CURRENT RESEARCH IN AIRCRAFT TIRE DESIGN AND PERFORMANCE

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SUMMARY

A review of the NASA experimental and analytical tire research programs which address the various needs identified by landing gear designers and airplane users is presented in this paper. The experimental programs are designed to increase tire tread lifetimes, relate static and dynamic tire properties, establish the tire hydroplaning spin-up speed, study gear response to tire failures, and define tire temperature profiles during taxi, braking and cornering operations. The analytical programs are aimed at providing insights into the mechanisms of heat generation in rolling tires and developing the tools necessary to streamline the tire design process and to aid in the analysis of landing gear problems.

INTRODUCTION

For many years tire researchers at Langley have maintained a close working relationship with the aircraft landing gear community, namely, the airframe manufacturers and the airline operators. This relationship has allowed NASA to keep abreast of constantly changing tire research needs and to adjust its program priorities accordingly. Recent inputs from various sources have indicated that research is needed to (1) improve tire lifetimes both in terms of reduced tread wear and greater blowout resistance; (2) solve such landing gear dynamic problems as shimmy, gear walk, truck pitching, and braking and cornering performance in adverse weather; and (3) streamline the tire design process. NASA currently has several research programs underway to address these needs and the purpose of this paper is to present a status report on these activities and to provide some indication as to the direction of future research efforts.

TREAD WEAR

Tire replacement due to tread wear is a major safety and economic concern of airline operators. For this reason, NASA has since the early 1970's (refs. 1 to 3) been involved in a program to examine the effects of tire tread wear attributed to the various ground operations of an airplane. In addition, attempts are underway to develop new elastomeric materials which would provide improved tire tread wear and blowout resistance without degrading traction characteristics. For the purpose of this program, braking and cornering tests are being conducted on specially-prepared test tires using the instrumented vehicle shown in figure 1. The main feature of this vehicle is the test fixture which is cantilevered from the rear of the truck and supports the test tire. For braking tests at fixed slip ratios the test tire and wheel assembly is driven through a universal coupling by interchangeable gears, which in turn are chain-driven by a driving wheel on the truck. Changing the slip ratio entails merely changing the gears in the drive unit and in this program the slip ratios are being varied from 0% to 50%. For cornering tests the universal coupling is disconnected and the fixture is rotated to the desired steering or yaw angle and clamped in place. Yaw angles to 25-degrees are being evaluated. The braking tests are being conducted on both asphalt and concrete runway surfaces, but the cornering tests are being limited to a relatively smooth asphalt surface.

A sample of the wear, friction, and temperature data obtained during this test program is presented in figure 2. These data are for size 22 × 5.5, type VII, 12-ply rating aircraft tires which had been retreaded with four different elastomers whose compositions were as follows:

Elastomer	Composition
A	100% natural rubber
B	75% natural rubber and 25% cis-polybutadiene
C	75% natural rubber and 25% vinyl-polybutadiene
D	75% natural rubber and 25% trans-polypentenemer

Elastomer A was tested because natural rubber has been considered the elastomer best suited to meet the tire requirements for supersonic transport-type aircraft. Elastomer B comprises a stock representative of the current state-of-the-art treads for jet transports, and elastomers C and D are experimental blends developed specifically for this program. A fifth experimental elastomer which consists of a tri-blend of natural rubber, cis-polybutadiene, and vinyl-polybutadiene, is currently being evaluated. Presented on the left of figure 2 are plots of the tire wear rate as a function of the slip ratio from the braking tests and yaw angle from the cornering tests; a lower wear rate indicates a longer tire tread life. The data indicate that the 100-percent natural rubber tread (elastomer A) has the highest wear rate and the state-of-the-art tread (elastomer B) has the lowest wear rate of the elastomers tested to date. Treads fabricated from the two experimental elastomers had similar wear characteristics but neither had a wear resistance as good as the present state-of-the-art elastomer. Other characteristics of the experimental treads such as heat buildup, cut growth, and heat blowout resistance could, however, tip the balance in favor of one of the experimental elastomers for some applications. It is apparent from the figure that extended operations at high slip ratios and/or high yaw angles significantly shorten tread life for all tread materials.

While experimenting with the composition of the tire tread to improve its wear characteristics it is important that the tire friction capabilities not be compromised. The friction measurements obtained from the various tires in either the braking or cornering modes are faired by a single curve in figure 2, thereby suggesting that the various tread elastomers studied to date do not significantly affect the tire friction performance.

