

Experimental Investigation of the Influence of Tire Design Parameters on Anti-lock Braking System (ABS) Performance

Srikanth Sivaramakrishnan, Kanwar Bharat Singh, and Peter Lee
Goodyear Tire & Rubber Co.

ABSTRACT

Anti-lock Braking System (ABS) is a critical safety component and its performance is crucial for every vehicle manufacturer. The tire plays an important role during an ABS braking maneuver as it is the component that connects the vehicle to the ground and is responsible for generating braking force. The steady-state and transient properties of the tire affect the operation of the vehicle's ABS system and consequently affects its performance/ operational efficiency. The main objective of this study is to investigate how tire design changes influence its interaction with the ABS and its eventual effect on stopping distance. This was conducted through an experimental study where tires were built with three levels of variation in carcass stiffness, tread stiffness and tread compound. Following this, ABS braking maneuvers were performed on two instrumented vehicles including a mid-tier sedan and a high-performance sports car. The steady-state properties of the tire were calculated from experimental data measured both on the vehicle and from the braking skid trailer and thereafter the sensitivity of a given ABS system to such changes in tire properties were analyzed. Lastly, the feasibility of adding intelligence in ABS controllers is investigated through an on-line tire identification routine to determine the tire slip set point value for the ABS controller to maximize the tire braking force.

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INTRODUCTION

The mechanism of force generation during an emergency braking situation consists of multiple steps. The first step involves the application of pedal force from the driver, which builds up pressure in the master cylinder and the wheel calipers. The braking moment exerted by the calipers is then translated into force through slip generation at the contact path of the tire-road interface. The ABS controller simultaneously activates and begins monitoring and regulating brake pressure at the wheel calipers through solenoid valves using a pre-programmed logic until the vehicle speed falls below a specified threshold. It can be observed that the performance of the ABS system in this process is governed by influencing factors at multiple stages such as controller lag, hydraulic delays and finally the dynamics of the tire and its interaction with the road surface at the contact patch. Due to its cascading nature, an excessive delay at any stage can compound into a significant effect on stopping distance.

From the perspective of a tire manufacturer, developing an in-depth understanding of the various delaying factors at the tire level and the factors influencing its interaction with the ABS will serve beneficial in identifying problem points and consecutively tweaking tire design to reduce stopping distance. This would also help in identifying tire performance changes during normal usage where properties such as tread depth continuously change.

Based on this premise, multiple studies have been undertaken to understand how tires interact with the ABS. Roth et al [1] indicate through simulation and experimental data that the relaxation length of a tire affects ABS performance only under certain criteria. Kidney et al [2] show that the shape of the tire-force curve plays an important role in the cycling behavior of the ABS. Adcox et al [3] showed through simulation studies and later by experimental verification through Hardware-In-the-Loop (HIL) [4] that the influence of torsional dynamics of the tire is dependent on the wheel speed filter and no effect was found for a minimum filter cut-off frequency of 15 Hz. The influence of inflation pressure on stopping distance was performed in [6,7]. Srikanth et al [5,17] extended this study by also investigating the influence of other operating conditions such as tire construction, temperature and tread depth of a tire on ABS efficiency and the extent of variation it can cause on stopping distance.

The objective of this study is to understand how certain tire design parameters, namely carcass stiffness, tread compound and tread stiffness affects the performance of an ABS system. This is explained in two sections. The first part of the study deals with the design of experiments and the methods employed to collect data from instrumented vehicle braking tests and traction trailer with different sets of tires. The second part analyzes the effect of these tire design parameters on steady-state tire characteristics derived from the

braking skid trailer. This is followed by an analysis of the variation of stopping distance under different tire constructions for two types of vehicles followed by more detailed explanations of the reasons behind such variations inferred based on signals measured from the instrumented vehicles. The final part of the study provides an illustrative example of the use of tire identification for introducing intelligence in ABS algorithms to further improve vehicle safety and reduce stopping distance.

DESIGN OF EXPERIMENT

The first step towards understanding the relationship between tire design properties and ABS performance through experimental means is the selection of parameters to vary and analyze. Any given tire has multiple components that can be changed to affect the overall properties of the tire. In this study, the choice was made to construct tires with combinations of different carcass stiffness, tread compound and tread stiffness because these tire properties have the highest influence on longitudinal tire-force characteristics such as braking stiffness, peak grip and shape of the curve as shown in Figure 1, all of which play a role in ABS braking performance of a vehicle.

