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3 authors:

Vasiliy V Krivtsov
The Ford Motor Company

Dmitry Tananko
General Dynamics

Tim Davis
The University of Warwick

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Regression approach to tire reliability analysis

V.V. Krivtsov*, D.E. Tananko, T.P. Davis

Ford Motor Company, MD 412/PDC, 20901 Oakwood Blvd, Dearborn, MI 48121-2053, USA

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Abstract

The paper considers an empirical approach to the root-cause analysis of a certain kind of automobile tire failure. Tire life data are obtained from a laboratory test, which is developed to duplicate field failures. A number of parameters related to tire geometry and physical properties are selected as explanatory variables that potentially affect a tire's life on test. Analysis of the life test data is performed via the Cox survival regression model. The paper also elaborates on the application of an ordinary (non-survival) linear regression to modeling the failure initiation and propagation. The developed statistical models help to identify the elements of tire design affecting the probability of tire failure due to the failure mode in question. © 2002 Published by Elsevier Science Ltd.

Keywords: Reliability; Hazard; Survival regression; Multiple regression

1. Introduction

By the design intention, an automobile tire should exhibit no failures during its useful life and/or while the tread depth is still adequate. However, some tires do fail prematurely. There are several kinds of failure modes observed in the field. This paper focuses on a particular failure mode known as tread and belt separation (TBS). In the event of TBS, the whole (or a part of the) tread and the second (upper) steel belt leave the tire carcass and the first (lower) steel belt (see Fig. 1). Usually, this failure occurs at highway speeds, so pieces of tread produce local damage to the vehicle body. More importantly, the rubber between steel belts (whose durability characteristics differ from those of tread material) becomes exposed to the road surface. This failure mode can affect lateral stability of the vehicle and may lead to an accident.

TBS type of tire failure can be postulated as a stochastic event when tire capacity (characterized by its geometry and material properties) is exceeded by the demand made on the tire through its use (inflation pressure, radial load, and linear speed). From the standpoint of mechanical engineering, a tire is a complex physical system, the capacity and performance of which are characterized by highly non-linear viscoelastic material properties, complex geometry, dynamic phenomena, etc. When exposed in the field, the tire is subjected to a multi-dimensional stress (demand) vector. Both capacity and demand variables are subject to considerable variability and change over time and mileage. All these circumstances complicate a purely analytical approach to the field-failure root-cause analysis and stimulate the use of empirical (regression) methods.

2. Engineering hypothesis

One could consider TBS as a sequence of two events: failure crack initiation in the wedge area (which usually starts as a 'pocketing' at the edge of the second belt) followed by the crack propagation between the belts. Finite element analysis of tire geometry [1] suggests that the largest strain occurs in the wedge area (see Fig. 1) and is proportional to the wedge gauge. Moreover, the location of the wedge is critical to heat dissipation.

While a small wedge encourages crack initiation, it is not itself a sufficient condition for TBS to occur. In order to propagate further, the crack must have favorable conditions, e.g. low adhesion strength between belts and the proper energy input to separate the belts. These characteristics depend on physical, chemical, and mechanical properties of the rubber skim stock as well as the age of the tire. Hence, the following tire design characteristics have been selected as explanatory variables (covariates) that could potentially affect the tire's life until the TBS failure:

* Corresponding author. Tel./Fax: +1-313-323-8711.
E-mail address: vkrivtso@ford.com (V.V. Krivtsov).

