Error Analysis of Rapid Wear Estimation in Tread Separation

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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. A model for estimation of the these values was recently proposed. That model was developed using published crack growth rates and changes in strain energy density to estimate the rate at which fatigue crack propagation develops between the steel belts in a radial tire. This paper provides a detailed error analysis of the proposed model. The error analysis shows that the use of such a model produces tread wear rates that are essentially independent of the initial assumptions, but that the total accumulated mileage varies widely with the same assumptions. As a result of the error analysis of the model, a simplification of the model is developed.

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?

Daws [1] proposed a model for estimating responses to these questions. In that model, several assumptions about the stress state at the belt edge of the tire are made in order to produce a model of the stress development that corresponded to those found in the literature. The method developed by Daws simultaneously simulates the development of the underlying fatigue crack and the rapid wear overlying the fatigue crack. The final size of the fatigue crack and the amount of rapid wear come from observations in a forensic examination. The current work will examine the effect of varying the assumed values on the stability of the model output.

Background
The model proposed by Daws provides the forensic analyst 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. Daws proposed a similar approach to the estimation of the development of rapid wear over a tread separation. In that model, the amount of rapid wear (depth of the flat spot) and the size of the fatigue crack observed in the forensic examination are used as end points for a incremental simulation of the simultaneous development of the both the underlying fatigue crack and the rapid tread wear. Published crack growth rates as a function of the change in the strain energy release rate, ΔG, in both the loading and unloading phases of the cycle are used to estimate the rate at which the fatigue crack will expand. The model proposed by Daws [2] is used to estimate the rate of accelerated wear based on the size of the underlying fatigue crack system.

Daws used the crack growth model developed by Näser, et al. [3]. This model, developed specifically for tire belt skim stock, provides a relationship between ΔG and crack growth for both the loading and unloading phases of the tire's rotation. Since Daws' method provides for the calculation of the value of ΔG_{max} in the simulation, the particular model chosen is not particularly important. Therefore, the method could use the crack growth model given by Eirich [4] for natural rubber. Other models, such as the one developed by Mandell [5] for natural rubber reinforced with carbon black and containing a wire matrix, might also be used. The value of ΔG_{max} computed during the simulation will be dependent upon the model chosen, but the model output in terms of the development of rapid wear will be invariant.

The model Daws used for the ΔG function was taken following Govindgee's [6] 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.

In Daws' model, the value of ΔG_{max} is computed such that the amount of rapid wear computed matches that observed in the forensic examination when the fatigue crack has reached the size observed in the forensic examination. However, the initial value of ΔG (400 J/m^2), the depth of 10 mm where the value of ΔG transitions from a constant to an increasing value, and the depth of 35 mm, where the value of ΔG reaches ΔG_{max} are all assumptions. The question then becomes what effect each of these assumptions has on the estimation of the distance traveled and the amount of rapid wear that was present at some distance prior to the tire failure.

Analysis of Error

In order to facilitate the analysis of error desired here, the model of ΔG can be generalized as shown in Figure 1. In Figure 1, the value of ΔG at the belt edge will be represented by ΔG_0. The depth of the fatigue crack at which the value of ΔG begins to increase will be denoted h_1, and the depth of the fatigue crack at which the value of ΔG becomes equal to ΔG_{max} will be denoted h_2.

The approach used in this analysis will be to use the sample analysis Daws presented and vary each of the assumed variables ΔG_0, h_1, and h_2 independently. The mileage to develop the fatigue crack and the amount of rapid wear present 2,045 miles before the tire failure will be the output variables.

Variation of ΔG_0

ΔG_0 represents the level of stress at the edge of the outer steel belt. Govindgee's analysis showed that ΔG_0 varied with load and pressure, in the case of a single tire. This value also depends upon the geometric design of the tire itself, as shown by Näser, et. al. [4]. ΔG_0 will therefore vary over the life of any given tire, and another tire of a different design will not generally have the same levels of ΔG_0 at the same loads and pressures. In Daws' model, then, the value of ΔG_0 is intended to represent an average value over the early life of the fatigue crack development.

