Can Mathematics Make a Difference? Exploring Tire Troubles in NASCAR

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Abstract

The National Association for Stock Car Auto Racing (NASCAR) has experienced tire difficulties for many years, but the problem came to the forefront of the sport at the 2008 Brickyard 400 race in Indianapolis. After a few laps, tires literally disintegrated resulting in a substantial number of laps run under caution. Racing tires differ in design and construction from the tires on personal automobiles necessitating research and testing to create more durable racing tires. The Rapid Design Exploration and Optimization (RaDEO) project has used a parameterization modification of MSC/PATRAN to explore the design of both street and racing tires. In addition, the Society of Automobile Engineers (SAE) has demonstrated the power of mathematics by creating a tire test matrix to investigate multiple variables vital to NASCAR and street tire manufacturers. This article discusses the factors involved in the design of race tires and how mathematics in used in creating and evaluating the design of race tires.

Introduction

Trouble with tires has long plagued the National Association for Stock Car Auto Racing (NASCAR). Difficulties at various speedways across America have contributed to frustration among drivers and fans. Recently, tire mishaps came to the forefront of the racing league as well as sports commentary throughout the United States. At the 2008 Indianapolis Motor Speedway Brickyard 400 race, tires lasted only 12 laps, the equivalent of 30 miles instead of the normal 80 miles (32 laps). A record setting 52 of the 160 laps were run under caution due to the disintegration of tires[1]. Devoted fans of the race were displeased to say the least. With track capacity of approximately 350,000, attendance at the 2009 race was significantly low with an estimated 180,000 fans[2]. In addition, the Brickyard lost its sponsor of five years, Allstate, announcing after the race that it would not renew its contract with the Indianapolis Motor Speedway[3].

What happened?

The domino effect at the Indianapolis Motor Speedway could be attributed to increasing economic difficulties that have significantly impacted business and industry throughout the United States. However, the real problem stems from a mathematical error. Goodyear, the official tire producer for NASCAR, underestimated the current design of the car. The new heavier model placed additional stress on the right-side tires. At the 2008 Brickyard 400 race, the tires could not withstand the pressure, and as a result, they began to literally fall apart after a few short miles around the track[4].

The compound for racing tires varies and is dependent on the track surface, number and tightness of turns, and banking at the track[5]. In the case of the Indianapolis Motor Speedway, the track is a 2.5 mile oval with 9° turns and 0° straights which is among the least degree of banking for NASCAR tracks[6]. Depending on the tread compound, tires may provide more grip but wear faster. Additionally, the location of the tires (inside or outside) is also a factor related to wear. At the Brickyard, limited track banking, miscalculated tire compound, and added stress to the outside tires from the new car design was a precarious combination that ultimately lead to a less than favorable outcome of the race.

Race Tires vs. Street Tires

To a common bystander, the question is raised: what is the “big deal” about tires? If a personal automobile can withstand countless miles and adverse conditions, what is wrong with the tires in NASCAR? It is important to note the significant divergence between NASCAR racing tires and the tires on personal automobiles, often referred to as street tires. While the two types of tires are very different, the design is firmly grounded in mathematics.

On a typical race weekend, between nine and fourteen sets of tires are used based on the length of the race and type of track[7]. While this figure includes both qualification and the actual race, tires are changed approximately every 80 miles during a race. In the case of the 2008 Brickyard 400 race, the tires lasted only about 38% of the designated life span, resulting in at least thirteen changes per car. For the length of the Brickyard race, this is a statistically significant high number of tire changes for the track. In comparison, the average set of street tires is replaced approximately every 50,000 miles (see Table 1.1). Additionally, the cost of NASCAR tires can be as much as twice the price of a street tire[7]. Research, development, and testing of the NASCAR tires contribute to the high cost.

Table 1.1 Comparing Racing and Street Tires[7]

	Goodyear Eagle Racing Tire	**Goodyear Eagle Street Tire**
Estimated Cost	$380+ each	$150 – 200 each
Estimated Life	80 to 150 miles	50,000 miles
Weight	24 pounds	30 pounds
Tread Thickness	1/8 inch	3/8 inch

Unlike street tires, most NASCAR teams use nitrogen in tires because it contains less moisture than compressed air. As the tires heat up, they expand when moisture evaporates causing the tire pressure to increase. Because changes in tire pressure have a significant impact on the handling of the car, it is imperative for teams to use nitrogen for added control of tire pressure[5]. Street tires use compressed air as the tires do not reach the excessive speeds of NASCAR and therefore evaporation is not a significant problem.