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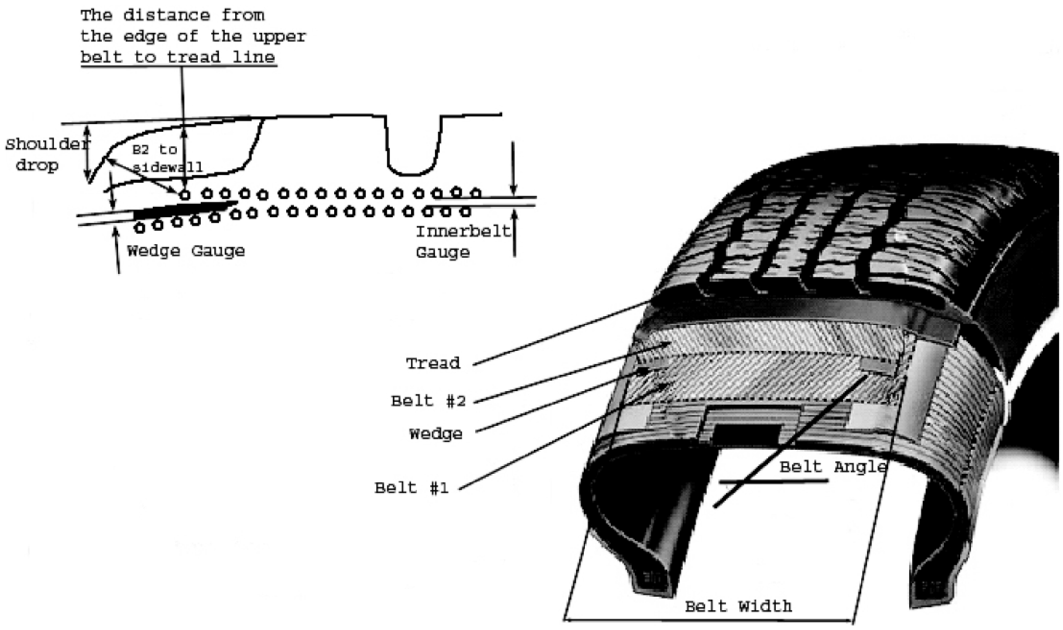

Fig. 1. Elements of radial tire.

- tire age
- wedge gauge
- interbelt gauge
- end of belt #2 to buttress
- peel force (adhesion force of rubber between steel belts, characterized as the force required to separate belts in the specimen of a given dimension)
- percent of carbon black (a chemical ingredient of the rubber affecting its mechanical characteristics, such as *tear resistance*).

Field failure data turn out to be insufficient for the construction of a tire reliability model with explanatory variables. While the survival times can be estimated and even censoring can be properly accounted for [2], the data on the above-defined covariates are difficult to obtain because of the disintegration of the tire as a result of TBS. In order to overcome this problem and duplicate field failures in controlled conditions, a special laboratory test has been developed.

3. Life test procedure

The laboratory study was performed on a mixture of new and field-exposed 15 in. radial tires manufactured at different plants. The testing was conducted on a dynamometer drum with monotonically increasing speed steps, at 100 °F, under the inflation pressure of 26 psi. Because of high variability in tire life, the testing procedure involved loads of 1300 and 1500 lb; i.e. for the tires that did not fail under the lower load, the higher load was applied. The test procedure consisted of three parts (see Fig. 2):

- warm up over 2 h at 50 mph
- cool down over 2 h at full stop
- in the 1300 lb regime: speed steps starting at 75 mph and increasing by 5 mph every half-hour till 90 mph and then every hour till failure
- in the 1500 lb regime: all the above speed steps are of half-hour duration

The test procedure above is a modification of the

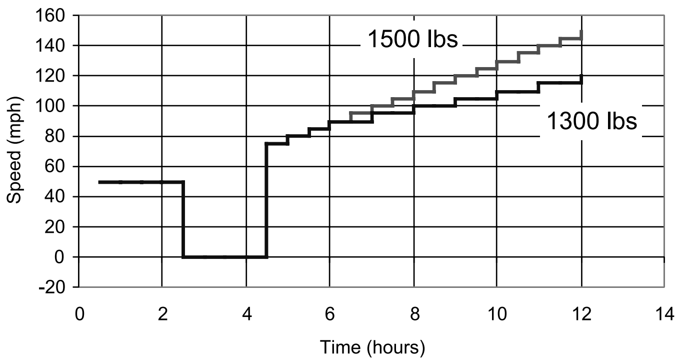

Fig. 2. Test speed profiles.

high-speed drum test, which is widely used in the tire industry as an accelerated key life test to identify potential failure modes, compare different designs, and validate design changes.

Several different failure modes can be observed during this test. Some of them are accompanied by detachment of the large chunks of material and even full disassembling of the tread and/or belt(s). To overcome the contradiction between the destructive nature of the test and the need to properly measure geometry and material properties of the tire, a special failure warning system has been developed [3]. The main idea of this system is based on the fact that the internal crack must be developed inside the tire prior to its catastrophic failure. As a result of centrifugal forces at high speed, the large chunk of material lifts up at the crack location, which accompanied by further crack growth, then leads to a change of the tire eccentricity. Therefore, the vibration signature of the rotating tire can be used for early detection of the failure.