Figure 2 shows the results of the variation of ΔG_0 ranging from a low of 100 J/m^2 to a high of 900 J/m^2. The mileage predicted for the development of the fatigue crack ranges from 47,628 miles when ΔG_0 is set to 100 J/m^2 to 6,836 miles when ΔG_0 is set to 900 J/m^2. As noted by Daws, the mileage is highly dependent upon the value selected for ΔG_0. The lower the value selected, the more miles will be required to extend the fatigue crack each incremental step in the simulation.

Figure 2 also shows the results of varying ΔG_0 through the same range on the prediction of the amount of rapid wear 2,045 miles before the tire failure. Here, the amount of rapid wear predicted varies from $^{1.24}/_{32}$ inch when ΔG_0 is 100 J/m^2 to $^{1.05}/_{32}$ inch when ΔG_0 is 900 J/m^2. The total variation in the predicted amount of rapid wear is about 15%. However, the amount of rapid wear would have to be at least $^{2}/_{32}$ inch for it to have been visible 2,045 miles prior to the tire's failure. The total variation of the estimate is only $^{0.19}/_{32}$ inch, or about ten times less than the threshold of detectability. This indicates that the predicted value of amount of rapid wear prior to the tread separation is essentially independent of the value of ΔG_0 selected, and that the variation in the predicted value is sufficiently small for forensic work.

Variation of h_1 and h_2

h_1 represents the depth of the fatigue crack from the edge of the inner steel belt where the value of ΔG begins to increase from ΔG_0. Govindgee's analysis suggested that h_1 was in the neighborhood of 10 mm for the tire design on which he performed his finite element analyses. The value h_2 represents the depth of the fatigue crack from the edge of the inner steel belt where the value of ΔG becomes equal to ΔG_{max}. Govindgee's analysis suggested that h_2 was in the neighborhood of 35 mm for the tire design on which he performed his finite element analyses. These values were obtained by observation of ΔG curves developed for numerous conditions of load and pressure, again with a single tire design.

Figure 3 shows the results of the variation of h_1 ranging from a low of zero to a high of 15 mm. The mileage predicted for the development of the fatigue crack ranges from 8,476miles when h_1 is set to zero to 11,685 miles when h_1 is set to 15 mm. This is expected, since the effect of increasing h_1 is to increase the distance traveled at low values of ΔG. Figure 3 also shows that amount of rapid wear predicted varies from $^{1.07}/_{32}$ inch when h_1 is zero to $^{1.09}/_{32}$ inch when h_1 is 15 mm. The overall range of the estimated amount of rapid wear occurring 2,045 miles before the tire failure is about 1.8%. Again, the range of the estimate is many times smaller than the $^{2}/_{32}$ inch level of detectability.

Figure 4 shows the results of the variation of h_2 ranging from a low of 25 mm to a high of 55 mm. The mileage predicted for the development of the fatigue crack ranges from 9,975 miles when h_2 is set to 25 mm to 11,829 miles when h_2 is set to 55 mm. This is expected, since the effect of increasing h_2 is to increase the distance traveled at lower values of ΔG than ΔG_{max}. Figure 4 also shows that amount of rapid wear predicted varies from $^{1.08}/_{32}$ inch when h_2 is 25 mm to $^{1.14}/_{32}$ inch when h_2 is 55 mm. The overall range of the estimated amount of rapid wear occurring 2,045 miles before the tire failure is about 5.3%. Again, the range of the estimate is many times smaller than the $^{2}/_{32}$ inch level of detectability.

Conclusions from Basic Error Analysis

The model initially proposed by Daws produces forensic estimates for the amount of rapid wear over a tread separation that are essentially insensitive to the assumed variables used to calculate the growth of the underlying fatigue crack at the belt edge. The range of the estimates produced are at least an order of magnitude less than the $^{2}/_{32}$ inch threshold of detectability of the spot of rapid wear used in forensic analysis. Therefore, the model works very well for estimating the amount of rapid wear over a tread separation at some point before the tire failure in forensic work.

In the case of the distance traveled during the growth of the underlying fatigue crack, the above analyses showed clearly that the estimates are heavily dependent upon the level of the variables assumed for ΔG_0, h_1, and h_2. Since the values of these variables cannot be known *a priori*, the model could be modified to be more straightforward. The values of ΔG_0, h_1, and h_2 have significant effect on the early development of the fatigue crack system. The fitting of the simulation through the final fatigue crack shape and the actual amount of rapid wear guarantee an acceptable level of estimation near the tire failure. Since these variables (ΔG_0, h_1, and h_2) apply to the development of the initial phases of the fatigue crack, and the goal of the forensic analyst is most heavily focused on what happened near the end of the tire life, it is reasonable that the ΔG function initially proposed by Daws be replaced by a single value, ΔG_{max}. Daws suggested this approach when dealing with failures involving bulges in the tire.

