Analyzing Tire Wear Before Detachment

By: J. W. Daws, Ph.D., P.E., Daws Engineering, LLC

Reference: *Rubber & Plastics News*, October 7, 2013, pp. 30-36.

Abstract

In forensic analysis of tires having suffered a tread and outer belt detachment, several questions need to be resolved by the forensic analyst regarding the development of the crack system leading to the tire disablement and the amount of rapid wear over the delamination at some point prior to the tread detachment. Unfortunately, a complete analytical computation of values like the amount of strain energy release rate at the edge of the tread belt is currently at or beyond the limit of the capability of finite element tools used within the tire industry, and is therefore outside the capability of the forensic analyst. This paper develops a method for estimation of crack growth and rapid tread wear that is akin to the process of accident reconstruction in that known characteristics and available measurements from the disabled tire are used to produce an analysis that is useful for estimating the development of the rate of delamination and the rate of rapid tread wear with distance traveled.

Introduction

When a tire forensic analyst encounters a tire that has experienced a tread detachment, the visual examination of the disabled tire will usually show the presence of a pre-existing fatigue crack thumbnail (i.e., a delamination) in the skim rubber between the inner and the outer working steel belt. Characteristics like the presence or absence of polishing of the skim rubber and the size of the fatigue crack thumbnail will be noted. Often, there is an area of rapid wear (i.e., a flat spot) located on the tread rubber immediately above the underlying fatigue crack thumbnail. In many cases, the analyst will be asked to respond to several questions, most notably the following:

1. How many miles before the tread actually detached was the tire developing this delamination?
2. How deep was the flat spot over this delamination at the time of some service that occurred some number of months or miles before the actual tread detachment?

Previous efforts to respond to these questions have typically been based on the analyst's experience, with little or no real scientific basis. This paper develops a model based on published tire material properties and characteristics observable in a forensic examination to estimate answers to these questions.

Background

The development of a model for estimation of crack growth rates and rates of rapid tread wear in tires suffering a tread detachment has been limited by a lack of fundamental data and analytical capacity. Most modern tire design analysis is performed using finite element tools. These systems are extremely expensive, and require detailed models of material behavior for the different rubber, textile and steel components in the tire. The tire's design and these material models are typically trade secret property of the tire manufacturer and are not available to the outside forensic analyst. Even having these systems and data, however, is not sufficient to perform the sort of analyses required to completely describe a tire disablement. For example, the computation of the strain energy release rate at the edge of the outer steel belt can be done with some assumptions about the shape of the crack. However, to go further and compute the strain energy release rate of the crack as it grows away from the belt edge into the tire remains at the limit of the capability of finite element tools available even to tire manufacturers, except perhaps in very limited cases where the shape of the crack front can be assumed. Tread wear, on the other hand, is not usually amenable to analysis by finite elements and is normally done using road test results. To address tread wear issues, the forensic analyst must rely on the wear shown on the incident tire and published data concerning flat spot development.

Given these difficulties, the forensic analyst can best be served in this area by examining a methodology similar to the process followed by accident reconstructionists. In that discipline, the reconstructionist is confronted with a vehicle path described by tire marks on pavement and perhaps furrows off the pavement. In addition, the amount of crush developed on the vehicle during the accident is observable, as are scratch patterns on the vehicle surface in the case of roll-over. The reconstructionist is able to make a determination of the vehicle's velocity, within some range, by using data for the vehicle and scene inspections along with crush data for the vehicle from previous crash testing, published coefficients of friction for tires on and off pavement, and so on. No finite element analysis of the entire vehicle structure, or detailed friction studies on the specific tires, are typically used.

In order to establish a computational procedure for crack growth in between the steel belts on a tire that has experienced a tread belt detachment, a relationship is needed linking the strain cycle present in the incident tire skim rubber and the rate that cracks grow under that level of strain. Näser, et al. [1] presented a Paris-Plot for filled natural rubber (the type of rubber used in steel belt skim) containing data from both the loading and unloading phases of a test cycle. They stated that the average of the loading phase and unloading phase results corresponds to a Paris-Plot based on the change in strain energy through a stress cycle. Following Näser, et al., the crack growth rate for the loading phase of the strain cycle is given by

$$\frac{da}{dn} = 0.6x10^{-10}\Delta G^{1.77} \qquad [1]$$

and the corresponding relation for the unloading phase of the strain cycle is

$$\frac{da}{dn} = 2.17x10^{-10}\Delta G^{1.70} \qquad [2]$$

where *ΔG* is the change in strain energy release rate in J/m2, and *da/dn* is the crack growth rate in mm/cycle. While filled natural rubber mixes from different manufacturers may show slightly different behaviors, it will be assumed for the purposes of this work that **Equations 1 and 2** can be used to represent the crack behavior of filled natural rubbers (i.e., belt skims) in general. This approach ignores the effects of temperature, the strain induced crystallization effect in natural rubber, and the effect of dwell time in the strain cycle.