The failure warning system involves specially mounted accelerometers and a PC-based data acquisition system. A signal to stop the test is generated when the system senses the change in the tire's vibration pattern (at the first vertical line in Fig. 3). If the test is not stopped, it leads to a full TBS separation. The associated time to partial TBS is thus equalized with that of full TBS for data analysis purposes.

The partially disintegrated tire is then conveniently available for further tests to properly measure the mechanical, physical, and chemical covariates.

4. Survival regression and data analysis

The proportional hazard model [4] offers a physically meaningful way of relating the life characteristic of an item to the vector of explanatory variables. According to this model

$$h(t,z) = h_0(t)\exp(\beta^{\mathrm{T}} z)$$

where t is the time to failure (TTF), $h(t,z)$ is the hazard rate, contingent on a particular covariate vector (of explanatory variables) z, $h_0(t)$ is the baseline hazard rate (when all explanatory variables are equal to zero), β^{T} is the transposed vector of regression coefficients.

The advantage of the Cox model over parametric survival regression models is that it does not make any assumption about the nature or the shape of the underlying survival distribution, thus reducing the uncertainty about model selection. The statistical estimation of the Cox model parameters is possible through maximization of the simplified partial likelihood function [5].

All covariates identified in Section 2 and included in the model have been checked for statistical independence and lack of autocorrelation. Failure time associated with competing failure modes (other than TBS) have been treated as censored responses.

In order to account for the difference in speed profiles between the two loads cases, the survival variable has been transformed from TTF to equivalent virtual work done against the tire until the failure, that is

$$W = LS,$$

where L is load against the tire, and S is the mileage

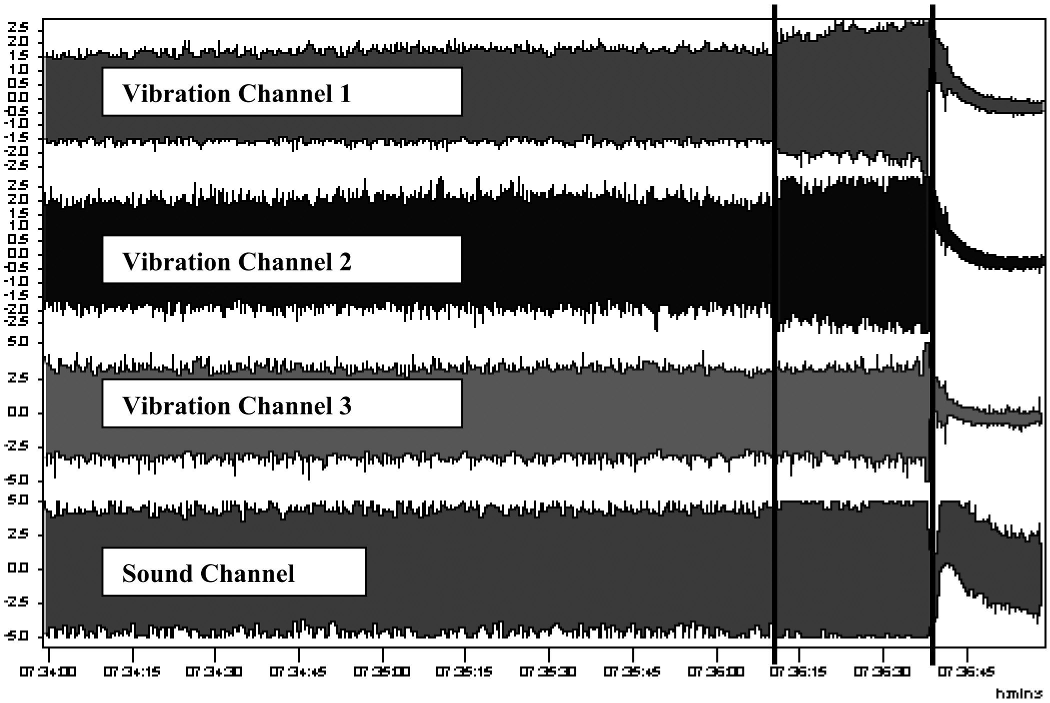

Fig. 3. Vibration and sound pattern of tire before TBS event.