Brico [7] described a 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 thirteen times faster) over the case where there was no bulge.

Other cases occur in forensic analysis of tread belt detachments wherein there are broken steel cords in either the inner or outer steel belts, often accompanied by a bulge in the casing. 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.

Daws discussed the use of the model in matters involving the above conditions. It was suggested that using a model having only a constant ΔG might be more appropriate. This can be explored using the previous model with the assumption that a bulge was present in the tire. Taking the values of the belt edge variables as $\Delta G_0 = 400$ J/m^2, $h_1 = 10$ mm, and $h_2 = 35$ mm, the analysis was run for bulge acceleration factors. Figure 5 shows the value of ΔG_{max} as the bulge acceleration factor increases from one to six. At bulge acceleration factors beyond five, the value of ΔG_{max} becomes increasingly large, and more importantly, well outside the bounds of values reported in the literature. The reason for this is simply that the growth of the fatigue crack in the region from zero to 10 mm takes 3,083 miles (given the assumption that $\Delta G_0 = 400$ J/m^2 and $h_1 = 10$ mm). In order to satisfy the end conditions that match the forensically observed ones (the depth of the fatigue crack and the amount of rapid wear at the point of tire failure), ΔG must increase without bound. In real terms, the simulation reached the rapid wear limit (as observed in the forensic examination) shortly after the depth of the fatigue crack reached 10 mm, so the fatigue crack had to grow from a depth of 10 mm to a depth of 5.1 in (129.5 mm) in a few tire miles. This is a physical impossibility at least as far as current understanding of the phenomenon of fatigue cracking. In practical terms, crack growth rates of that level constitute rapid tearing rather than fatigue cracking. Mathematically, solutions where the total distance traveled is less than the edge crack mileage become impossible to achieve across the range of bulge acceleration factors when edge conditions are considered in the analysis.

For this reason, along with the variability of total distance estimates based on unknowable values of ΔG_0, h_1, and h_2, it is worthwhile to explore the model using a constant value of ΔG. For this analysis, another tire failure, which had an obvious bulge in the casing at the time of the forensic examination, will be used. In this case, the underlying fatigue crack extended 3.5 inch into the tire radially from the point of broken steel cords, and extended 16.7 inch along the tire circumferentially. The nominal tread depth in the tread groove that would have passed over the widest end of the fatigue crack was $^{4}/_{32}$ inch. The rapid wear, at the time of the forensic examination, had reduced the tread depth to $^{0.5}/_{32}$ inch (i.e., the tread was worn below the level of the tread groove). In this case, the actual mileage on the tire was unknown. In order to perform the analysis, a wear rate of 4,000 miles per 32nd inch of tread depth was assumed. The forensic analyst in this matter was asked to estimate the amount of rapid wear that would have been on the tire at a distance of 360 miles before the tire failure. Figure 6 shows the value of the constant ΔG required at each bulge factor from four to thirteen. These values are bounded, and more importantly, well within the range of values published in the literature.

Also shown in Figure 6 is the amount of rapid wear that would have been on the tire at 360 miles prior to the tire failure. This ranges from $^{1.9}/_{32}$ inch when using a bulge acceleration factor of four to $^{0.09}/_{32}$ inch when using a bulge acceleration factor of thirteen. This range places an upper and lower bound on the amount of rapid wear that was possible in the tire. The more distortion of the casing found in the forensic examination, the higher the bulge acceleration factor is likely to be. Obviously, model results depend upon the nominal wear rate selected, so if this is not known from mileage and tread depth data, then the value should be selected with careful consideration given to the type of tire, mileage warranty, and so on. The more rapid the tire nominal tread wear, the higher the rate of rapid wear development over any fatigue crack system will be.

