring the driver to take any action, ESC

accomplish this by wheel-specific braking intervention and modification of the momentary engine torque. A typical working principle of ESC is illustrated in Figure 1.

While the effectiveness of ESC in enhancing vehicle stability, its performance can be influenced by a variety of factors, including tire pressure, vehicle speed, and weight distribution. Understanding how these parameters impact ESC operation is essential for optimizing its effectiveness across different scenarios.

It has been proven that electronic stability control (ESC) systems effectively prevent loss-of-control crashes in both regular cars and large commercial vehicles (Brown *et al.*, 2009). Kwon *et al.* (2017) propose test scenarios and criteria for evaluating electronic stability control (ESC) systems in medium commercial vehicles, showing their effectiveness in assessing yaw stability amidst factors like maneuvering, speed, tire forces, friction coefficient, road slope, and load condition.

Forkenbrock *et al.* (2005) introduce a methodology using accident data analysis, primarily focusing on Electronic Stabilization Programs (ESP) in passenger cars, finding ESP to be highly effective while noting ongoing investigation into the effectiveness of other safety systems like Brake Assist, Adaptive Cruise Control, and Lane Departure Warning.

Papelis *et al.* (2010) statistically proved that the loss of vehicle control was significantly lower with ESC than without it. The study's results showed 5% LOC with ESC and 30% without ESC, which is consistent with several epidemiological studies that examined the impact of ESC on actual collisions.

Shin *et al.* (2021) discussed the use of electronic stability control (ESC) systems to detect and predict rollovers in commercial vehicles. It

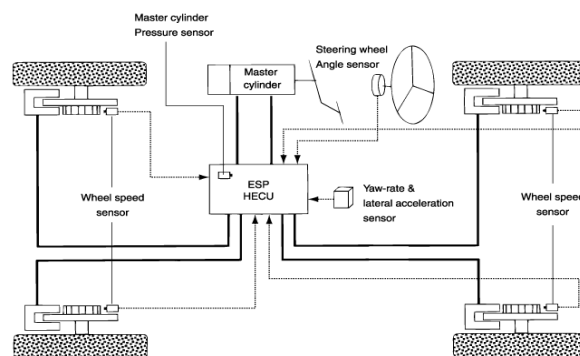


Figure 1. Working principle of electronic stability control

proposes a simplified rollover index and a method for estimating the road bank angle, both of which can be obtained from the ESC system. The paper also emphasizes the importance of including these functions in the standard ESC systems of commercial vehicles. Singh and Sivaramakrishnan (2015) develops an adaptive tire model for vehicle stability control systems, addressing variations in tire parameters like inflation pressure, tread depth, load, and temperature. They propose an intelligent tire system to monitor real-time tire-road interface forces, friction coefficient, slip conditions, and tire wear, discussing challenges in adapting the Pacejka magic formula to tire parameters simultaneously.

Watson *et al.* (2006) have discussed the challenges of creating repeatable yet unexpected scenarios for a study assessing the effectiveness of electronic stability control systems (ESC). It describes the scenarios used and presents data on the adequacy of these scenarios in assessing ESC effectiveness. The study utilizes five scenarios to study how the driver responds to different situations with and without the help of the ESC system. The paper provides a discussion of what constitutes loss of control and how to effectively measure its effect.

Wang *et al.* (2020) propose a vehicle stability control strategy for a dual-motor drive electric vehicle. The strategy is based on recognizing the driver's turning intention in real-time. A hybrid model of Gaussian mixture hidden Markov (GHMM) and Generalized Growing and Pruning RBF (GGAP-RBF) neural network is used for this recognition. It also describes the optimization theory-based allocation strategy for the vehicle stability control system.

Although ESC is proven to improve vehicle stability, a number of variables, such as tire pressure, vehicle speed, and weight distribution, can affect how effectively it works. Optimizing the effectiveness of ESC in various settings requires an understanding of how these characteristics affect its operation. The literatures has shown that, not much has been done to assess the performance and efficacy of ESCs under harsh circumstances, such as load distribution, tire inflation, and speed. The goal of the current study is to determine when ESC is helpful and when its intervention could have a negative effect on the vehicle.

Experimental Methods

CarSim software is used for all experiments, graphs, and simulations in this study. All the tests performed in this experiment are being conducted on a Double Lane Change maneuver with all cases installed with an Electronic Stability Control system in the

vehicle. The test is done with an initial velocity of 120 km/h.