Table 1
Test data set used in proportional hazard analysis

Tire age	Wedge gauge	Interbelt gauge	EB2B	Peel force	Carbon black (%)	Wedge gauge × peel force	Survival	Censoring (1-compl, 0-cens)
1.22	0.81	0.88	1.07	0.63	1.02	0.46	1.02	0
1.19	0.69	0.77	0.92	0.68	1.02	0.43	1.05	1
0.93	0.77	1.01	1.11	0.72	0.99	0.49	1.22	0
0.85	0.80	0.57	0.98	0.75	1.00	0.42	1.17	1
0.85	0.85	1.26	1.03	0.70	1.02	0.64	1.09	0
0.91	0.89	0.94	1.00	0.77	1.03	0.59	1.09	1
0.93	0.98	0.84	0.92	0.72	1.00	0.55	1.17	1
1.10	0.76	0.94	1.01	0.84	0.98	0.55	1.10	0
0.95	0.53	0.96	0.91	0.58	1.00	0.27	1.00	1
0.94	0.87	1.11	0.88	0.72	0.99	0.65	1.15	1
1.08	1.13	1.12	0.93	0.75	0.96	0.79	0.98	1
0.89	1.03	1.28	0.97	0.68	1.02	0.53	1.24	0
1.41	0.79	0.83	0.91	1.00	1.00	1.00	0.98	1
1.50	0.72	0.76	0.97	0.76	0.96	0.35	1.15	1
1.21	0.54	0.70	0.95	0.59	1.00	0.30	0.65	1
2.01	0.76	0.94	1.01	0.53	1.00	0.35	0.97	1
1.49	0.64	0.70	1.02	0.71	0.97	0.41	0.85	0
1.55	0.63	0.71	1.13	0.66	1.00	0.40	0.98	0
1.23	0.84	1.09	1.04	0.76	0.98	0.57	1.02	0
2.60	1.05	1.21	1.07	1.06	0.99	1.05	1.14	0
2.26	0.98	1.34	1.02	0.87	1.00	0.89	1.18	0
1.66	1.13	0.68	1.18	1.02	0.98	0.86	1.18	0
2.03	0.96	1.12	1.11	0.57	1.01	0.47	0.91	0
0.38	1.15	1.01	0.97	0.81	1.00	0.86	0.75	0
0.45	1.23	1.01	0.96	0.74	1.00	0.91	0.79	0
0.38	0.89	1.03	0.99	0.84	0.99	0.74	0.87	0
0.09	1.37	1.29	1.06	2.27	1.00	2.61	0.87	0
0.09	1.35	1.44	0.95	2.33	1.00	3.00	0.87	0
0.09	1.49	1.13	0.91	2.15	1.00	2.75	0.90	0
0.15	1.32	1.11	0.91	1.90	1.00	2.18	0.91	0
0.17	1.68	1.12	1.05	1.74	1.02	2.44	0.79	0
0.17	1.71	0.98	1.05	1.68	1.02	2.42	0.83	0
0.17	1.63	1.05	1.02	1.44	1.03	2.16	0.84	0
1.05	1.04	1.06	1.02	1.03	1.03	0.93	1.28	0

passed by the tire on the test. It must be noted that this is not actual work done against the tire due to the rolling resistance, but a cumulative characteristic proportional to the applied load and mileage of the tire until failure.

Table 1 shows the test data set (coded for confidentiality). The results of the survival regression analyses are shown in Table 2. The log-likelihood of the final solution is −16.008, while the log-likelihood of the null model (with all regression parameters being equal to zero) is −28.886. The likelihood ratio chi-square statistic (the null model minus the final solution) is 25.757 with 7 degrees of freedom and the associated p-value is 0.0005. Highlighted covariates are statistically significant at $p < 0.05$.

The developed life test does not appear to be sensitive enough to distinguish between aged and new tires, hence the non-significance of the tire age covariate. See Baldwin [6] for a more detailed discussion of the tire age factor.