The previous error analysis showed that the model proposed for ΔG by Daws was very repeatable in estimating the amount of rapid wear but less so in estimating total distance traveled in developing the fatigue crack system. This results from the nature of the analysis. The values of ΔG_0, h_1, and h_2 have significant effect on the early development of the fatigue crack system, but little, if any, on the full development of the crack system. The fitting of the simulation through both the final fatigue crack shape and the actual amount of rapid wear guarantee an acceptable level of estimation near the tire failure. If the constant ΔG form of the model is used to make the estimate of the amount of rapid wear discussed previously by Daws, a level of ΔG of 1,275 J/m^2 is computed (compared to the level of 1,346 J/m2 when ΔG_0 = 400 J/m^2, h_1 = 10 mm, and h_2 = 35 mm). The amount of rapid wear 2,045 miles before the tire failure is estimated to be $^{1.07}/_{32}$ inch, compared to the $^{1.08}/_{32}$ inch previously developed. Therefore, there is no significant advantage in forensic analysis to using a model for strain energy release rate that is any more complicated than constant ΔG.

Conclusions

The model proposed previously by Daws has been shown to have a low level of variation when estimating the amount of rapid wear over a tread separation prior to the tire failure. This variation is estimated to be at least an order of magnitude less than the threshold $^{2}/_{32}$ inch used for detection limit in forensic work. However, estimation of the travel distance for development of the underlying fatigue crack is highly dependent upon variables that cannot be known (or computed) in any reasonable manner. It is therefore recommended that the method developed by Daws for estimating rapid wear over tread separations be used with exclusively with constant ΔG. In analyzing a tire having a bulge, the such an analysis can present upper and lower bounds for the amount of flat spot wear.

References

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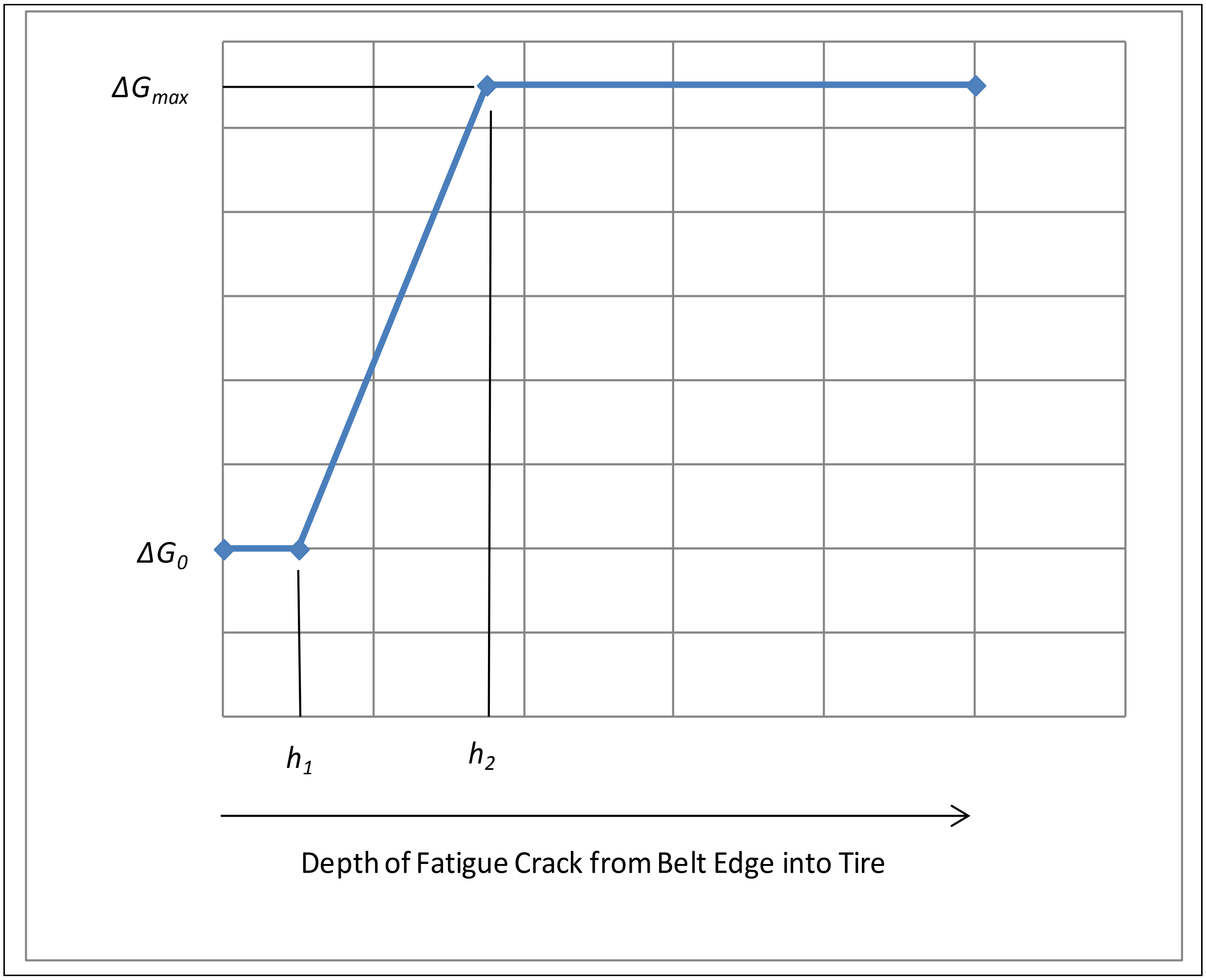