Tire Inflation Pressure

The first test is done to assess the ESC effectiveness in various tire inflation pressure conditions such as overinflated, underinflated, and correct inflation pressure. Due to the absence of an option to adjust tire inflation pressure directly in the software, the tire inflation is calculated by assuming the tire to act like a simple vertical spring connecting the unsprung mass to the ground which has its spring rate, and adding the spring rate or the tire stiffness to the actual spring rate of the wheel (Cho *et al.*, 2010). If the stiffness is not known, it can be estimated based on the fact that a tire at its rated load will experience a deflection of approximately 25 mm. That is, the estimated stiffness and is calculate using Equation (1):

$$\text{Tire Stiffness} \left(\frac{N}{mm} \right) = \frac{\text{Load}(N)}{25(mm)} \quad (1)$$

The total load of the vehicle which is being used in this case is 1500kg. The load on each tire would be 375kg. Applying this formula, the tire stiffness is approximately calculated to be 147N/mm for correct/ideal tire pressure conditions. The actual spring rate of the vehicle in the software is set to be 130N/mm.

In light of study, overinflating or underinflating a tire by 10-20% above/below the recommended pressure could roughly increase/decrease its stiffness by 15-30%. Therefore, the total spring rate of the vehicle is a sum of tire spring rate calculated using the formula and the actual spring rate. Table 1. Shows the actual and total spring rate values.

Table 1. Actual and Total Spring Rate

Tire Pressure Condition	Tire Spring Rate (N/mm)	Total Spring Rate (N/mm)
Ideal	147	277
Overinflated (20% more than ideal)	176.4 ~ 176	306
Underinflated (20% less than ideal)	117.6 ~ 118	248

Tire Inflation Pressure with Varying Speed

The second test is performed to evaluate the ESC performance in the vehicle by changing the speed in changing inflation conditions. In this case, the tests conducted will be at both 150 km/h and 120 km/h across three scenarios: overinflated, underinflated, and optimal tire pressure.

For the simulations in the first and second tests, CarSim's 2017 Pickup compact RWD model

shown in Figure 2 is used and its specifications are given in Table 2.



Figure 2. Test vehicle_1

Table 2. Vehicle Specifications for Test Vehicle_1

Name	Specification
Sprung Mass	1500 kg
Initial Spring Rate	130 N/mm
Wheelbase	4175 mm
Tire rating	315/75 R16
Powertrain	200kW, 6-speed., 4.1 ratio

Weight Distribution

The third test is to investigate how Electronic Stability Control (ESC) influences the safety of the vehicle under three loading conditions: fully loaded versus empty loaded, single side loaded, and front versus rear loaded. In CarSim software, there is no direct option to input loading conditions such as front-loaded, rear-loaded, single-side loaded, or fully loaded. To address this, Equation (1) to Equation (5) are employed to calculate the position of the centre of gravity (Gillespie, 1992).

For the simulations, CarSim's 2017 Pickup Full-Size Crew Cab 8-Bed model, shown in Figure 3, is used, and its specifications are provided in Table 3.



Figure 3. Test vehicle_2

Table 3. Vehicle Specifications for Test Vehicle_2

Name	Specification
Sprung Mass	2000 kg
Wheelbase	4470 mm
a	1400 mm
b	3070 mm
Powertrain	270kW, 6-speed., 4.1 ratio

a = distance from the front axle to the COG (Centre of Gravity) in the X-axis

b = distance from the rear axle to the COG (Centre of Gravity) in the X-axis

Fully loaded Versus Empty

In the first scenario, comparing fully loaded versus empty. Using the vehicle's wheelbase and (COG) Centre of gravity coordinates in the x and y axes, the weights on the front and rear axles are calculated using the formula:

$$\text{Front axle weight} = \frac{b}{a+b} * \text{Wheelbase} \quad (2)$$

$$\text{Rear axle weight} = \frac{a}{a+b} * \text{Wheelbase} \quad (3)$$

An average weight load capacity for an 8-bed pickup truck is determined to be 1140kg including the load and weight of the passengers. The load is equally added to the front axle weight and the rear axle weight in the Equation (2) and Equation (3) and the COG for a full load condition. The Table 4 shows the initial weight and Table 5 depicts the value of the front and rear axle weight after adding the load.

Table 4. Initial Weight on Front and Rear Axle

Front axle weight	1374 kg
Rear axle weight	626 kg

Table 5. Final Weight on Front and Rear Axle

Front axle weight	1994 kg
Rear axle weight	1196 kg

Using this in the same Equation (2) and Equation (3), the COG in the x-axis is determined which presents us the condition of the vehicle when it is fully loaded. The COG is observed to have shifted towards the rearwards slightly. The Table 6 displays the distance of COG from the front and rear axle in a fully loaded condition.

Table 6. Final values Distance from COG

a	1703 mm
b	2767 mm

Single Side Loaded

In the case of single-side loaded condition, the weight is added to a single side of the vehicle and the influence of ESC is determined. Adding a weight of 1140kg will make the vehicle trip-over, so the maximum load the vehicle can hold is simulated to be 600kg to test the double lane change investigation. Adding the load to the left or right side of the vehicle will have similar effects on ESC. Hence, adding the weight to the left side of COG is considered. Equation (4) and Equation (5) have been used to calculate left and right side weight of vehicle when vehicle is loaded with 600kg on the left side

of COG, which relates the trackwidth and weight on either side of the vehicle.

$$\text{Left side weight} = \frac{d}{c+d} * \text{Trackwidth} \quad (4)$$

$$\text{Right side weight} = \frac{c}{c+d} * \text{Trackwidth} \quad (5)$$

where c is the distance from the left side of the vehicle to the center of gravity (COG) along the Y axis, and d is the distance from the right side of the vehicle to the COG along the Y axis.