Another noticeable difference between race tires and street tires is the composition and inflation of the tires (see Figures 1.1 and 1.2). For tracks in excess of one mile, speeds are notably faster and therefore additional tire safety precautions are required by NASCAR. An inner liner is necessary which is essentially a second tire mounted inside the outer tire[5]. If the outer tire blows, the inner tire is still intact, allowing the driver to bring the car to a controlled stop. Air pressure in the inner liners is required to be 12-25 pounds per square inch (psi) greater than the outer tires; for the technical inspection, left front and rear tires should be inflated to 26 psi with right front and rear inflated to 36 psi[8]. With respect to street cars, the inflation varies based on the type and purpose of the tire.

Figure 1.1 Race Tire Composition[9]

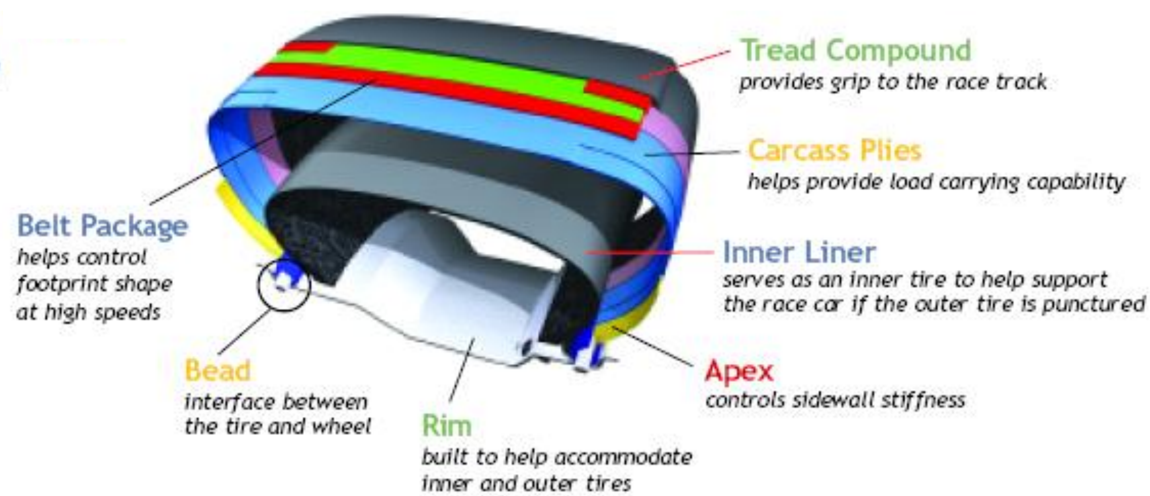
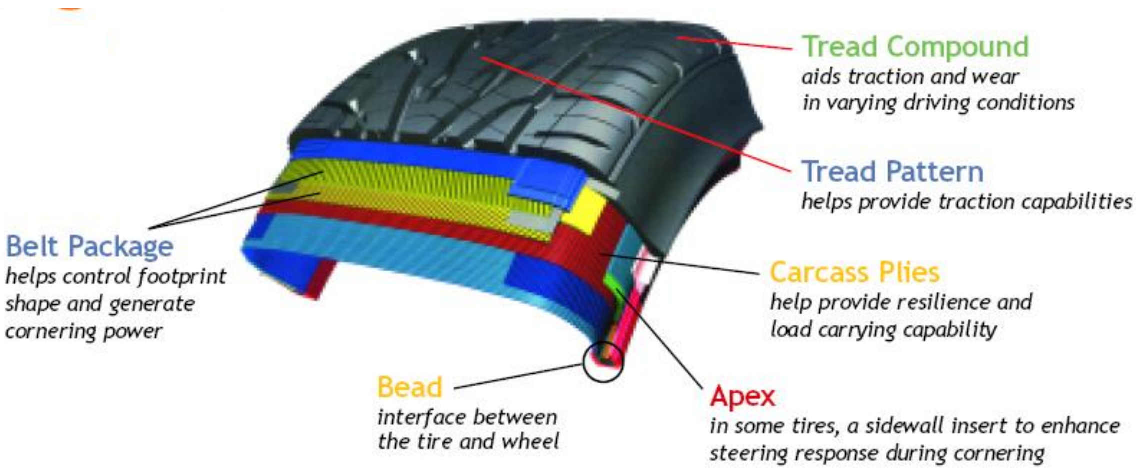