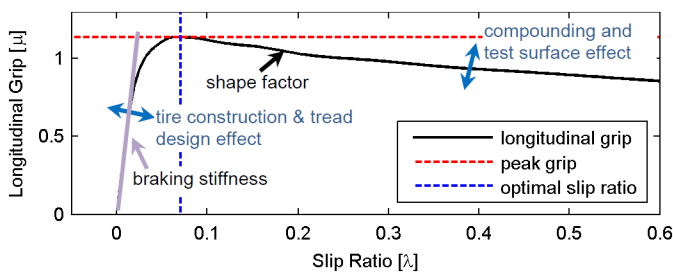


Figure 1. Influence of tire design parameters on the longitudinal force-slip curve

Table 1 shows the levels of variation that were employed while constructing tires for this study and the total number of unique constructions of tires that were built based on all possible combinations of carcass stiffness and tread cap compounds used in this study are shown in Table 2. The variation of tread stiffness was achieved by changing the tread depth of the tire as it is known that the reduction of tread depth leads to an increase in tread stiffness, thus leading to a total of 27 tire constructions. All constructions were derived as variations of a high performance summer tire.

Table 1. Tire design property variation

Tire property	Levels of variation		
Carcass stiffness	Low stiffness	Medium stiffness	High stiffness
Tread compound	Low friction	Medium friction	High friction
Tread stiffness	Low stiffness (full tread depth)	Medium stiffness (half tread depth)	High stiffness (low tread depth)

Table 2. Tire constructions based on design combinations

Tire construction	Carcass stiffness	Cap compound friction
1	Low	Low
2	Medium	Low
3	High	Low
4	Low	Medium
5	Medium	Medium
6	High	Medium
7	Low	High
8	Medium	High
9	High	High

EXPERIMENTAL DATA

The collection of experimental data was performed on three different experimental setups:

1. Tire data - Braking skid trailer
2. Vehicle ABS braking data
 - a. Instrumented high-performance vehicle
 - b. Instrumented mid-tier passenger sedan

Braking Skid Trailer

The main purpose of the braking skid trailer, as shown in Figure 2, is to obtain the longitudinal force-slip curve of the tire and extract properties such as braking stiffness, peak grip, optimal slip ratio and sliding grip.

Experimental Procedure

In this setup, the vertical load on the tire is controlled and the reaction forces are measured at the hub of the tire in the longitudinal and vertical direction after application of braking torque. The rolling radius r_e is calculated from the initial free-rolling speed ω of the tire as $V_x = r_e \omega$ where V_x is the absolute velocity calculated from GPS, which is maintained at a constant speed. This value of rolling radius is then assumed to be fixed throughout the experiment and used to calculate the slip ratio λ based on the measured wheel speed as:

$$\lambda = \frac{V_x - r_e \omega}{V_x}$$



Figure 2. Braking Skid Trailer at Goodyear Proving Grounds, San Angelo, Texas



Table 3. Traction trailer operating conditions

Operating condition	Value
Surface	Dry asphalt (smooth)
Load (lbf)	1389,695
Inflation Pressure (psi)	34
Velocity (mph)	60

The operating conditions maintained in the experiments are shown in Table 3. The loads were selected to reflect static load on the high performance vehicle used in this study on the tires at the front axle and the rear axle. It was ensured that the lockup rate for the tires is kept constant during all the runs by maintaining the same brake pressure ramp-up rate to generate uniform data for comparison.

Data Processing

The collected force-slip data is smoothed and averaged over multiple lockups using locally weighted scatterplot smoothing to obtain an approximate force-slip curve for the tire, as shown in Figure 3. The composite curve, which is obtained at two loads for each tire is then utilized to obtain the peak grip, braking stiffness and optimal slip ratio at the front and rear axle.