Most of the analyses in the literature discuss the value of *ΔG* at the edge of the outer steel belt. However, there is little analysis in the literature as to the value of *ΔG* as the fatigue crack propagates radially into the tire. This is not surprising, since the level of strain experienced depends upon the tire's design, material properties, load and pressure, and the shape of the crack among other variables. Govindgee [2], in the analysis of the Firestone Wilderness AT tires, indicated that *ΔG* had a constant value of about 400 J/m^2 from the edge of the outer steel belt to a location about 10 mm into the tire, and then increased to over 900 J/m^2 at a location 35 mm radially into the tire, and that these values varied with load and inflation pressure. His report showed *ΔG* curves for a number of load and pressure conditions on the tire being analyzed. Govindgee also commented that, at greater than 35 mm into the tire, the value of *ΔG* tended to "flatten out" (i.e., become constant) due to non-linear and hysteretic behavior. Based on **Equations 1 and 2**, the higher the value of *ΔG*, the more rapid the crack growth rate, or the farther the crack extends into the tire with each tire rotation. This means that a *ΔG* representation that starts out with a small constant value near the belt edge and increases to some finite value at about 35 mm into the tire (in passenger and light truck tires) will result in large number of cycles required to increase the crack size near the belt edge, and smaller number of cycles to increase the crack size as the crack grows into the tire. This is consistent with the current understanding of fatigue crack development in tires.

The rate of development of rapid wear in tire tread immediately over a fatigue crack thumbnail has also been studied. Brico [3, 4] tested tires with built-in delaminations of a fixed size and measured the rate of acceleration of the wear over the known-sized delaminations. While the data in Brico's study is limited to one tire size, one track condition, and a limited number of tires, it remains the only published source for indications as to how tread wear over a delamination accelerates. Daws [5] used some of these data to develop a relationship between the delamination size and the rate of acceleration of the tread wear with respect to the nominal tread wear rate away from the delaminated area in tires having normal inflation pressure. The Daws model shows that the relative wear rate over a delaminated area increases as the size of the delamination increases. The model generates the estimate of the wear rate over the underlying delamination based on the tire's nominal wear rate, which allows the forensic analyst to minimize the influence of wear variables such as the type of road surface, the type of tread rubber, and so on.

Development of an Analytical Procedure

Daws [5] observed that the fatigue crack thumbnail shape could be represented as a parabola oriented as shown in **Figure 1**. In this case, the shape function would be

$$y^2 = kx \qquad [3]$$

where the *x*-axis is aligned in the radial direction and the *y*-axis is aligned parallel to the tire centerline. In the disabled tire, the distance the fatigue crack thumbnail extends radially into the tire will be termed *H*, while the width of the fatigue crack thumbnail will be termed *B*. Obviously, for any observed fatigue crack thumbnail, *k* is given by

$$k = \frac{B^2}{4H} \qquad [4]$$

The area of the parabola, *S*, is given as by

$$S = \frac{2BH}{3} \qquad [5]$$

Daws [2] showed that the ratio, *R*, of the wear rate over the fatigue crack thumbnail to the nominal wear rate away from the fatigue crack thumbnail is given by

$$R = 0.117S \qquad [6]$$

If it is assumed that the fatigue crack thumbnail maintains roughly the same shape as it grows radially into the tire (i.e., the delamination has roughly the same geometric shape throughout its development), then the area of the fatigue crack can be calculated for any penetration depth. If the fatigue crack thumbnail is divided into *N* segments each having a height $\Delta h = H/N$, then in the *ith* segment, the height of the parabolic segment describing the fatigue crack is given by

$$x_i = i\Delta h \qquad [7]$$

The half-width of the parabolic segment describing the fatigue crack can be obtained from **Equation 3** as

$$y_i = \sqrt{kx_i} \qquad [8]$$

The area of the parabola segment describing the fatigue crack extending from $x=0$ to $x=x_i$ is obtained from **Equation 5** as

$$S_i = \left(\frac{4}{3}\right) x_i y_i \qquad [9]$$

Therefore, at any fatigue crack penetration depth (i.e., at any time earlier than at the tire's disablement), the area of the fatigue crack thumbnail can be estimated from **Equation 9**. The acceleration of the wear in the tread rubber over the fatigue crack during the number of cycles for the crack to grow from x_{i-1} to x_i will be given by substituting S_i into **Equation 6** to yield the acceleration factor R_i that exists when the fatigue thumbnail is at that size.