Figure 1. Shear strain release rate model used by Daws.

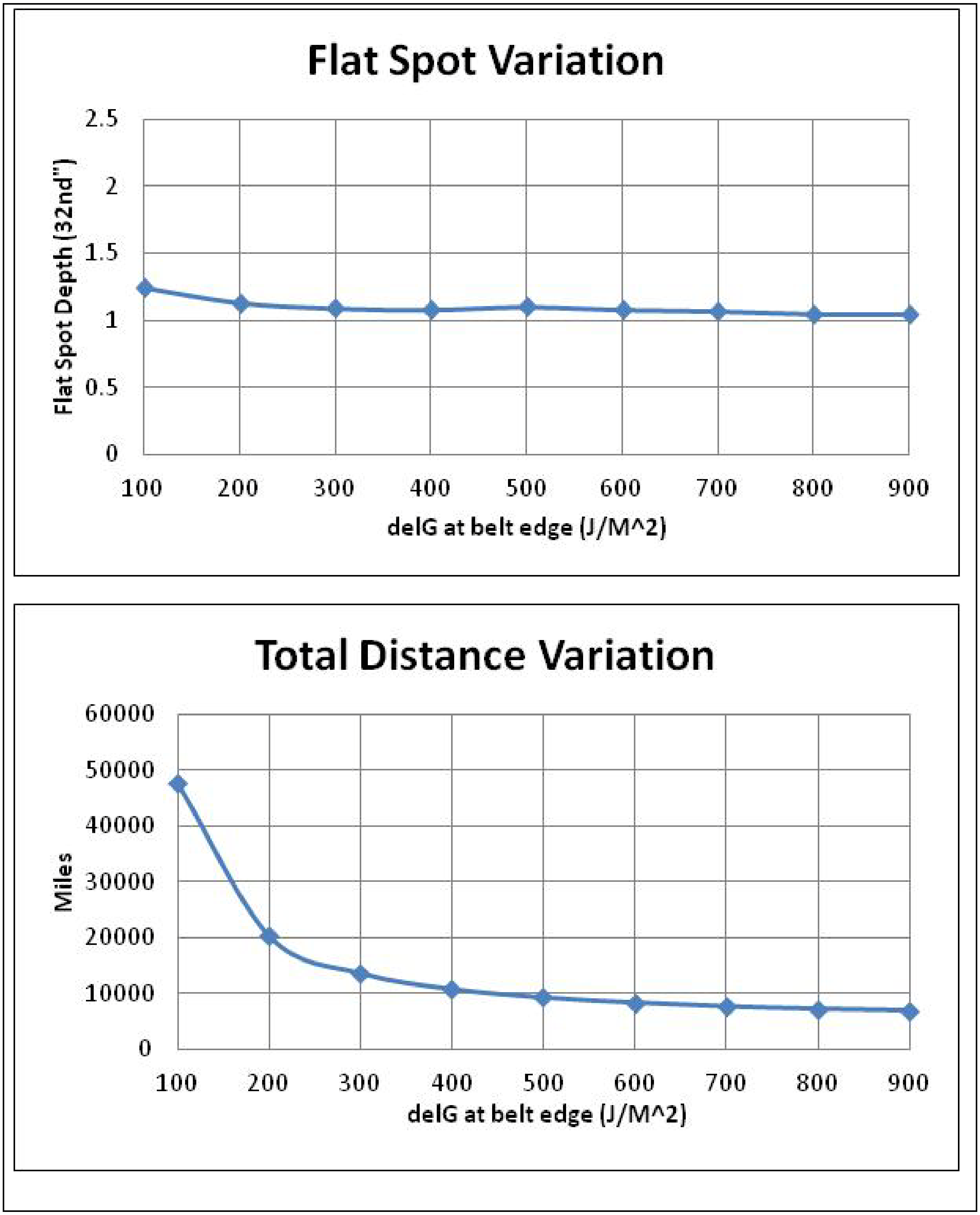


Figure 2. Simulation results for various levels of ΔG_0 at the belt edge.