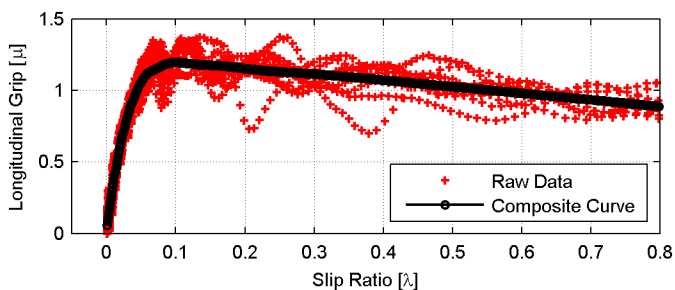


Figure 3. Traction trailer experimental data

Instrumented Vehicle Braking

The main purpose of conducting instrumented vehicle braking tests is to have a standardized method of measuring stopping distance which would account for variations that occur due to changes in braking patterns by test drivers. In this study, it was chosen to obtain braking data from two different classes of vehicles to understand how stopping distance sensitivity to tire design varies across different ABS systems. Both vehicles were chosen to have similar curb weights, although load distribution may vary due to different vehicle configurations. Table 4 shows the list of devices used and the signals measured. Brake pressure at the wheels were measured at the caliper. Figure 4 shows the instrumentation at the individual wheels.

Table 4. Devices used for vehicle instrumentation

Device	Measurement
VBOX IMU	GPS location Forward velocity Deceleration
IMC Data-logger	Forces and moments (lateral, longitudinal, vertical) (Force hubs at 4 wheels) Brake pressure (master cylinder and 4 wheels) Wheel speeds (4 wheels)

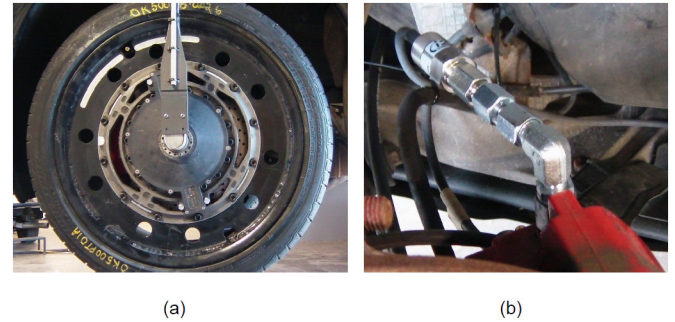


Figure 4. Vehicle Instrumentation using a) Force hubs and b) Pressure sensors at brake calipers

Experimental Procedure

The initial velocity for all braking runs were at speeds slightly above 100 kph under similar surface and weather conditions as the traction trailer tests. A maximum of 8 braking runs were conducted for each tire construction per vehicle in which the test driver applies the pedal force.

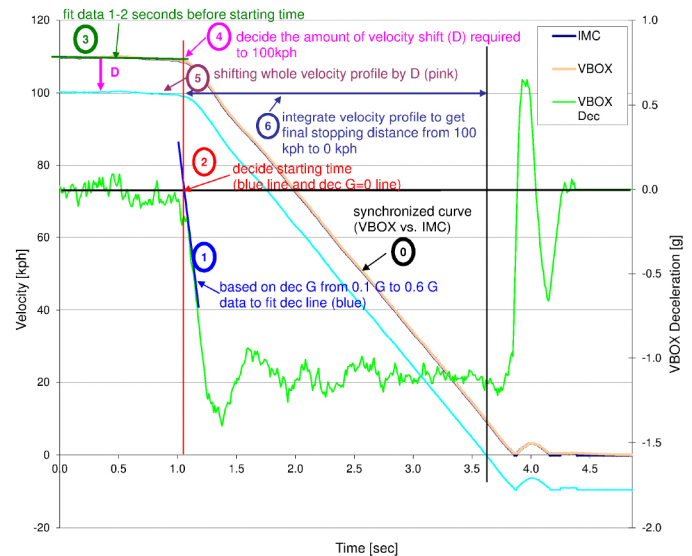


Figure 5. Procedure adopted for calculation of stopping distance

Data Processing

For all the braking runs, the following procedure was followed to obtain standardized values of stopping distance from 100 kph to 0 kph for all constructions as shown in [Figure 5](#):

1. The start of braking is detected from the intersection of slope of initial increase in deceleration from 0.1g to 0.6g with g=0 line.
2. A straight liner is fitted to data up to 2 seconds before the start of braking to obtain the shift in the velocity profile to 100 kph.
3. The shifted velocity profile is then integrated from 100 kph to 0 kph to obtain the stopping distance.
4. The average stopping distance for a given tire construction is then calculated from all 8 braking runs after removing outliers which can occur due to variations in the test procedure that are outside the control of the operator.