At each step, the crack growth rate for loading and unloading are averaged to generate the number of strain cycles. In order to perform such a computation, a value of ΔG must be assumed. As mentioned previously, the value of ΔG is able to be calculated only by finite element means and only in special circumstances. There does not, however, appear to be a complete description of the behavior of ΔG as the fatigue crack thumbnail progresses radially into the tire at depths that are significant to a forensic analysis. There are certainly some insights that can be developed:

1. The value of ΔG depends upon the tire design and the tire usage as previously discussed. Every tire is likely different, and tires from different manufacturers will likely have more significant differences owing to different design strategies applied. Overload and under-inflation will change the value from some optimal loading condition. Over the tire lifetime, then, the tire will be exposed to many levels of ΔG.
2. The value of ΔG cannot continually increase by significant amounts as the fatigue crack progresses radially into the tire (i.e., it must become limited). If this did not happen, then the number of stress cycles needed to grow the crack away from the belt edge would drop to near zero, and there would be no possibility to develop significant rapid wear in the tread.

Models using increasing values of ΔG from the belt edge to some arbitrary penetration distance describe the phenomenon discussed by Govindgee in his analysis of the Firestone Wilderness A/T tires. Directionally, low values of ΔG will result in very low crack growth rates near the belt edge, which likely describes the process that occurs at the start of radial crack development in a tire (i.e., socketing at the belt edge extends circumferentially and then begins to grow radially into the tire). As discussed previously, in a forensic analysis the interest is in the progress of the fatigue crack over the development of the predominant portion of the crack area. The model for

ΔG for use in this analysis will be taken following Govindgee's analysis (for passenger and light truck tires):

1. ΔG = 400 J/m^2 from the belt edge to a crack depth of 10 mm.
2. ΔG increases linearly from 400 J/m^2 at 10 mm of crack depth to some arbitrary value (ΔG_{max}) at 35 mm of crack depth.
3. ΔG becomes constant (equal to ΔG_{max}) beyond 35 mm of crack depth.

As mentioned previously, this model ignores the temperature, the strain induced crystallization behavior of natural rubber, and the dwell effect in the strain cycle. Strain induced crystallization can retard crack growth in cases where the ratio of the minimum strain (G_{min}) to the maximum strain (G_{max}) in the cycle is greater than zero. Since this ratio is a function of the design (shape) of the tire, it is unknown. Similarly, the dwell effect relates to the time between the stress peaks that occurs because the materials are subjected to essentially a constant G_{min} strain away from the contact patch and a rapid excursion to G_{max} and back inside the contact patch. This leads to an accelerated crack growth rate, and the effect will be larger at low speeds than at high speeds. This is again a function of the tire size and vehicle speed, which are, like temperature, unknown and time-varying factors. Since the objective of the present analysis is to infer the rate at which the fatigue crack delamination develops over the life of the tire, ΔG_{max} in this study is simply a variable that will be used to adjust the level of strain to fit the observations obtained in the forensic examination. Thus, the value of ΔG_{max} is intended to account for loads and pressures over the tire lifetime as well as amounts of acceleration and retardation of crack growth linked to strain induced crystallization and dwell effect related to tire design, along with environmental temperature and vehicle speed experienced. The method for determining the arbitrary value of ΔG_{max} for the model above will be discussed below.