Also presented in figure 2 are the maximum tread temperatures as obtained from an optical pyrometer mounted on the tire fixture which continuously monitored the tread temperature of a point on the rotating tire approximately 3/8 of a revolution out of the footprint. Tread temperatures were observed to be independent of the elastomer and the figure shows that this temperature increases with increasing slip ratio and increasing yaw angle.

STATIC AND ROLLING TIRE BEHAVIOR

NASA research on static and rolling behavioral characteristics of the pneumatic aircraft tire is concerned with studies of gear response to tire failures (blowouts); tire carcass temperatures during various aircraft ground operations; wet runway friction/hydroplaning; and certain key tire mechanical properties. The following paragraphs briefly discuss each of these planned or on-going programs.

Gear Response to Tire Failures

The need for a study of landing gear response to tire failures has become more critical in recent years due to the increasing number of tire failures experienced by the wide-body airplane fleet. A tentative test matrix has been outlined for a NASA program which calls for studies of the friction forces developed by deflated (blown) tires and by wheels rolling on rims; an assessment of debris trajectory patterns associated with tire blowouts; and the response of the strut, antiskid braking system, and the demands placed on the nose gear steering system following a main gear tire failure. A planning session has been scheduled with representatives from airline, tire, and other aviation industries and interested government agencies to finalize the test matrix and testing will probably commence in mid-1981.

Tire Carcass Temperatures

The generation of heat in aircraft tires is undergoing study to determine the temperature profiles which are necessary to define the strength and fatigue limitations of the tire carcass structure. Both experimental and analytical efforts are currently underway in this study. The experimental tests are being carried out on size 22 × 5.5 aircraft tires and the test vehicle is the same instrumented truck shown in figure 1. For these tests, the tires are equipped with a number of thermocouples located within the tire carcass on one side of the tire centerline as illustrated in the schematic of figure 3. A photograph of one such tire installed on the test vehicle is presented in figure 4 which also shows the modified hub and slip ring assembly for transmitting the thermocouple signals to the on-board recording equipment. Temperature data are being acquired while the tire is operated under free-rolling, light-braking, and yawed-rolling conditions. Since only one side of each tire is instrumented, symmetry is presumed about the tire centerline for free-rolling and light-braking conditions. For yawed rolling conditions, tests are run at yaw angles of equal magnitude on either side of 0^{0} to account for any asymmetrical heating conditions. Typical results from the free-rolling tests are presented in figure 5 which shows the carcass temperature profiles of a test tire after travelling distances of 1500 m, 3000 m, and 4500 m at a ground speed of 17 knots. The data indicate that the hottest portions of the tire carcass are beneath the tread near the shoulder area and along the inner surface of the sidewall.

The analytical effort to model the heat generation mechanisms within an aircraft tire is being conducted at the University of Michigan under a NASA grant. The model employs an assembly of finite elements to represent the tire cross section and treats the heat generated within the tire as a function of the strain energy associated with the predicted tire flexure.

Figure 6 presents a comparison between the experimental data and the results from a preliminary analysis performed on a free-rolling tire. The figure shows the temperature rise as a function of time as measured and calculated at two thermocouple positions for two tire deflection conditions. The thermocouple positions include the inner and outer surface of the tire sidewall near the bead, and their positions are denoted on figure 3 by asterisks. The data presented in figure 6 show good agreement between the experimental and the calculated temperature rises. Current analytical work is aimed at refining the strain energy terms in the model to provide even closer agreement in the free-rolling case and to address the braking and cornering cases.

Wet Runway Friction/Hydroplaning

For many years the Langley Research Center has been associated with friction and hydroplaning research. (See refs. 4 and 5 for examples.) As a result of these early research efforts, the critical hydroplaning speed at which the tire begins to spin down when water is encountered on the runway has been well established. These early tests also indicated that a speed reduction to a second, lower critical speed is necessary to allow the tire to spin up again, but this critical hydroplaning spin-up speed has not been well documented. Tests are currently underway on the Langley Landing-Loads Track to establish the speed reduction necessary to allow tire spin-up, and to measure the hydrodynamic pressures within the footprint.