Table 2
Estimates of proportional hazard model with covariates identified in Section 2

Explanatory variable	Beta	Standard error	t-value	p-value
Tire age	2.109	1.393	1.514	0.130
Wedge gauge	−9.686	4.638	−2.088	0.037
Interbelt gauge	−10.677	4.617	−2.313	0.021
Belt 2 to sidewall	−13.675	8.112	−1.686	0.092
Peel force	−34.293	13.651	−2.512	0.012
Carbon black (%)	−48.349	33.448	−1.445	0.148
Wedge × peel force	20.839	8.860	2.352	0.019

Table 3
Estimates of proportional hazard model with statistically significant covariates

Explanatory variable	Beta	Standard error	t-value	p-value
Wedge gauge	−9.313	4.069	−2.289	0.022
Interbelt gauge	−7.069	2.867	−2.466	0.014
Peel force	−27.411	10.578	−2.591	0.010
Wedge A × peel force	18.105	7.057	2.566	0.010

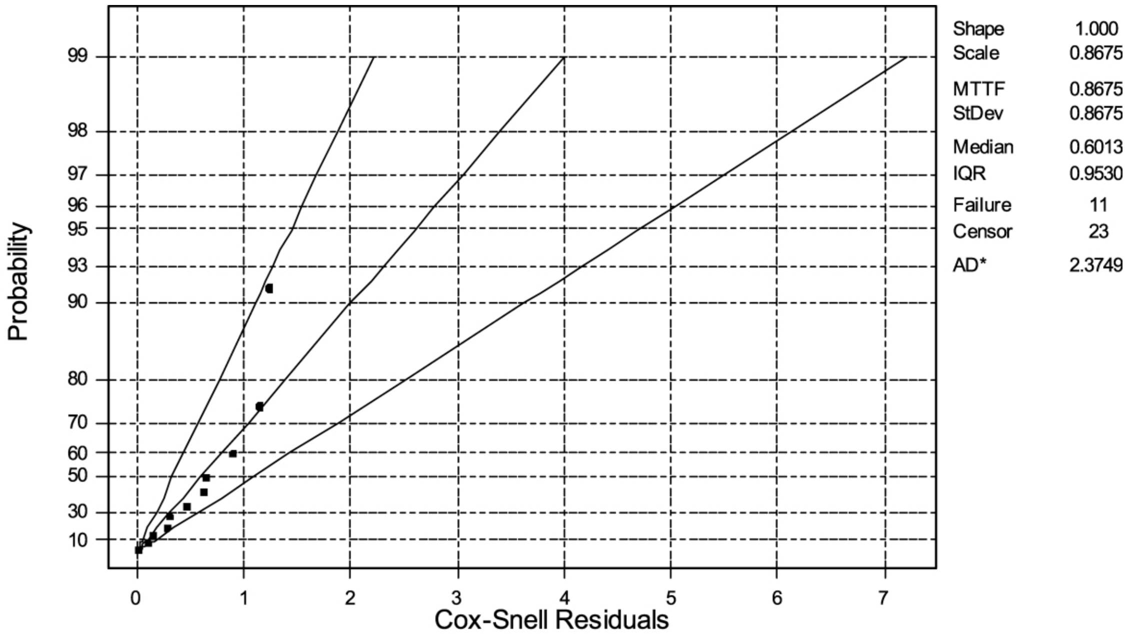

Fig. 4. Exponential probability plot of Cox–Snell residuals.

Table 3 shows the estimation results of the model that includes only statistically significant covariates. The log-likelihood of the final solution is −19.968, while the log-likelihood of the null model is −28.886. The likelihood ratio chi-square statistic is 17.837 with 4 degrees of freedom and the associated p-value is 0.001.

Shown in Fig. 4 is the exponential probability plot of Cox–Snell residuals, which confirms the adequacy of the fitted model.

Fig. 5 displays the cumulative hazard function predicted from the estimated model based on some typical values of covariates for 'poor' and 'good' tires. The poor tire is modeled to have wedge and interbelt gauges of 0.5 and peel force of 1, and the good tire, wedge and interbelt gauges of 1.2 and 1, respectively, and peel force of 2.

5. Regression analysis of TBS crack propagation

This section discusses some aspects of crack initiation and propagation prior to TBS. Research of related work [7–9] has revealed several approaches to modeling the crack growth phenomenon in elastomeric material such as rubber. All of them are based on energy release and material relaxation mechanisms. With introduction of the J-integral, these methods have been refined, and it now becomes possible to utilize these methods in complex finite element models such as that of a tire. A considerable amount of work was dedicated to find the precise characteristics required to estimate and calculate the crack growth in the rubber specimen.

However, there is no very well suited theory or a calculation procedure, which could adequately perform rubber rupture analysis. Most of the researchers agree that the energy release mechanism is the most appropriate approach to characterize the rubber crack growth. The energy required to fracture the rubber depends on geometry of the specimen and material characteristics. In this work, we characterize the crack growth on the macro level and statistically regress the design and material properties of the tires to the crack growth rate.