Regardless of the model selected for ΔG (different values could be chosen for the initial minimum and the transition crack depths, and other models of a more complex nature could certainly be developed and applied), the crack growth rate from x_{i-1} to x_i will be given by applying **Equations 1 and 2** to the value of ΔG_i, the value of ΔG at x_i. This yields the crack growth rate as

$$\left(\frac{da}{dn}\right)_i = 0.5\left(0.6x10^{-10}\Delta G_i^{1.77} + 2.17x10^{-10}\Delta G_i^{1.70}\right) \qquad [10]$$

which gives the length of crack growth per stress cycle. Since the tire experiences one stress cycle per rotation, the number of rotations, M_i, for the crack to grow from x_{i-1} to x_i will be given by

$$M_i = \frac{\Delta h}{\left(\frac{da}{dn}\right)_i} \qquad [11]$$

Give the tire's rotations per unit distance, r, the travel distance required to move the fatigue crack incrementally one step of Δh, *or* D_i, can be computed as

$$D_i = \frac{M_i}{r} \qquad [12]$$

The distance traveled is then used to compute the amount of wear developed both away from the fatigue crack thumbnail and immediately over it. This is done using the nominal wear rate, W, of the tire, which is usually given in miles per 32nd-inch or km per mm. Normally, this value is obtained by dividing the service mileage of the tire by the amount of tread that has been worn away in a location away from the fatigue crack. If the tread grooves of the tire have unequal wear, the tread groove that contains the base of the flat spot is likely the most representative of the phenomenon being analyzed here. The amount of wear on the tread rubber away from the fatigue crack (i.e., the nominal wear), Δt_i, is then given by

$$\Delta t_i = \frac{D_i}{W} \qquad [13]$$

The wear over the fatigue crack thumbnail will be accelerated by a factor of R_i given by **Equation 6**, so the change in tread depth over the fatigue crack thumbnail, $\Delta t'_i$, will be given by

$$\Delta t_i' = R_i \Delta t_i \qquad [14]$$

At any value of x_i between 0 and H, the total distance traveled (D), the total nominal tread wear (Δt), and the total tread wear over the fatigue crack thumbnail ($\Delta t'$) can be computed by summing the incremental values as shown in **Equations 15**.

$$D = \sum_{i=0}^{N} D_i \qquad [15.1]$$
$$\Delta t = \sum_{i=0}^{N} \Delta t_i \qquad [15.2]$$
$$\Delta t' = \sum_{i=0}^{N} \Delta t'_i \qquad [15.3]$$

When the fatigue crack thumbnail has reached a penetration of H, the difference between the tread depth away from the fatigue crack thumbnail (the nominal tread depth) and that immediately over it (the flat spot tread depth) must match the difference in level observed in the forensic inspection. This is accomplished by adjusting the arbitrary constant value of ΔG_{max} in the model described above. Since ΔG cannot be computed theoretically, this approach provides a value that ensures that the tread depth difference between the tread over the fatigue crack thumbnail and that away from it matches the forensically observed value. In that way, differences in tire design, environmental loading, and so on are accommodated in the analysis. The nominal tread depth value computed at the end of the simulation can then be adjusted to the forensically observed value by selecting an appropriate value of tread depth to apply when $x_i = 0$.

Execution of the Procedure

The procedure outlined above was implemented in a simple spreadsheet format. The spreadsheet increments a parabola into the tire in a fixed number of increments, N. ΔG is assumed to follow the model described above. At each increment of depth, the value of ΔG for that step is used with **Equations 1 and 2** to generate a value of crack growth rate. The rotations per unit distance value for the tire is then used to compute the distance traveled during this increment of crack growth. The width of the parabola shape and its corresponding area are calculated at each step, and the rate of acceleration of the nominal tread wear is generated according to **Equation 6**.

Based on the distance traveled during each increment, the amount of nominal tread wear and the amount of rapid tread wear are generated. The nominal tread depth and the flat spot tread depth are computed by subtracting the corresponding amount of wear in each increment from the tread depth of the previous increment.

The tread depth at the start of the delamination is chosen arbitrarily at the start of the analysis. Once the value of ΔG_{max} is found that provides the observed flat spot tread depth difference, then the tread depth at the beginning of the delamination is adjusted to provide the nominal tread depth away from the flat spot that was observed in the forensic examination. The estimated distance required to generate the flat spot with the observed difference in tread depth can be computed from **Equation 15.1**. The nominal tread depth as well as the tread depth over the flat spot, at some point a defined distance before the tread detachment, can now be estimated by finding the nearest distance value to that defined point in the tabular computation and reading the tread depth difference from the computed values.