Tire Mechanical Properties

NASA's continuing investigation of tire mechanical properties (refs. 6 and 7 are typical of earlier work in this area) was recently expanded to support a program sponsored by the Society of Automotive Engineers (SAE) to measure both the static and dynamic properties of two sizes of modern aircraft tires. Data were generated using 49 × 17 and 18 × 5.5, type VII tires and provided some insight into the relationship of certain static and dynamic tire properties. An example is shown in figure 7, which presents the lateral spring rates determined from static and dynamic tests performed on a 49 × 17 size tire. The key to relating the static and dynamic data lies in the interpretation of static load-deflection curves similar to the one sketched in figure 7. As will be noted, tire static load-deflection curves generate a substantial hysteresis loop. It has been customary to assign a single value to the tire spring rate and generally, as in references 6 and 8, this rate was defined by the slope of the line which connected the loop extremes. Unfortunately, these spring rates were always lower than those obtained during dynamic tests. Observations from the SAE test program suggested that two spring rates would be more representative of tire response to static loadings. One rate would be the slope of the loading portion of the static hysteresis loop and the other rate would be defined by the initial slope of the load relaxation curve following attainment of the peak static load. Both of these rates and that obtained from dynamic (free vibration) tests are presented in figure 7. The figure suggests that the two statically determined rates define an envelope which would include all the possible spring rates obtained under dynamic loading conditions, with the lower bound of the envelope defined by the static loading curve and the upper bound defined by the initial static relaxation curve.

ANALYTICAL TIRE MODEL DEVELOPMENT

NASA is developing a family of analytical tire models which will be useful in tire design and landing gear analysis. This is a joint venture between NASA, the College of William and Mary, and George Washington University. The approach being taken is to use finite elements based on nonlinear shell theory (refs. 9 and 10). The shell theory is limited to small strains but can handle anisotropic, nonhomogeneous, elastic material characteristics; bending extensional coupling; large deformations; and moderate rotations. To date two quadrilateral shell finite-element models have been developed which feature the use of a reduced-basis solution algorithm and automatic selection of load or displacement incrementation (refs. 11 and 12). One model is a 16-node finite element based upon the displacement formulation and the second model is a finite element based upon a mixed formulation with 9 nodes along the periphery where displacements are the fundamental unknowns and 4 internal nodes where the stress resultants are the unknowns. For the mixed formulation the internal stress resultants are discontinuous across the interelement boundaries and the stress parameters and their path derivatives are eliminated on the element level. The performance of these two shell tire models is being verified by applying inflation pressure loads. Typical results from these verification studies are presented in figure 8 for a 10-ply tire of elliptical cross section mounted on a rigid wheel. A schematic of the model cross section is presented on the left of the figure. Also presented in the figure is a plot of the pressure load against the crown displacement of the tire illustrating the hardening spring characteristic of the tire. The drawing of the uninflated and inflated tire model geometries are shown to scale and illustrate the large deformations associated with this simple loading system.

Future work in tire analytical model development will be concentrated in the major areas of material characterization, modeling techniques, and load determination. In the area of material characterization the next effort will be aimed at the extension of the current linear elastic material model to includ the nonlinear effects of viscoelastic material behavior. This effort will also include studies of the effects of elevated temperature on the material strength and its mechanical properties. Modeling techniques in the future will include rational approximations to the comprehensive nonlinear shell theory and solution algorithm refinements that reduce computer costs while maintaining solution accuracy. Future loading systems imposed upon the model will be consistent with studies of the tire/runway contact problem, the inclusion of braking and cornering forces, and the investigation of the dynamic effects of rolling.

The importance of the analytical tire model development program can best be expressed in terms of its anticipated applications. A mature family of tire models should furnish a means of streamlining new tire development and qualification procedures. Furthermore, these analytical tools should be able to predict tire failure modes during the design phase so that appropriate steps can be taken to prevent undue tire failures during aircraft ground operations. The family of tire models should provide the means of solving such landing gear dynamic problems as wheel shimmy, truck pitching, and gear walk. Eventually these models could provide the information necessary to tailor the mechanical properties of aircraft tires to make them more compatible with aircraft antiskid braking and nose gear steering systems and, thereby, optimize the ground handling capability of modern aircraft.

CONCLUDING REMARKS

Langley Research Center is conducting both experimental and analytical tire research programs to address the various needs identified by the landing gear designers and the airplane users. The experimental programs are designed to increase tire tread lifetimes, relate static and dynamic tire properties, establish the tire hydroplaning spin-up speed, study gear response to tire failures, and define tire temperature profiles during taxi, braking and cornering operations. The analytical programs are aimed at providing insights into the mechanisms of heat generation in rolling tires and developing the tools necessary to streamline the tire design process and to aid in the analysis of landing gear problems.