The crack propagation test procedure is similar to the one discussed in Section 3, except that tires were run at relatively high constant speed and under relatively high constant load. The test was interrupted at the equal time (mileage) intervals in order to perform shearography[1] of the tire after which the test was continued until a pre-determined mileage or a failure, whichever came first. (An example of a tire shearography output is shown in Fig. 6.) After each stop, the obtained snapshot of the crack length was measured and recorded, thus forming the time series history of crack growth.

For each tire, the vector of the crack size as the function of the test time was used as a response and measured characteristics of the tire were used as explanatory variables. In addition to the covariates discussed in Section 2, the following covariates were included in the crack propagation study (see Fig. 1):

- the distance from the edge of the upper belt to tread line
- width of steel belts
- angle of steel belts

[1] Shearography is a non-destructive test allowing to identify the crack or voiding inside the specimen.

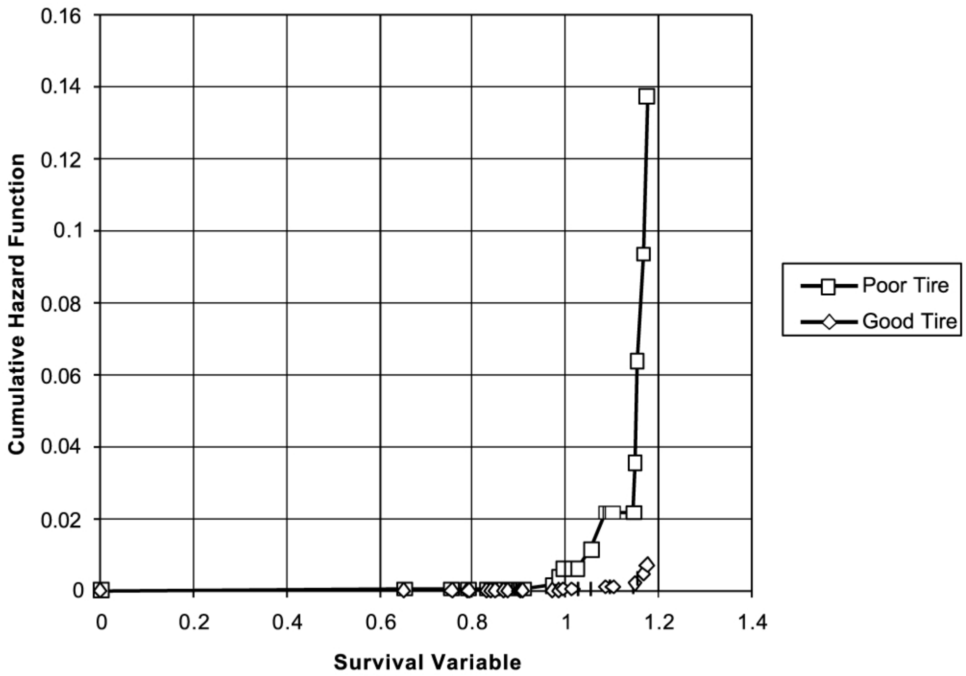

Fig. 5. Cumulative hazard function predicted from the estimated model based on some typical values of covariates for 'poor' and 'good' tires.

- tire weight
- tread durometer (characterizing the strength of the rubber)
- tread radius (of the curvature, measured by the set of templates across the tread)
- shoulder drop (horizontal distance from the top of the tread to sidewall)
- specific gravity of the tread (equivalent to rubber density)
- tread weight

In the course of study, some of these covariates were dropped due to the reasons of multi-collinearity and statistical insignificance. Table 4 shows the results of linear regression estimation, which only includes significant covariates ($p < 0.05$). The original data set is omitted due to its size. All significant covariates have meaningful engineering interpretation, i.e. crack length is inversely proportional to tread radius and peel force and directly proportional to operating time.