Sample Calculation

Figure 2 shows the data entry and results portion of the spreadsheet discussed above. The sample calculation was for a tire that failed with a complete tread detachment. The fatigue crack thumbnail was found to penetrate radially into the tire about 5.1 in (129.5 mm) and extend along the edge of the outer steel belt for a length of about 18.2 in (462.3 mm). The fatigue crack region height was divided onto sixty (N=60) segments. The tire had a service life of 53,334 miles (85,334 km) and was worn to a nominal 5.5/32 in (4.37 mm) in the tread groove that passed over the base of the fatigue crack delamination area. This yielded a nominal tread wear rate of 5,926 mi/32nd-in (11,945 km/mm) in that tread groove. The new tread depth for the tire was given in the manufacturer's data as 14.5/32 in (11.5 mm). The rotations per unit distance value for the tire was given in the same data as 682 rev/mi (426 rev/km).

In the forensic examination of the tire, the depth of the flat spot was found to be 3.0/32 in (2.38 mm). That is, the tread depth immediately above the fatigue crack thumbnail was found to be 2.5/32 in (1.98 mm). For this analysis, it was assumed that there was no bulge in the tire during the development of the tread detachment. It can be seen in **Figure 2** that a value of 1,345 J/m^2 for the ΔG_{max} portion of the ΔG model was required to give a flat spot difference of 3.0/32 in (2.38 mm) at a fatigue crack thumbnail depth of 5.1 in. The value of the tread depth at the start of the analysis was set to 7.3/32 in (5.79 mm) in order to get the nominal tread depth to the value of 5.5/32 in that was observed in the forensic examination.

Based on these values, then, the fatigue crack thumbnail of the size observed in the forensic examination took an estimated 10,460 mi (16,740 km) to develop. This was consistent with the level of polishing observed in the skim rubber near the belt edge within the fatigue crack thumbnail during the forensic examination. This total distance is highly dependent upon the initial value of ΔG at the belt edge. The forensic analyst is therefore encouraged to explore a range of values for this factor in order to fully understand the variability of this portion of the analysis. That said, the analysis suggests that the tire traveled about 42,840 mi (68,540 km) before the fatigue crack began propagating radially across the tire. The forensic analyst in this matter was asked to determine the likely depth of the flat spot at the time of a service provided on the vehicle some 2,045 mi (3,272 km) prior to the disablement of the tire. Looking back 2,045 mi in the computation shows that the flat spot tread depth differential was about 1.06/32 in (0.84 mm) at the time of the service. This value is almost exclusively dependent upon the value of ΔG_{max}, which was obtained by fitting the model to the depth of the flat spot actually observed. This portion of the analysis therefore has far less variability, which was the objective in creating a forensic model.

It is recognized in the field of tire forensics that, in order for a flat spot to be readily visible to a tire technician during normal service operations in the best of situations, there needs to be at least 2/32 in (1.6 mm) less tread depth than the surrounding unaffected tread. By "best of situations", it is meant that the technician has the opportunity to inspect the entire circumference of the tire in adequate lighting. That is, if the vehicle is being serviced for, say, an oil change, it would be pure chance that the technician would identify such a flat spot (i.e., the flat spot would have to be on the shoulder of the tire facing out on the vehicle, the flat spot would have to be in a visible location, there would have to be adequate lighting on the flat spot, and the technician would have to have sufficient luck to notice it). If, on the other hand, the tires were being rotated, then the technician would be able to see the entire surface of each tire and have a much better opportunity to identify the flat spot, since the tires would be removed from the vehicle and likely rolled to the next mounting location. The conclusion for the analyst in this matter was that the tire was developing a tread delamination at the time of the service, but that the flat spot would likely not have been visible to the tire technician at that time. **Figure 3** shows the results of the analysis in terms of the nominal tread depth, and the tread depth over the fatigue crack thumbnail, both as a function of miles traveled. As expected, the nominal tread depth changes linearly with distance since the wear rate was developed using the long-term average value for the tire. Also as expected, the tread depth in the flat spot decreases at an ever-increasing rate as the fatigue crack size increases. The number of miles required to propagate the fatigue crack away from the belt edge is significantly larger than that required to grow the crack further into the tire, again as a result of the increasing value of ΔG in the first 35 mm of crack growth. As noted above, the value of ΔG selected at the belt edge has a significant impact on the total distance traveled, but very little impact on the development of the crack and flat spot near the end of the tire's life.