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Figure 1.- Instrumented test vehicle.

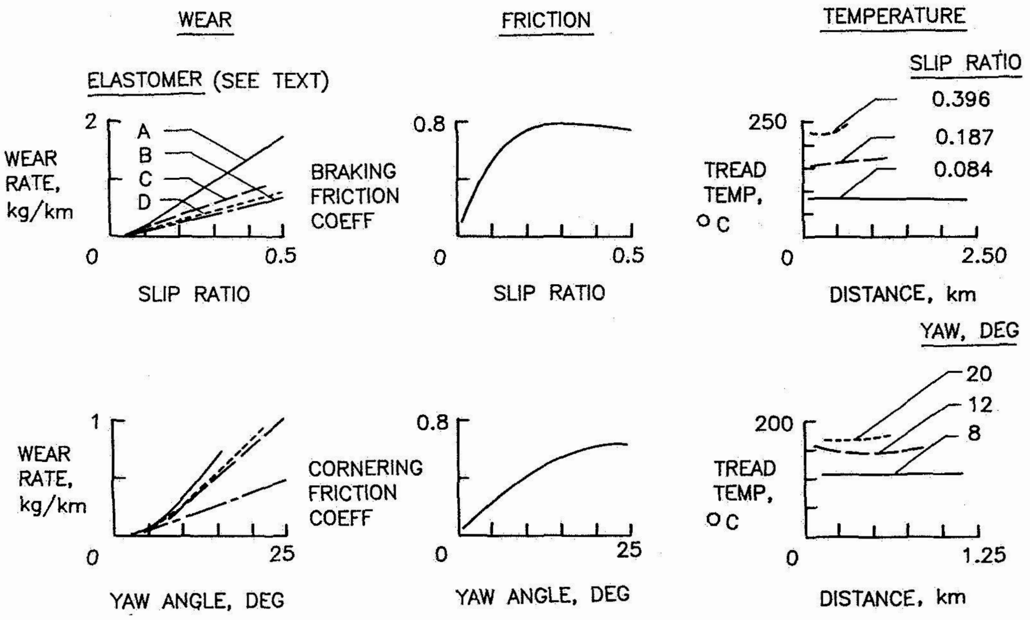
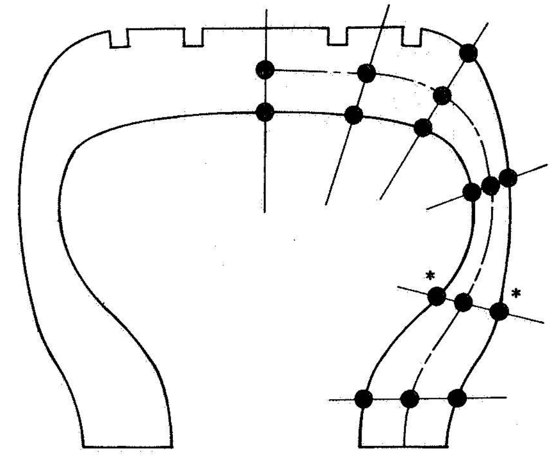


Figure 2.- Wear, friction, and temperature characteristics of a size 22 × 5.5 tire on a smooth asphalt surface.



*: DATA FROM THESE THERMOCOUPLES COMPARED WITH MODEL PREDICTIONS

Figure 3.- Location of thermocouples in tire carcass.