Considering the load in normal conditions without any lateral movement of load, Table 7 provides the value of base condition trackwidth and distance from COG values which is exactly at the center of the vehicle.

Table 7. Final Weight on Front and Rear Axle

Trackwidth	2010 mm
C	1005 mm
d	1005 mm

Now the distance from the front axle (c) has been moved towards the left making it left side single-loaded condition accordingly the the value of track width has been changed as shown in the Table 8.

Table 8. Lateral Distance from COG for Single Side Loaded

C	621 mm
d	1389 mm

Front Loaded Versus Rear Loaded

The third test under the load distribution condition is the front-loaded vs rear-loaded. In this condition, the front and rear axles are loaded with the maximum load capacity of 1140kg, and the effectiveness of ESC is valued and determined. Like in the first case, a similar set of calculations were done for the front-loaded vs. rear-loaded vehicle to find the values of 'a' and 'b' and it is displayed in the Table 9 and Table 10.

Table 9. Front Loaded Vehicle

a	891 mm
b	3579 mm

Table 10. Rear Loaded Vehicle

a	2514 mm
b	1956 mm

Results and Discussion

Tire Inflation Pressure

To draw conclusions about how the tire inflation pressure impacts the ESC's performance, the plots of the slip angle, lateral distance to the path, roll angle of sprung masses, and steering wheel angle are examined and analyzed.

Slip Angle and Lateral Distance to Path

Overinflated tires due to their high stiffness Underinflated tires prove to be less optimal but still effective. Larger slip angles, indicating that the tires are sliding rather than gripping the road surface due to their low stiffness. The underinflated tires tend to have a high slip angle due to their ability to deform more. This condition will cause the tire to wear although comparing it to the lateral distance to the path graph in Figure 3, the Underinflated condition tends to follow the path better than the other two inflation conditions due to the tire's high compliance and higher contact patch area. (Papelis, 2006).

Overinflated tires due to their high stiffness have less deformation which results in lower slip angle. Although the tires have lower slip angles in the overinflated conditions, relating the slip angle data and the Lateral distance to path data shows the deviation of the vehicle to the actual intended path. Refer to Figure 4 and Figure 5. The vehicle tends to skid in overinflated conditions because of its higher stiffness which reduces its ability to deform when brakes are applied in specific tires due to ESC. The stiffer tires can lead to more abrupt responses and may limit the system's ability to smoothly apply brake forces using the ESC. Although the responses on the tire act abruptly due to tires' higher stiffness and less flexing, the tire's overall responsiveness will be faster to the ESC inputs than the underinflated condition.

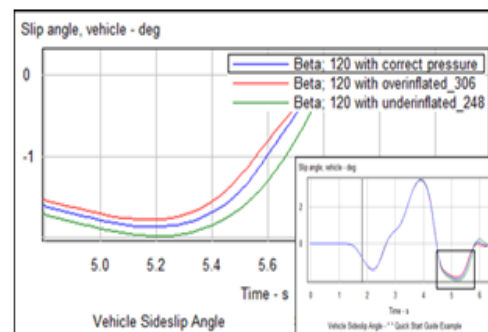


Figure 4. Variation of Slip angle(deg) with Time(s) for different tyre inflation pressure

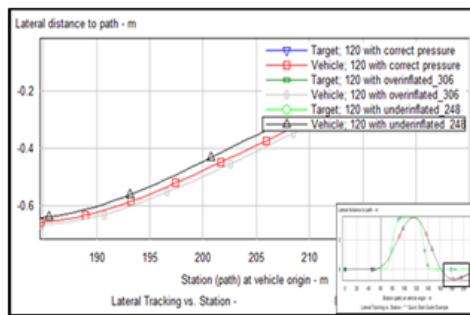


Figure 5. Lateral Distance to Path(m) vs. Intended Path(m) for different tyre inflation pressure

Correctly inflated conditions provide a compromise between the two. Correctly inflated tires provide a balanced level of traction. This makes the vehicle more predictable. With the correct pressure conditions, the ESC will be able to act effectively by applying precise brake forces to the tires to prevent excessive slip.

Roll Angle of Sprung Masses

There is a variation of roll angle in a over and under inflated tires as shown in Figure 6. Due to the overinflated tire's low flexibility, it has a more rigid connection to the road. With lower lateral grip, the vehicle may experience increased understeer, where it tends to push wide through a turn, leading to a decrease in roll. As the grip is compromised in overinflated conditions ESC works to provide grip to the vehicle and help. In cornering and adverse weather conditions ESC with overinflated tires tends to perform better than underinflated tires.