Figure 1.2 Street Tire Composition[9]



Race tires consist of a flat, smooth surface called racing slicks that increases adhesion to the race track, often referred to as grip. On a dry track, tires can generate additional traction if more of the tire rubber is in contact with the ground[5]. Therefore, racing slicks provide increased contact with the track surface. Obviously, this design is inappropriate for racing during rainy conditions as a tread pattern is important in wet weather. Street tires have treads designed to withstand significant changes in weather conditions. For additional grip, the width of racing tires is significantly greater than traditional street tires (see Figure 1.3). With the increase in width of approximately four inches per tire, a racing tire provides sixteen inches of additional contact with the track and added traction in comparison to traditional street tires.

Figure 1.3 Tire Surface in Race Tires and Street Tires[7]

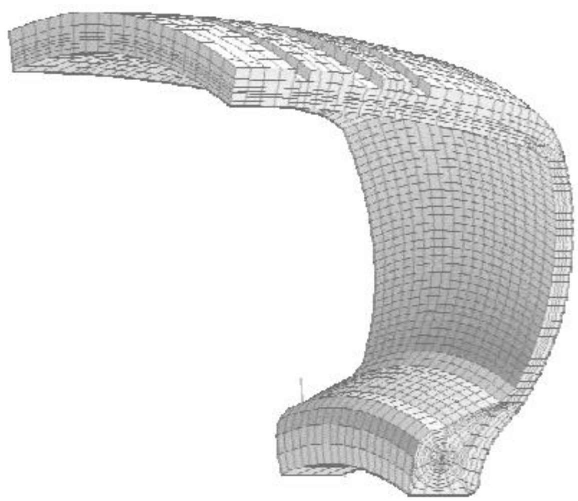
In addition to the width of the tire, the depth is also significant in NASCAR. For racing tires, the smooth surface does not react in the same manner as the grooves on street tires. In particular, the tires wear differently than traditional street tires. Due to these factors, the tread compound is paramount to successful tire wear and must include a carefully constructed mixture of rubber and polymer chemicals to give strength and durability while providing good grip on the track[10]. In the case of the Brickyard 400, the tire compound was inaccurately calculated resulting in the rapid disintegration of tires.

Mathematics is Making a Difference

While the majority of a car's components can be easily quantified, it can be difficult to describe tires in the same manner. As a result, research groups are now using mathematical modeling to explore tire conditions based on multiple variables. The Rapid Design Exploration and Optimization (RaDEO) project created an automated parametric analysis to explore complex design processes using computational resources. In conjunction with the Ford Motor Company, Rocketdyne, and the St. Louis divisions of Boeing Aircraft Company, this project used a parameterization modification of MSC/PATRAN to explore the design of a street tire. The modification permits the use of named variables to replace the usual fixed numerical values of the modeling parameters thus allowing the mathematical models to have multiple components called functional models[11]. The Robust Design Computational System (RDCS) computer program provides for automation of design processes including parametric design scanning. Specifically, the program depends on multi-disciplinary parametric math models that simulate the behavior of the object being designed.

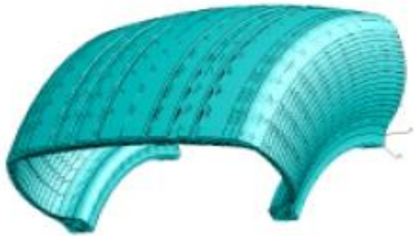
In the case of the rubber tire model, the exploration of a 30 degree sector of the tire consisted of parametric descriptions including tread, radial ply composites, bias steel belt composite, wire bead, rim cushion, bead wrap, filler, inner liner, and chafer. In addition, the mesh strategy and loading was parameterized to preserve sound modeling while making significant changes in the geometry of the materials as well as the overall tire size, variable inflation pressure, vehicle speed, and vehicle weight[11]. Figure 1.4 illustrates the model generated by the RDCS program.