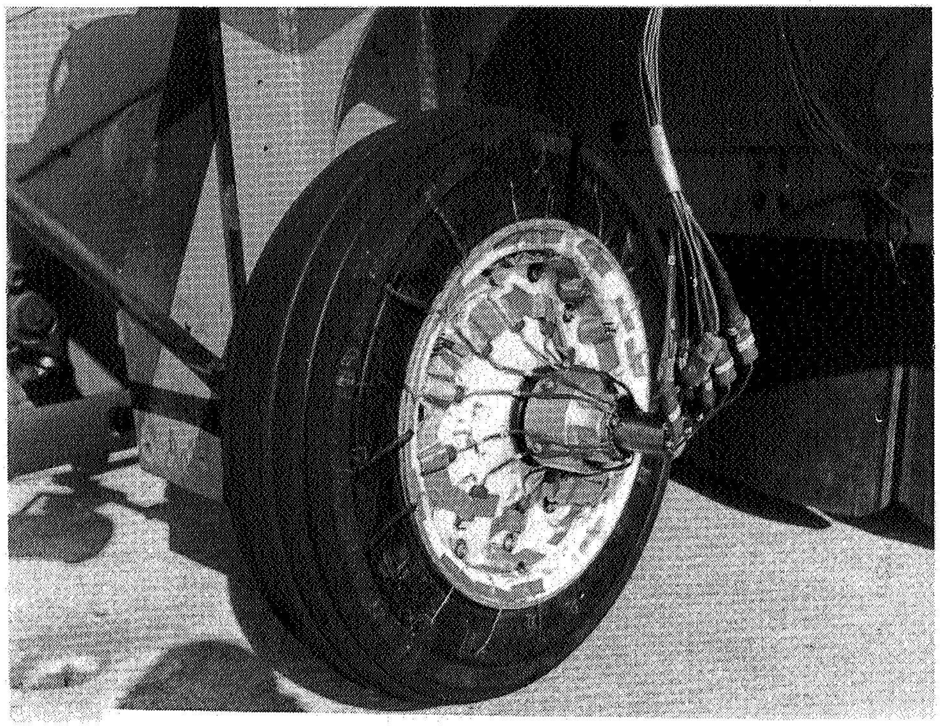


Figure 4.- Size 22 × 5.5 test tire with thermocouples installed.

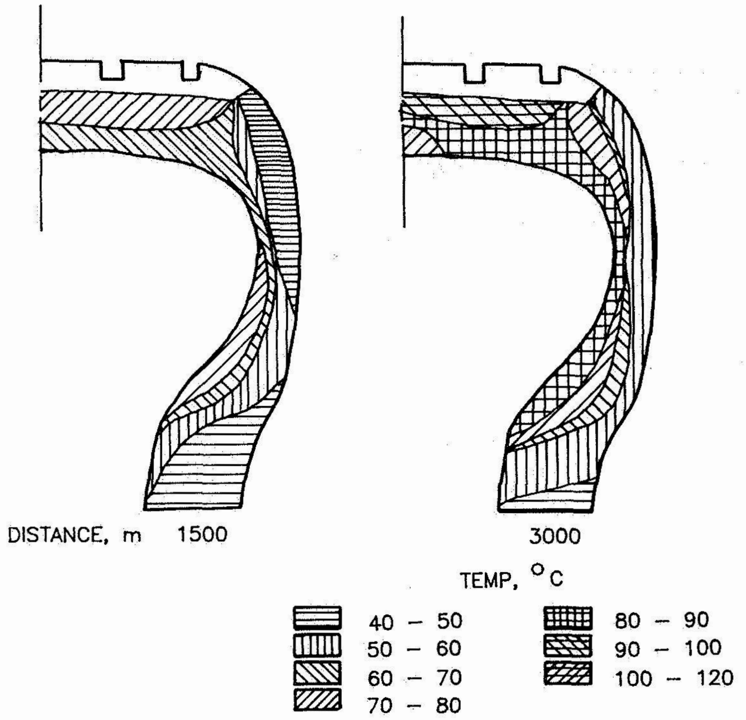


Figure 5.- Temperature profiles during free roll. 22 × 5.5, 12-ply tire; ground speed, 17 knots.