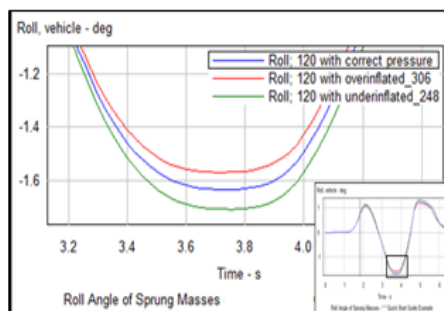


Figure 6. Variation of Roll Angle(deg) with Time(s) for different tyre inflation pressure

In an underinflated condition, due to the tire's stickiness to the road and sluggishness of the vehicle, and increased contact patch, it can affect the vehicle's suspension geometry, leading to changes in alignment angles which causes the vehicle to roll a lot more than the other two conditions. Usually, when vehicles roll in a corner the tires also should have some flexibility to roll with the vehicle to

produce a proper change in direction. In this case, the tires exhibit reduced damping characteristics making the vehicle more prone to rollover. As Responsiveness is compromised in underinflated conditions so in this case ESC works to provide help in conditions like rapid lane changes or navigating tight corners.

Correctly inflated tires contribute to the damping effect, helping absorb and dissipate energy during dynamic movements. correct pressure allows for an optimal amount of tire deformation, which allows the ESC to work the best (Lie *et al.*, 2006).

Steering Wheel Angle

The steering wheel angle variation between overinflated and under inflated tires are depicted in Figure 7. Overinflated tires tend to have reduced contact patches with the road, leading to decreased lateral grip. This can result in a more sensitive steering response, requiring a larger steering wheel angle to execute the double lane change which could possibly cause oversteer in most conditions. So, ESC performance may be affected negatively here rather than helping.

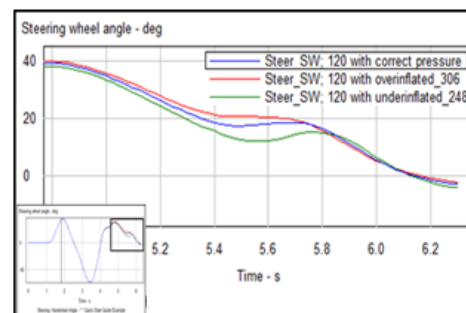


Figure 7. Variation of Steering Wheel Angle(deg) with Time(s) for different tyre inflation pressure

Underinflated tires have an increased contact patch with the road, providing more lateral grip. This can result in a more stable and less responsive steering feel. The lower steering wheel angle suggests that the vehicle requires less steering input to execute the double lane change, but it might feel less agile and more sluggish due to the increased tire compliance. Here, ESC performance may be compromised.

Increased grip in some situations: Underinflated tires may provide a larger contact patch with the road, potentially leading to increased lateral grip in certain situations. In cases such as quick changes or uneven road surfaces, the ESC tends to perform better in underinflated situations than in the correct pressure condition.

Tires inflated to the correct pressure offer the best compromise between grip and stability. The medium steering wheel angle makes a balanced and controlled response to the DLC. The vehicle exhibits a stable behavior, responding predictably to steering inputs without being overly sensitive or sluggish.

Varied Tire Pressure with Change in Speeds

Changing the speed while varying the tire inflation pressure was simulated to assess the vehicle's ESC performance. In the previous section when examining tire inflation the speed of the vehicle maintained constant at 120 Km/h. In this section, the impact of tire inflation was investigated at the change in speed from 120 km/hr and 150 km/h. The time difference in both sets of data is due to the speed which is at 150km/h and 120km/h. The test at 150km/h with its inflation conditions tends to stop abruptly at 5.1 seconds due to the completion of the test by the software. However, the data collected allows us to draw the primary observations and inferences.

On observation, the conditions with speed set at 150 km/h with various inflation conditions follow a similar pattern as compared to the condition of 120 km/h and their inflations. The major parameters taken into consideration are slip angle, yaw rate, and roll of the vehicle and these are depicted in Figure 8, Figure 9 and Figure 10.

Overall Behavior of Both Speeds

At 150 km/h, similar trends are observed in tire behavior compared to 120 km/h, with slight time differences due to the increased speed. Overinflated tires exhibit slightly higher slip angles and are prone to skidding when ESC intervenes due to their stiffness.

Underinflated tires have lower slip angles but offer better compliance, resulting in improved lateral path following. Correctly inflated tires strike a balance between traction and compliance, allowing ESC to act effectively. Overall, the observations at 150 km/h follow a linear pattern to those at 120 km/h, with slight adjustments in timing due to the higher speed.

Comparison of 150km/h Overinflated and 120km/h Underinflated

At 150 km/h, the behavior of overinflated tires differs notably from their performance at 120 km/h underinflated. On observation, these certain conditions (150km/h overinflated and 120 km/h Underinflated) exhibit a difference in roll angle and yaw stability of the vehicle although the slip angle follows the trend in the usual pattern for both speeds.