Figure 1.4 Parametric Model of 30° Sector of a Rubber Tire[11]



In addition to creating a sector of the tire, the RDCS program can be adapted to create additional permutations of the base line design. The models shown in Figure 1.5 were based on the same session file but included changes in the variable parameter values. The RaDEO project has demonstrated ways in which mathematics can affect the tire design process resulting in better quality street and racing tires.

Figure 1.5 Permutations of the Base Line Design[11]



Default Street Tire

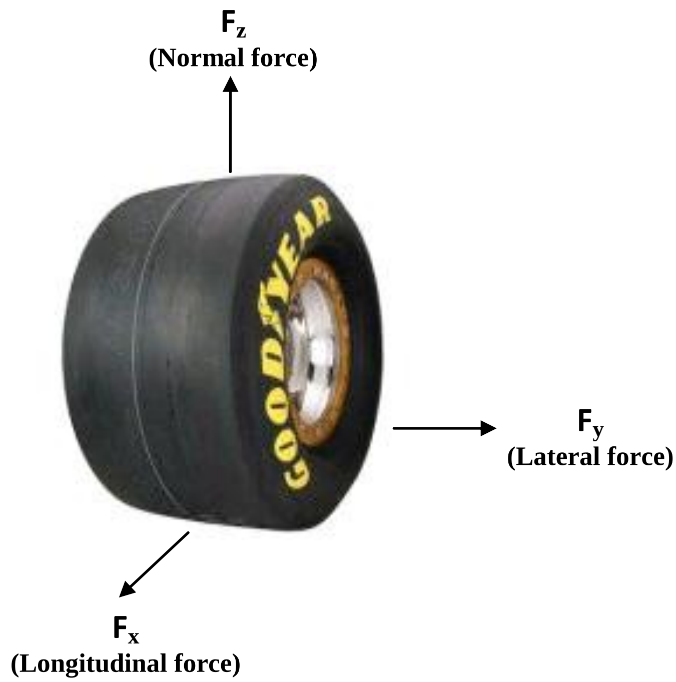
Racing Tire

The Society of Automobile Engineers (SAE) has also demonstrated the power of mathematics to impact tire design through the creation of a tire test matrix. Specific to racing tire research, the Formula SAE Tire Test Consortium (FSAE TTC) was established to provide high quality tire data to participating FSAE teams for use in the design and setup of their racecars. The Calspan Tire Research Facility (TIRF) uses a low capacity flat-belt tire test machine that was created through the inspiration of a machine first produced by Cornell Aeronautical Laboratories (CAL) in the 1960s[12]. This testing facility contracts with NASCAR as well as street tire manufacturers.

Directors of the consortium along with input from the Goodyear Tire Company developed a tire test matrix that included five main components: operating conditions, relevant parameters, Calspan TIRF machine capabilities and setup, budget/time constraints, and tire popularity and availability. Relevant parameters explored during testing included normal load, slip angle, inclination angle, slip ratio, inflation pressure, and roadway speed which was held constant. Of particular interest, another “parameter” incorporated before implementing the test matrix was the warm-up and condition of the new tire. The initial break-in of a new tire brings the tire up to temperature as well as works the tire in such a manner that the internal molecular crosslinks and various plies rearrange into their “used” condition[12]. This is considered the final major step in curing a tire and was completed prior to data collection.

Using the created matrix, tests were completed by the FSAE TTC to explore the interaction of parameters and collect relevant data on the tires. Graphical outputs were produced to illustrate the interaction between variables. Of particular interest were the outcomes for lateral and longitudinal force. It is important to note that three specific forces act on tires: normal force (F_z) or vertical load on the tire, longitudinal forces (F_x) or the forward and backward motion of the tire, and lateral forces (F_y) or the side-to-side movement of the tire (see Figure 1.7).