INFLUENCE OF TIRE DESIGN PARAMETERS ON TIRE CHARACTERISTICS

One of the key components to approaching tire design variations is to understand the effect of tread stiffness, carcass stiffness and tread compound on tire characteristics that impact ABS performance, which are:

1. Peak Grip
2. Braking Stiffness
3. Optimal Slip Ratio
4. Shape factor (drop after the peak)

Tire design parameters have a combined effect on all these characteristics and it becomes essential to analyze which parameters have a dominant effect on important tire characteristics. Data extracted from the traction trailer is utilized for this purpose.

In this section, the variation of tire characteristics at front tire loads are considered for analysis and interpretation due to a high contribution of braking force from the front axle during an ABS braking maneuver. For all analysis, low grip tread compound, low tread stiffness (new tire) and low carcass stiffness are considered to be the nominal design for the tire in this study and all tire property values will be normalized around this tire to show characteristic variations as a percentage change. It is assumed that in this set, the level of variation in tread stiffness due to tread depth is much higher than the change due to tread compound. A summary of all the observed sensitivities are shown in [Table 5](#).

Variation of Peak Grip

The peak grip of the tire has a direct correlation with stopping distance as this parameter signifies the maximum deceleration the vehicle can attain. Although this parameter doesn't directly impact the operation of the ABS, average vehicle deceleration changes by the actual magnitude of the change in peak grip, which makes this parameter important for braking performance.

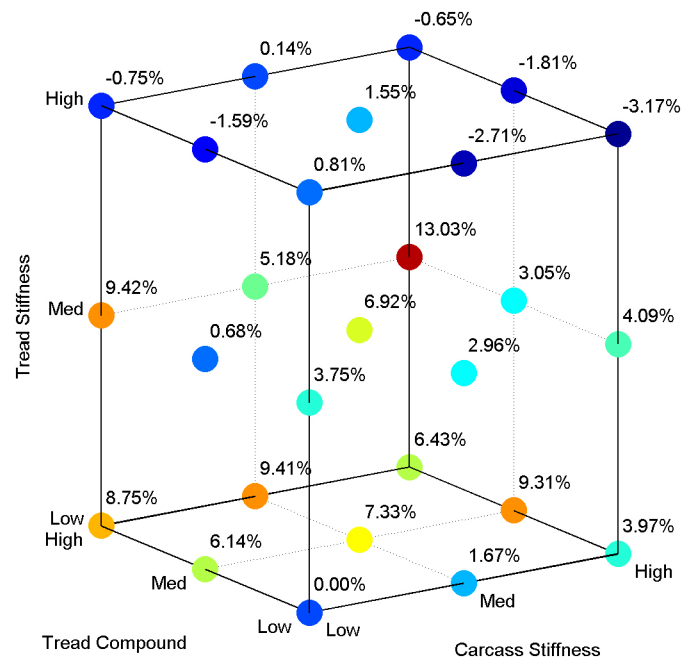


Figure 6. Variation of peak grip for different tire constructions at front axle load

[Figure 6](#) shows the variation of peak grip as influenced by tread compound, tread stiffness and carcass stiffness, computed from the longitudinal force versus slip curve of the tire obtained from braking skid trailer experiments. The following observations were made based on the results:

- It is observed that the change from low to high grip tread compound leads to a consistent increase in peak grip. This sensitivity is reduced at higher values of tread stiffness. This might be due to very low tread depth that reduce the effectiveness of a change in tread compound.
- Low values of peak grip were computed for tire constructions with high tread stiffness across all combinations of carcass stiffness and tread cap compound indicating that a worn tire would have less grip in comparison to a new tire.
- As expected, carcass stiffness does not show any conclusive effect on the peak grip of the tire.

Variation of Braking Stiffness

The braking stiffness can be expressed as the resultant stiffness from a combination of carcass stiffness and tread stiffness [8]:

$$\frac{1}{C_x} = \frac{1}{C_{cx}} + \frac{a}{C_{p\lambda}}$$

Where

C_x - Braking stiffness (linear slope around zero slip)

C_{cx} - Carcass stiffness (function of construction, belt package)

$C_{p\lambda}$ - Tread stiffness per unit length of contact patch (function of tread depth and cap compound)

a - Half of contact patch length (function of load)



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