When tires are overinflated, they tend to have less contact patch area with the road surface, which leads to lower grip levels. However, because these tires are inflated beyond their recommended pressure, they maintain a stiffer sidewall structure. This stiffness helps to minimize the deformation of the tire during cornering, reducing the potential for excessive slip angle changes as observed in Figure 11. As a result, when ESC intervenes in response to oversteering or understeering situations, it has an easier time counteracting those forces since the tire's structural integrity remains relatively stable. This results in a lower roll angle and yaw rate, indicating greater stability and control.

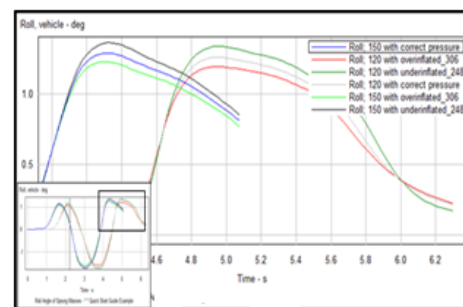


Figure 8. Variation of Roll Angle(deg) with Time(s) for different tyre inflation pressure

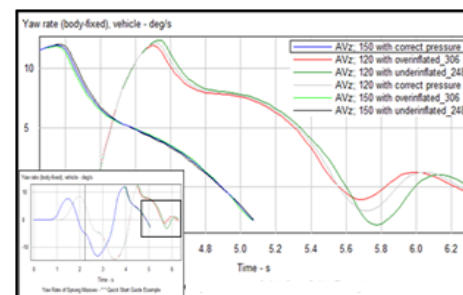


Figure 9. Variation of Yaw Rate(deg) with Time(s) for different tyre inflation pressure

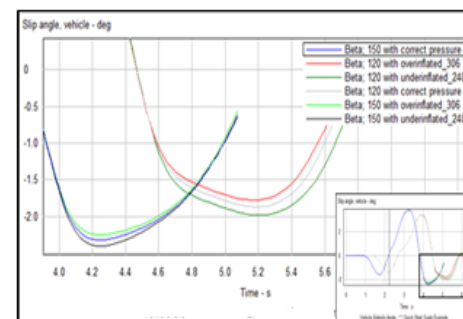


Figure 10. Variation of Slip Angle(deg) with Time(s) for different tyre inflation pressure

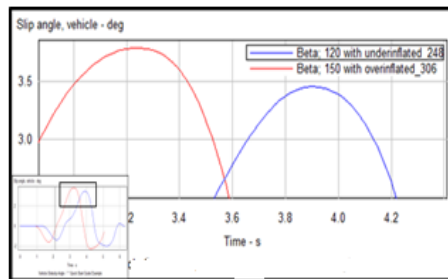


Figure 11. Variation of Slip Angle(deg) with Time(s) for over inflated pressure and under inflated pressure

In contrast, when tires are underinflated, they experience increased contact patch area but also greater deformations as they roll along the road surface. These deformations lead to larger variations in slip angles, making it harder for ESC systems to predict and control the vehicle's movements accurately. Additionally, under-inflated tires generate more heat, which could further compromise their performance and increase the likelihood of tire failure. This results in a higher roll angle and yaw rate as observed in Figure 12 and Figure 13, indicating a greater risk of instability and loss of control. (Li *et al.*, 2019 and Chen *et al.*, 2011)

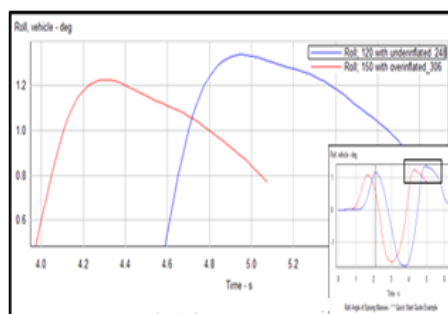


Figure 12. Variation of Roll Angle(deg) with Time(s) for over inflated pressure and under inflated pressure

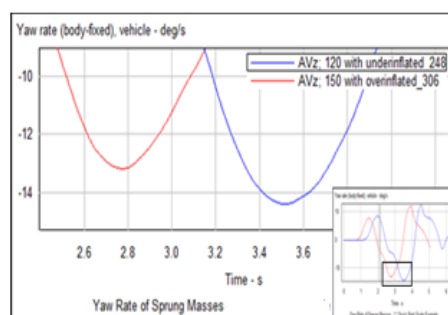


Figure 13. Variation of Yaw Rate(deg) with Time(s) for over inflated pressure and under inflated pressure

Therefore, the lower roll angle and yaw rate observed with overinflated tires at 150 km/h suggest that ESC interventions are more effective in stabilizing the vehicle and reducing slip angles. In contrast, the higher roll angle and yaw rate observed with underinflated tires at 120 km/h suggest that ESC interventions may struggle to effectively reduce slip angles and stabilize the vehicle.