Figure 1.7 Forces Exerted on a Tire[13]



A miscalculation of force can be linked to faulty tire design and adversely impact tire performance including grip, deformation, and disintegration. For example, the longitudinal force exerted by a tire on the wheel at the contact point is given by a characteristic function *f* of the tire[14]. The components of this function include velocity, rolling radius, and slip which can significantly impact tire execution if plagued with mathematical errors.

Longitudinal Force:

$$F_x = f(\kappa', F_z)$$

where:
κ' is the contact patch slip ($-V'_{sx}/|V_x|$)
V_{sx} is the wheel slip velocity ($V_x - r_e\Omega$)
V'_{sx} is the contact point slip velocity ($V_x - r_e\Omega'$).
Wheel angular velocity (Ω)
Contact point angular velocity (Ω')
Effective rolling radius (r_e)

In the case of FSAE TTC tire tests, the relationship between lateral force and slip angle (angular difference between the rolling direction of the tire and plane of the wheel) as well as longitudinal force and slip ratio (locking status of the wheel) appear to be modeled by a cubic function. The correlation between longitudinal force and slip ratio can be related to a function in the form $f(x)=ax^3$, while the relationship between lateral force and slip angle are modeled as the reflection in the form $f(x)=-ax^3$ (see Figures 1.8 and 1.9).

Figure 1.8 Analysis of Typical Lateral Force vs. Slip Angle[12]

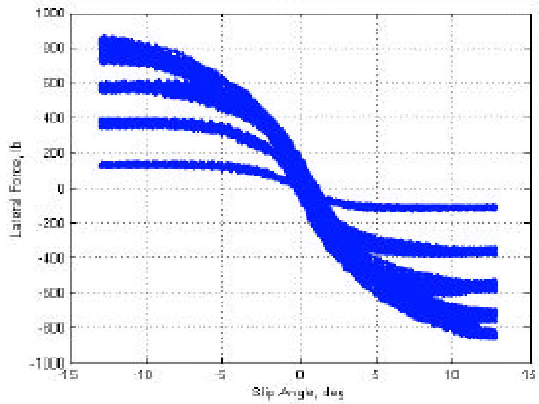
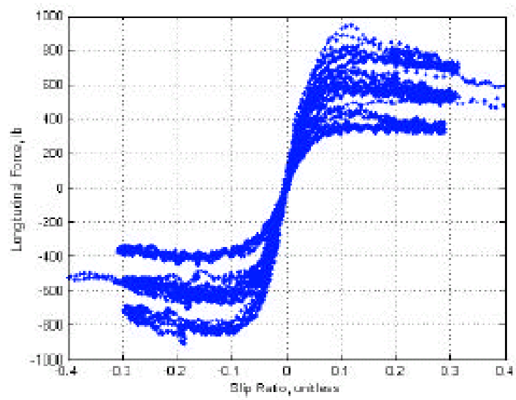


Figure 1.9 Analysis of Typical Longitudinal Force vs. Slip Ratio[12]



Slip angle and ratio are particularly significant in racing tires. Specifically, in NASCAR, if the turning force goes above the normal slip angle (about two to four degrees), the tires may skid too much and cause a lack of control[15]. The graphics from the FSAE TTC tire tests illustrate that a decrease in lateral force results as the slip angle increases and an increase in longitudinal force occurs as the slip ratio decreases. Of additional interest, the longitudinal force (F_x) is approximately proportional to the vertical load (F_z) due to lateral force (F_x) generated by contact friction and the normal force (F_z)[14]. The relationship is considered somewhat nonlinear due to tire deformation and slip.

Problem Resolved? Looking Towards the Future

Goodyear and NASCAR believe tire difficulties have been resolved as evidenced by the smooth running of the Brickyard 400 in 2009. Tire problems that plagued the track only one year earlier were unnoticeable with a limited number of cautions and normal pit stops throughout the race. After eleven months of research and testing, it certainly appears Goodyear found the right compound for the racing tires[16].