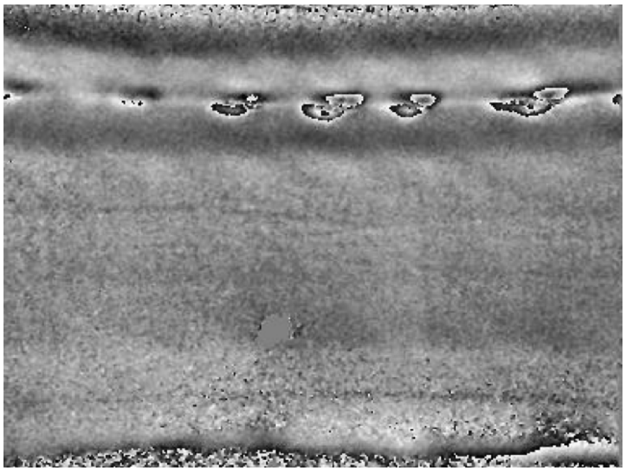

Fig. 6. Example of tire shearography.

Table 4
Estimates of linear regression with statistically significant covariates

	Beta	Standard error	*t*-value	*p*-value
Constant	126.173	17.304	7.292	0.0000
Peel force	− 1.213	0.184	− 6.597	0.0000
Tread radius 1	− 0.073	0.016	− 4.729	0.0000
Tread radius 2	− 0.166	0.071	− 2.327	0.022
Operating time	0.163	0.015	10.948	0.0000

Shown in Fig. 7 is the probability plot of regression residuals, which seems to follow the normal distribution reasonably well.

6. Concluding remarks

The statistical analysis of laboratory test data shows that the wedge and interbelt gauges as well as the peel force are significant factors affecting the hazard rate of TBS failures in an inversely proportional way. This is in good agreement with the engineering hypothesis formulated above. It must be noted that obtained results should be viewed as qualitative (i.e. helping to compare tire designs from a reliability standpoint) rather than quantitative (i.e. predicting the actual reliability of a tire in the field).

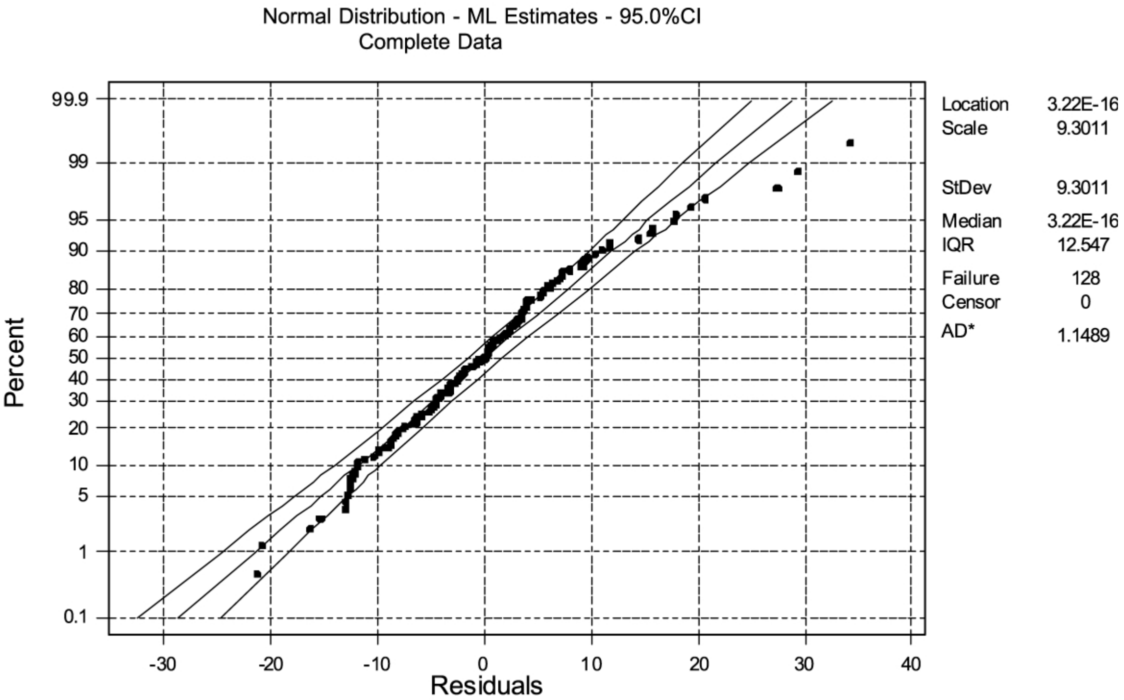

Fig. 7. Normal probability plot of linear regression residuals.

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