The difference in roll angle and yaw rate of 0.1 deg and 0.6 for overinflated versus underinflated tires does not necessarily imply a substantial difference in the functioning of the ESC. Therefore, the 0.1-degree roll angle and 0.6 yaw rate difference alone would not significantly alter the ESC's ability to maintain vehicle stability and control. Other factors - such as tire compound, temperature, and road conditions - play a far more prominent role in determining the effectiveness of ESC.

Varied Weight Distribution

In this section, we aim to investigate how Electronic Stability Control (ESC) influences the safety of the vehicle under three loading conditions: fully loaded versus empty loaded, single side loaded, and front versus rear loaded. By examining these three scenarios, we aim to understand how ESC functions in different weight distributions within a vehicle.

Fully loaded vs Empty

In a double lane change test, the pickup truck that is fully loaded experienced a high roll angle compared to the empty-loaded one as observed in Figure 14. In this situation, ESC plays a crucial role in helping to prevent accidents by detecting and correcting situations where the vehicle is losing traction or stability. In this case, the ESC's main role is to control the rollover of the vehicle rather than controlling the yaw moment of the vehicle.

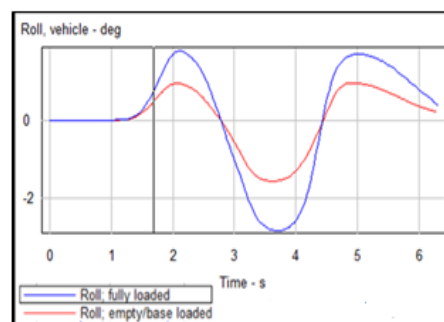


Figure 14. Variation of Roll Angle (deg) with Time(s) for fully loaded and empty-loaded vehicle

Having high yaw rates compromises the vehicle's ability to respond to steering inputs. the vehicle may enter a spin-out, where it rotates uncontrollably around its vertical axis. In extreme cases, high yaw rates can contribute to rollover accidents. Although the yaw rate is high for empty loaded condition as observed in Figure 15, it is so because it is controlled by the ESC and has been decreased. In an empty loaded condition, the vehicle is more responsive to abrupt steering inputs and slippery road conditions which may lead to severe accidents. In this condition, ESC plays the role of controlling the high yaw rates rather than roll angle

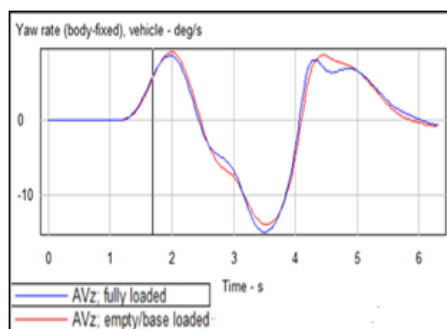


Figure 15. Variation of Yaw Rate(deg) with Time(s) for fully loaded and empty loaded vehicle

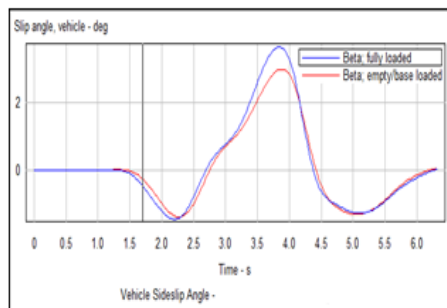


Figure 16. Variation of Slip angle (deg) with Time(s) for fully loaded and empty loaded vehicle

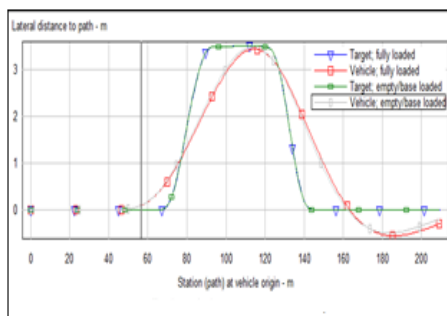


Figure 17. Lateral Distance to Path(m) vs. Intended Path(m) for fully loaded and empty loaded vehicle

to provide the vehicle stability and balance (Kulikov and Bickel, 2019).

The lower slip angles for the empty truck and lower lateral distance to the path compared to the fully loaded condition depicted in Figure 16 and Figure 17, would mean that the empty loaded has better directional changes and is sensitive to the steering wheel handle.

Overall, ESC tends to act more effectively in preventing accidents in both fully loaded and empty-loaded vehicles by adjusting yaw rates, slip angles, and roll angles to maintain stability.

However, its impact may be more pronounced in fully loaded vehicles due to their higher susceptibility to rollovers. Therefore, ESC is crucial in both scenarios but may have a more significant preventive effect in fully loaded vehicles where the risk of accidents due to high roll angles is higher.

Single Side Loaded

When weight is added to one side of the vehicle, it increases the load on that side, causing the vehicle to lean more towards that side. This increased body roll shifts the vehicle's center of gravity, making it more prone to tilting excessively during lateral movements. In this scenario, the heightened body roll observed in Figure 18, may exceed the thresholds or predictions programmed into the ESC system, potentially leading to delayed or less effective intervention. The system may struggle to differentiate between normal body roll and excessive tilt caused by the uneven weight distribution, which could compromise its ability to intervene promptly and effectively to prevent loss of control.