Other Conditions

The analysis described above applies to fatigue crack growth driven by shear stresses between the two steel belts of the tire. Brico [4] described an additional scenario for rapid wear in which there was air infiltration from the casing into the delamination area. The tread and outer steel belt actually formed a bulge over some of the artificial delaminations in his study. In forensic work, road hazard impact can create a radial split in the inner liner which allows air infiltration into the steel belt package in a similar manner. Brico's study indicated that the presence of a bulge in the fatigue crack area could accelerate the development of rapid wear by around an order of magnitude (Brico specifically noted wear rates from four to 13 times faster) over the case where there was no bulge. In order to apply the above analysis to a tire that the forensic analyst concludes had a bulge, the value of R_i for each step must be multiplied by an arbitrary bulge acceleration factor (in the range of values identified in Brico's study). For completeness, the analyst should perform the analysis at both a low and a high bulge acceleration factor in order to develop a range of values for distances and tread depths.

Other cases occur in forensic analysis of tread belt detachments wherein there are broken steel cords in either the inner or outer steel belts. When the fatigue cracking is observed to grow from the broken steel cord ends rather than from the belt edge, then the model developed here must be applied carefully. For example, the penetration of the fatigue crack radially into the tire must be taken from the broken steel cords rather than from the belt edge. Other alterations to the basic analysis may also be necessary, such as using a constant ΔG rather than the model applied above, since the delamination begins not at the belt edge but at a location interior to it. For this reason, the forensic analyst should consider several alternative analysis methods in order to best describe the actual fatigue delamination observed in the forensic analysis.

In both of the conditions described above, tire damage occurs prior to the development of any cracking. In such cases, it is rare to find any significant level of polishing of the skim rubber, consistent with the crack system in the tire having developed rapidly. This forensic feature is at odds with a low initial value of ΔG. This suggests that a model using a constant value of ΔG, as noted above, may better reflect the real crack development process in such situations since a precursor to either of these conditions is tire damage. As noted previously, the same analysis process developed here can be used with any arbitrary model of ΔG.

Conclusions

A model has been developed to allow a piecewise estimation of the development of crack growth and rapid wear in a radial tire that has experienced a tread detachment. This model adjusts the change in strain energy, which cannot be computed, to provide a result that agrees with the forensic observations made on the tire.

References

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[2] Govindgee, S., "Firestone Tire Failure Analysis", January 30, 2001.