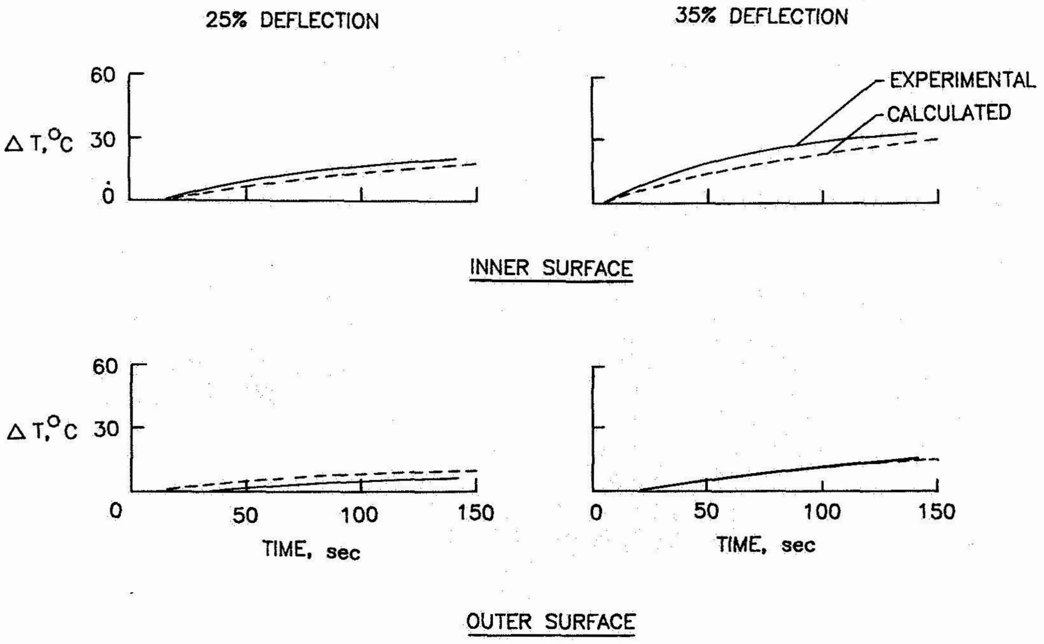


Figure 6.- Comparison of experimental and calculated temperature rise. 22 × 5.5 tire; ground speed, 17 knots.

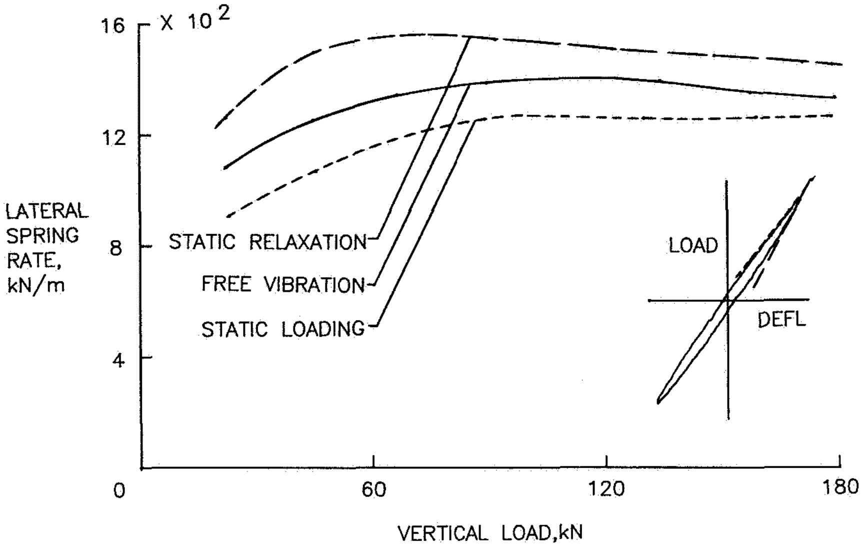


Figure 7.- Comparison of static and dynamic lateral tire spring rates for a 49 × 17 tire.

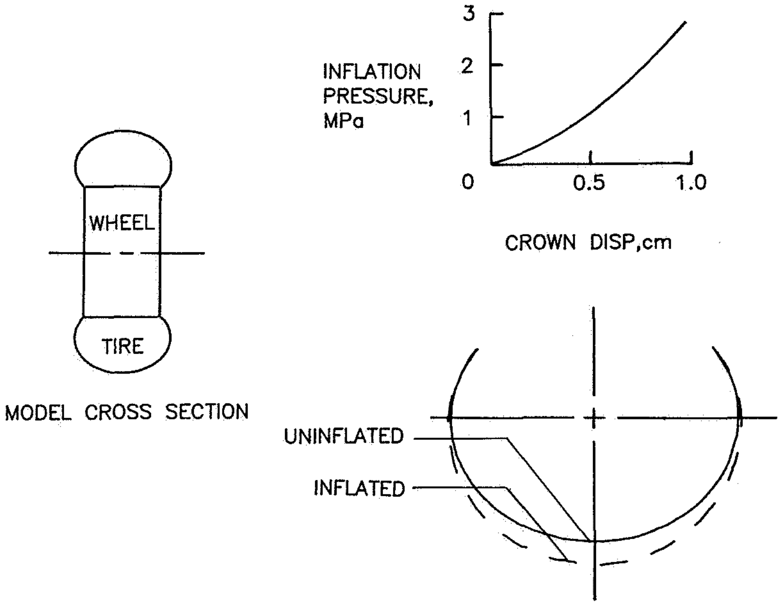


Figure 8.- Typical model results. 10-ply elliptical tire on a rigid wheel.