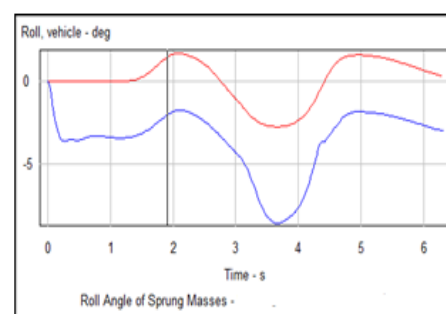


Figure 18. Variation of Roll Angle(deg) with Time(s) for single side loaded vehicle

The additional weight on one side of the vehicle increases the load on the tires on that side, altering their contact patch with the road surface. This uneven tire loading can lead to differences in traction between the two sides of the vehicle, causing one side to lose grip more easily, changing the alignment of the tires and increasing the slip

angle. The vehicle may exhibit more pronounced oversteer or understeer tendencies, causing the tires to slip more as they struggle to maintain traction.

The high slip angles observed in Figure 19, resulting from the single side-loaded condition pose challenges for the ESC system in accurately detecting loss of traction. The system may struggle to differentiate between intentional steering inputs and instability caused by the uneven weight distribution.

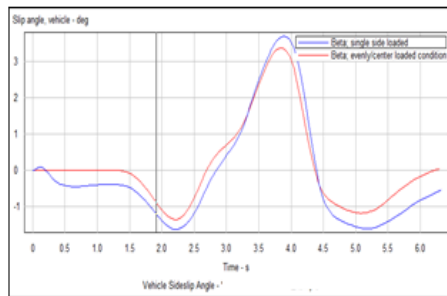


Figure 19. Variation of Slip angle(deg) with Time(s) for single side loaded vehicle

In this scenario, the uneven weight distribution can lead to asymmetrical forces acting on the vehicle, causing it to rotate differently about its vertical axis compared to a balanced condition. This can result in unexpected and potentially higher yaw rates as observed in Figure 20, making the vehicle more prone to oversteer or understeer.

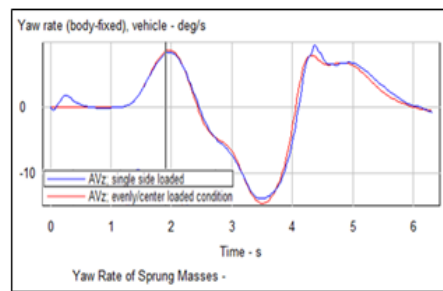


Figure 20. Variation of Yaw Rate(deg) with Time(s) for single side loaded vehicle

In the single side-loaded condition, ESC may need to apply asymmetric braking forces to counteract the uneven weight distribution and restore balance to the vehicle. ESC may apply more braking force to the wheels on the side with less weight to help reduce the yaw rate and stabilize the vehicle.

From the span of 3s to 4s in the vertical forces plot, the rear right tire which is referred to as R2 in the graph experiences zero vertical forces which means that the whole weight is concentrated

towards the front axle and the rear left axle while going back into the corner for a few milliseconds. In a right turn, ESC would typically apply braking force to the rear right wheel to assist in steering and prevent loss of control. However, if the rear right tire is experiencing zero vertical forces, it implies that there is no weight on that tire, making it ineffective for ESC to apply braking force to that wheel.

The scenario of the rear right tire experiencing zero vertical forces as observed in Figure 21, poses a challenge to the effectiveness of ESC in stabilizing the vehicle. ESC will struggle to apply braking force effectively and maintain a balanced brake distribution.

In conclusion, the nearly inactive or delayed state of Electronic Stability Control (ESC) in situations where the vehicle is single-side-loaded poses significant safety concerns. The system may require additional time to analyze the vehicle's behavior and determine the appropriate corrective action. Distributing weight evenly across the vehicle helps maintain balanced handling characteristics reduces the risk of instability and maximizes the effectiveness of ESC and enhances overall safety on the road.

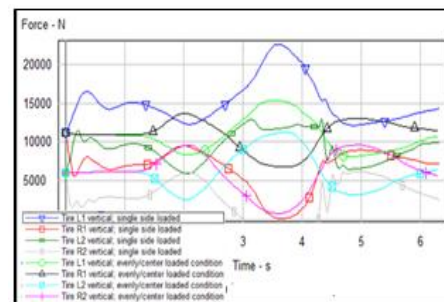


Figure 21. Variation of Vertical Forces(N) with Time(s) for all the tyres at single-side-loaded condition

Front Loaded Vs Rear Loaded

In this case, we load the vehicle to the front and to the rear with the maximum weight the vehicle can handle which is around 1140kg.