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List of Figures

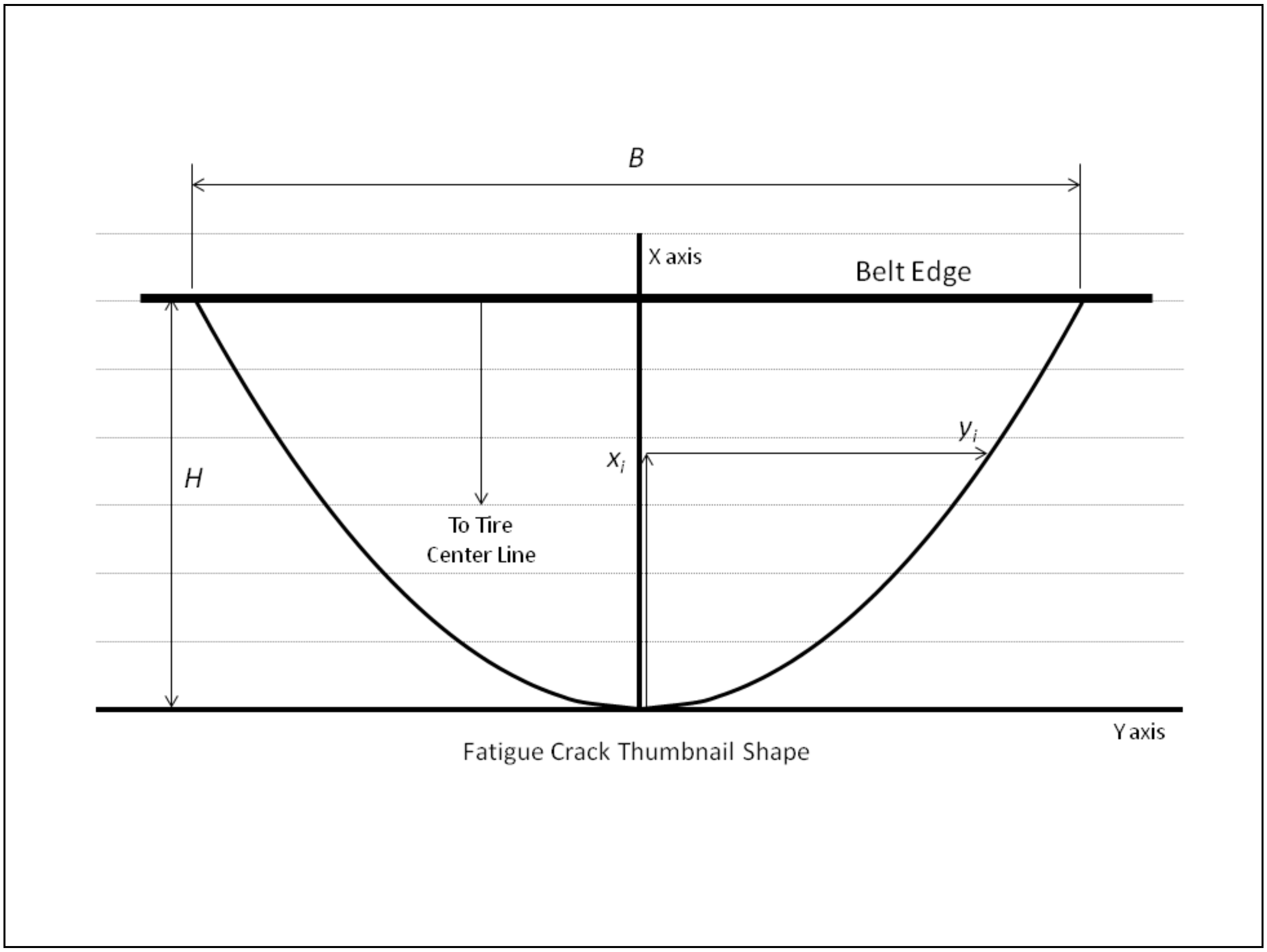
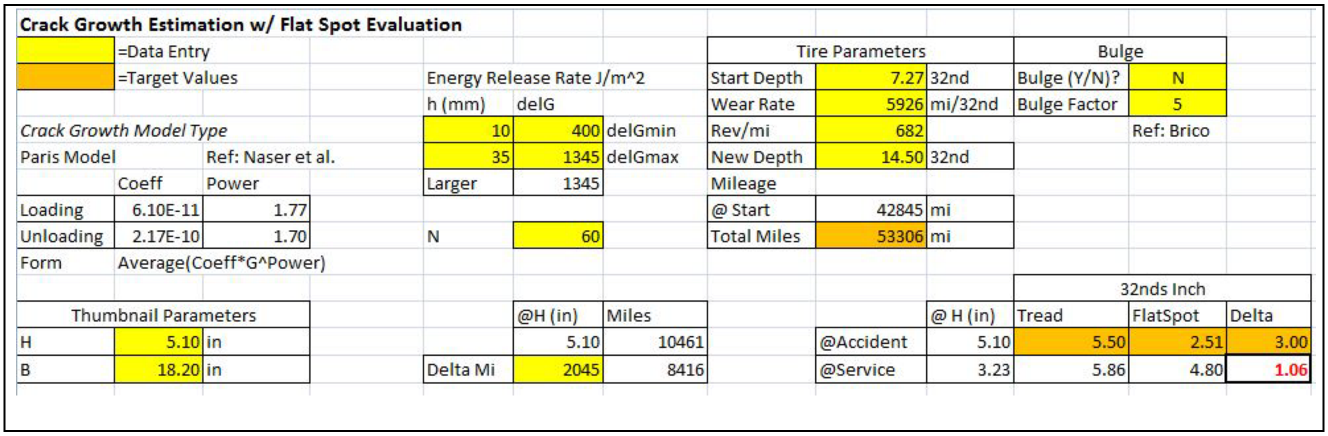


Figure 1. Parabolic model for fatigue crack thumbnail.



Crack Growth Estimation w/ Flat Spot Evaluation											
🟨	=Data Entry					Tire Parameters			Bulge		
🟧	=Target Values		Energy Release Rate J/m^2			Start Depth	7.27	32nd	Bulge (Y/N)?	N	
			h (mm)	delG		Wear Rate	5926	mi/32nd	Bulge Factor	5	
Crack Growth Model Type			10	400	delGmin	Rev/mi	682			Ref: Brico	
Paris Model		Ref: Naser et al.	35	1345	delGmax	New Depth	14.50	32nd			
	Coeff	Power	Larger	1345		Mileage					
Loading	6.10E-11	1.77				@ Start	42845	mi			
Unloading	2.17E-10	1.70	N	60		Total Miles	53306	mi			
Form	Average(Coeff*G^Power)										
									32nds Inch		
Thumbnail Parameters				@H (in)	Miles			@ H (in)	Tread	FlatSpot	Delta
H	5.10	in		5.10	10461		@Accident	5.10	5.50	2.51	3.00
B	18.20	in	Delta Mi	2045	8416		@Service	3.23	5.86	4.80	1.06

Figure 2. Data Entry and Analysis Results from spreadsheet model implementation.