As NASCAR continues to evolve, running races under adverse weather conditions could be a possibility for the future. Currently, NASCAR suspends racing in the Sprint Cup series for rain as the tire tread and compound is not conducive to racing on a wet track. However, in other NASCAR affiliated series, races have been attempted during light precipitation. Most recently, part of qualifying and the final laps of the Nationwide series (considered the minor league of the Sprint Cup) were held on Sunday, August 30, 2009 during rain. While the final laps provided great excitement for spectators, some drivers are reluctant to drive in the rain when the cars are not fully equipped for the changing weather conditions[17]. It is evident that additional research is needed to provide a safe and reasonable driving experience. The question must be asked: can mathematics make the difference?

1. N. Ryan, Goodyear, Brickyard Try to Put Bad Tires in Rearview Mirror, USA Today. (2009), available at: http://www.usatoday.com/sports/motor/nascar/2009-07-23-brickyard-goodyear-tires_N.htm
2. E. Berman, Attendance Visibly Lower at 2009 Brickyard 400. Emmis Interactive, Indiana. (2009), available at: http://www.wibc.com/news/Story.aspx?id=1119359
3. Associated Press, *Allstate Not Returning as Sponsor for Brickyard 400*. (2009a), available at: http://www.nascar.com/2009/news/business/07/28/allstate.not.returning.to.indianapolis/index.html
4. J. Fryer, Goodyear Goofed, but NASCAR blew it on Brickyard Tire Problems, Hearst Seattle Media, LLC. (2009), available at: http://www.seattlepi.com/motorsports/372571_autos29.html
5. K. Nice, How NASCAR Race Cars Work, How Stuff Works Inc., A Discovery Company. (2009), available at: http://auto.howstuffworks.com/auto-racing/nascar/nascarbasics/nascar5.htm
6. NASCARBet. NASCAR Race Track. (2009), available at: http://www.nascarbet.com/nascar-race-track_1.html
7. NASCAR.com, Race Tires vs. Street Tires, Turner Sports Interactive, Inc. (2009), available at: http://www.nascar.com/news/features/tires/index.html
8. Goodyear Racing, Fast Facts for July 24-26, 2009, The Goodyear Tire & Rubber Company. (2009), available at: http://www.racegoodyear.com/news/072409.html
9. Goodyear Global Communications, Goodyear 2009 Racing Media Kit. (2009), available at: http://www.racegoodyear.com/pdf/2009GoodyearPress.pdf
10. J. Briggs, How NASCAR Tire Technology Works. How Stuff Works Inc., A Discovery Company. (2009), available at: http://auto.howstuffworks.com/auto-racing/nascar/nascar-basics/nascar-tire.htm/printable
11. J. G. Crose, D. A. Marx, M. Kranz, P. Olson, & C. Ball, Parametric Design/Analysis with MSC/PATRAN – A New Capability, The MacNeal-Schwendler Corportation. (n.d.), available at: http://www.civl.port.ac.uk/FEM/CALFEM/parametric_design.pdf
12. E. M. Kasprzak, & D. Gentz, The Formula SAE Tire Test Consortium – Tire Testing and Data Handling, Society of Automotive Engineers, Inc. (2006), available at: http://www.millikenresearch.com/TTC_SAE_paper.pdf
13. B. Volk, Tires – Cars, Trucks, You Name It, AOL. (2009), available at http://shopping.aol.com/articles/2009/09/17/tires/
14. SimDriveline, Vehicle Components: Tire, The MathWorks, Inc. (2009), available at: http://www.mathworks.com/access/helpdesk/help/toolbox/physmod/drive/index.html?/access/helpdesk/help/toolbox/physmod/drive/tire.html
15. C. Neiger, Why Doesn't NASCAR Race in the Rain? How Stuff Works Inc., A Discovery Company, (2009), available at: http://auto.howstuffworks.com/auto-racing/nascar/nascar-basics/nascar-rain.htm
16. Associated Press, Jimmie Johnson Becomes Three-time Winner at Brickyard, WorldNow & WTHR. (2009b), available at: http://www.wthr.com/Global/story.asp?S=10791585
17. D. Caraviello, Montreal '08 Gives Some Hope for Cup Race in Rain, Turner Interactive Sports, Inc. (2009), available at: http://www.nascar.com/2009/news/headlines/cup/08/27/montreal.race.rain/index.html?eref=/rss/news/headlines/cup

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