In the front-loaded vehicle, the center of gravity shifts towards the front. And due to that the rear is loose and can lose direction and mostly lead to oversteer or rollover due to its center of gravity being ahead. a pickup truck in general would have its center of gravity to the front in an empty condition because when the truck is rear-loaded the center of gravity would shift to the center of the vehicle and would act in a balanced and stabilized manner. But when the load is added to the front of the pickup truck, the center of gravity would shift more ahead with the front heavily loaded and act in

an unstable manner due to its vertical forces towards the front and having high roll angle as seen in Figure 22, which increases its tendency to rollover and in this case the ESC effectiveness would not be enough to control the excessive roll or can even counteract negatively because the rear tires are unevenly loaded and front tires are heavily loaded as seen in the Figure 23.

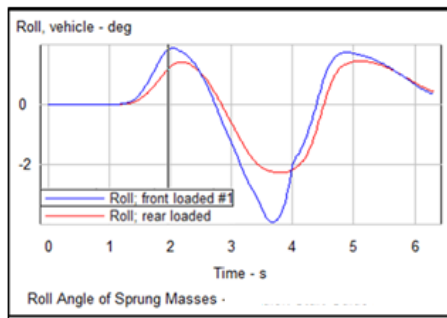


Figure 22. Variation of Roll Angle(deg) with Time(s) for the front-loaded and rear-loaded vehicle

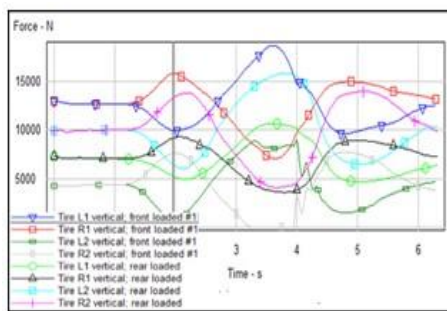


Figure 23. Variation of Vertical Forces(N) with Time(s) for all the tyres of front and rear-loaded vehicle

Even in this case, it is observed that the vertical forces on the rear right tire R2 experience zero vertical forces which poses a challenge to the effectiveness of ESC while braking to that wheel.

When heavy-duty trucks are unloaded, their center of gravity typically resides towards the front, which may increase the likelihood of instability and rollover risk. A more balanced weight distribution can enhance the effectiveness of Electronic Stability Control (ESC), as they have a more stable platform from which to operate.

Conclusion

The investigation was aimed at analyzing the performance of the ESC under different operating and environmental conditions. The tests were done

to validate the variation in performance of ESC under different circumstances.

In the case of varied tire inflation pressures, it is observed that the overinflated tires provide lower slip angles but may lead to skidding due to reduced deformation and compromised grip. On the other hand, underinflated tires exhibit larger slip angles affecting the responsiveness and increasing the risk of rollover. Although it may be seen that underinflated tires provide increased grip in certain situations, ESC will find it hard to predict the vehicle's response.

In the next test of varied speeds with varied tire inflation pressure, the overall response of ESC and tires is linear and expected. However, on observation, the condition of overinflated tires at 150 km/h appears to offer better stability and control compared to underinflated tires at 120 km/h. Overinflated tires maintain a stiffer structure, reducing deformation during changing lanes and allowing ESC systems to counteract more effectively oversteering or understeering. This results in lower roll angles and yaw rates, indicating greater stability. Whereas, underinflated tires experience larger variations in slip angles due to increased deformations, making it harder for ESC systems to predict and control the vehicle's movements accurately.

In the next condition where the vehicle is fully loaded and compared to empty loaded vehicle, ESC primarily focuses on controlling rollover tendencies in fully loaded vehicles, it also addresses high yaw rates in empty-loaded conditions to maintain stability. ESC effectively adjusts yaw rates, slip angles, and roll angles to ensure stability in both scenarios, with a potentially more significant impact in fully loaded vehicles due to their higher risk of rollovers. In single-side-loaded vehicles, the uneven weight distribution poses significant challenges for ESC systems. The heightened body roll and increased slip angles make it difficult for ESC to accurately detect and correct loss of traction, potentially leading to delayed or less effective intervention. Asymmetric forces acting on the vehicle can cause unexpected yaw rates, increasing the risk of oversteer or understeer. While ESC may apply asymmetric braking forces to restore balance, its effectiveness may be compromised in these scenarios. In the case of a vehicle being front or rear-loaded, when loaded to the front, the center of gravity shifts forward, increasing the risk of instability, oversteer, or rollover. In such cases, ESC faces challenges in effectively applying braking forces to stabilize the vehicle, particularly if certain wheels experience zero vertical forces, as seen in the scenario described. This uneven weight distribution

compromises ESC's ability to maintain balanced brake distribution and effectively control excessive roll angles.

Therefore, it is essential to maintain the recommended tire pressure, speed, and ideal weight for optimal vehicle performance and safety. While ESC can help stabilize the vehicle in challenging driving conditions, it is not a substitute for proper tire maintenance and safe driving practices.

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