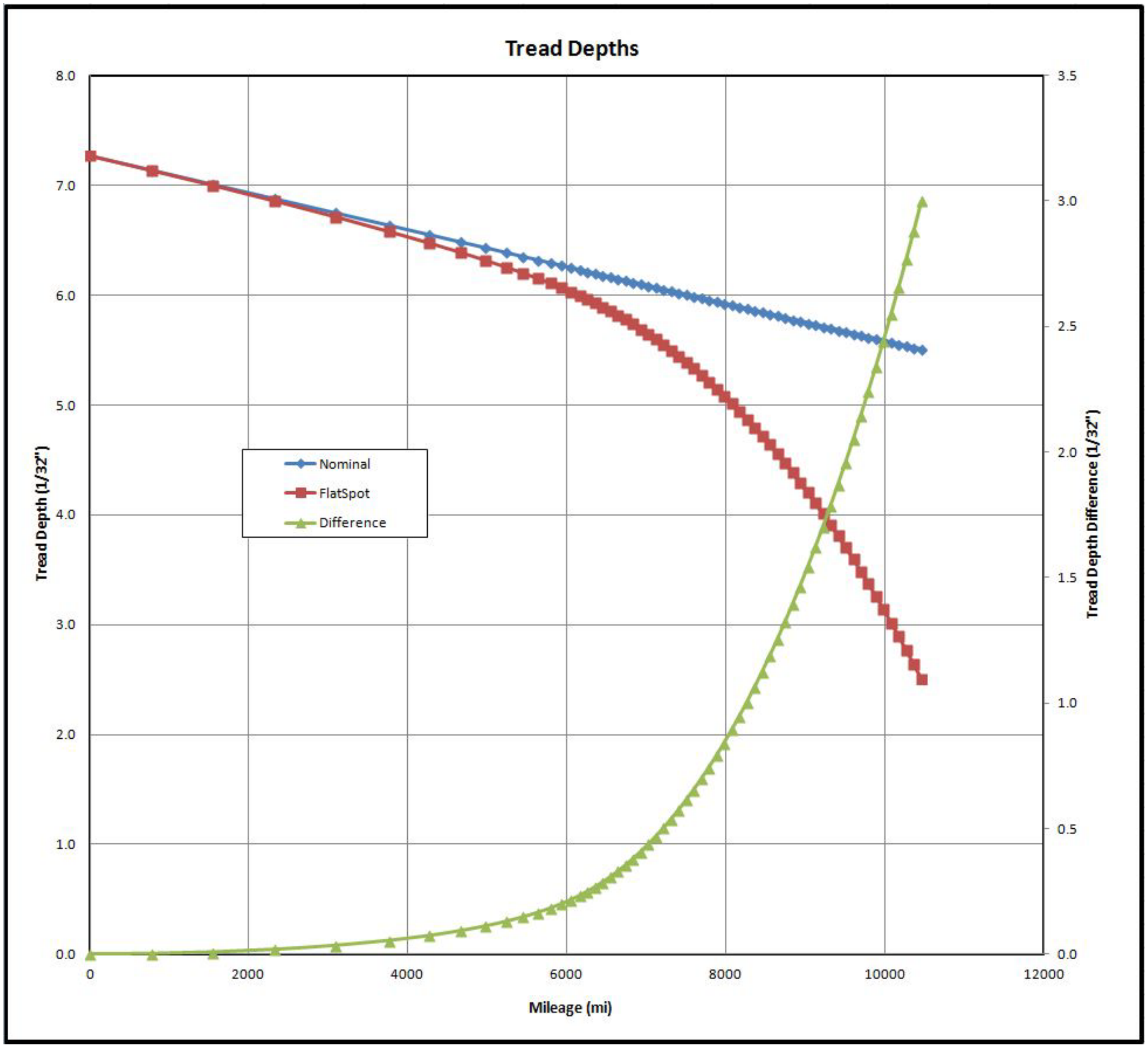


Figure 3. Tread depths over Flat Spot and Nominal Tread for Sample Calculation.