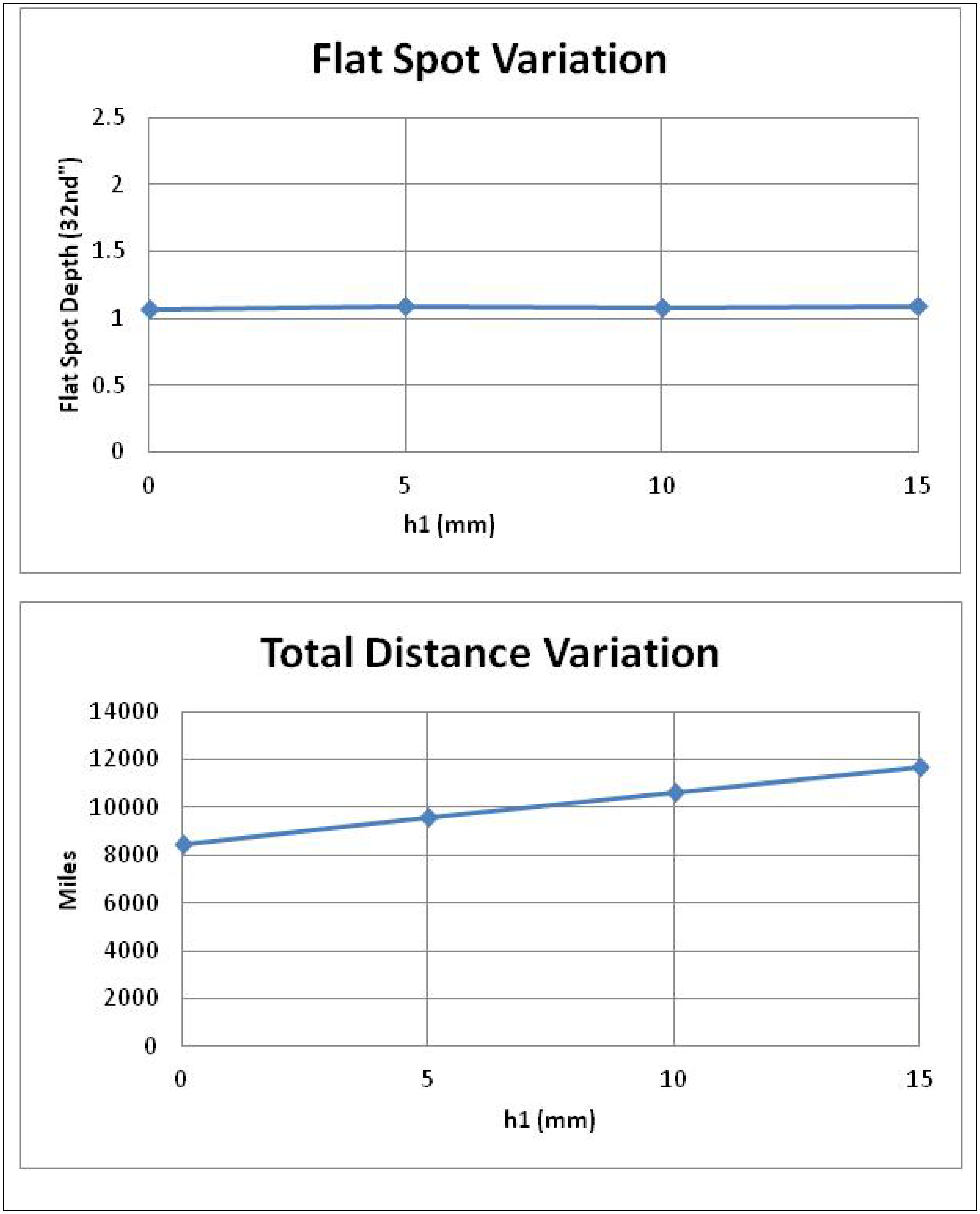
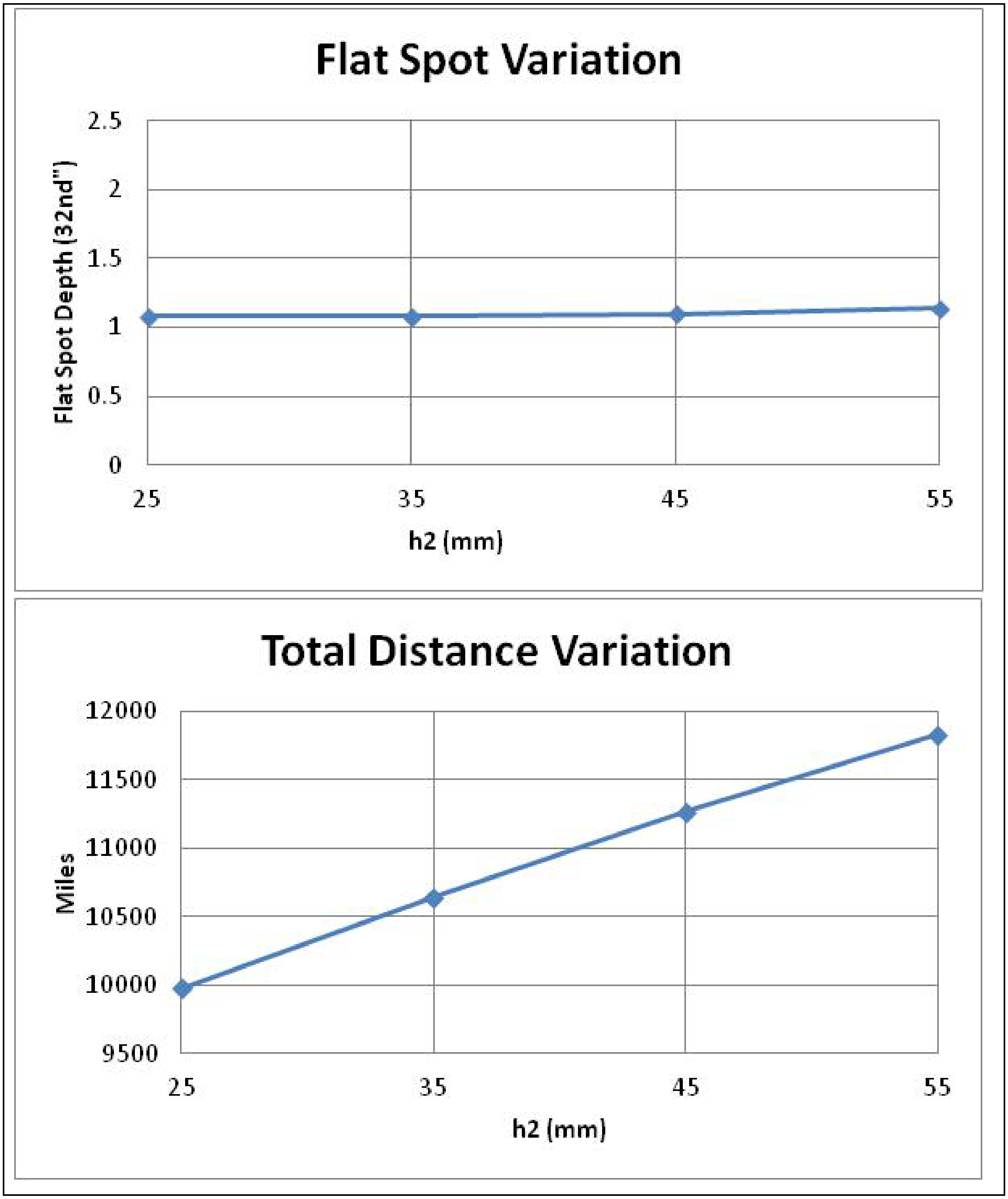


Figure 3. Simulation results for various values of h_1 with ΔG_0 = 400 J/m^2 and h_2 = 35 mm.



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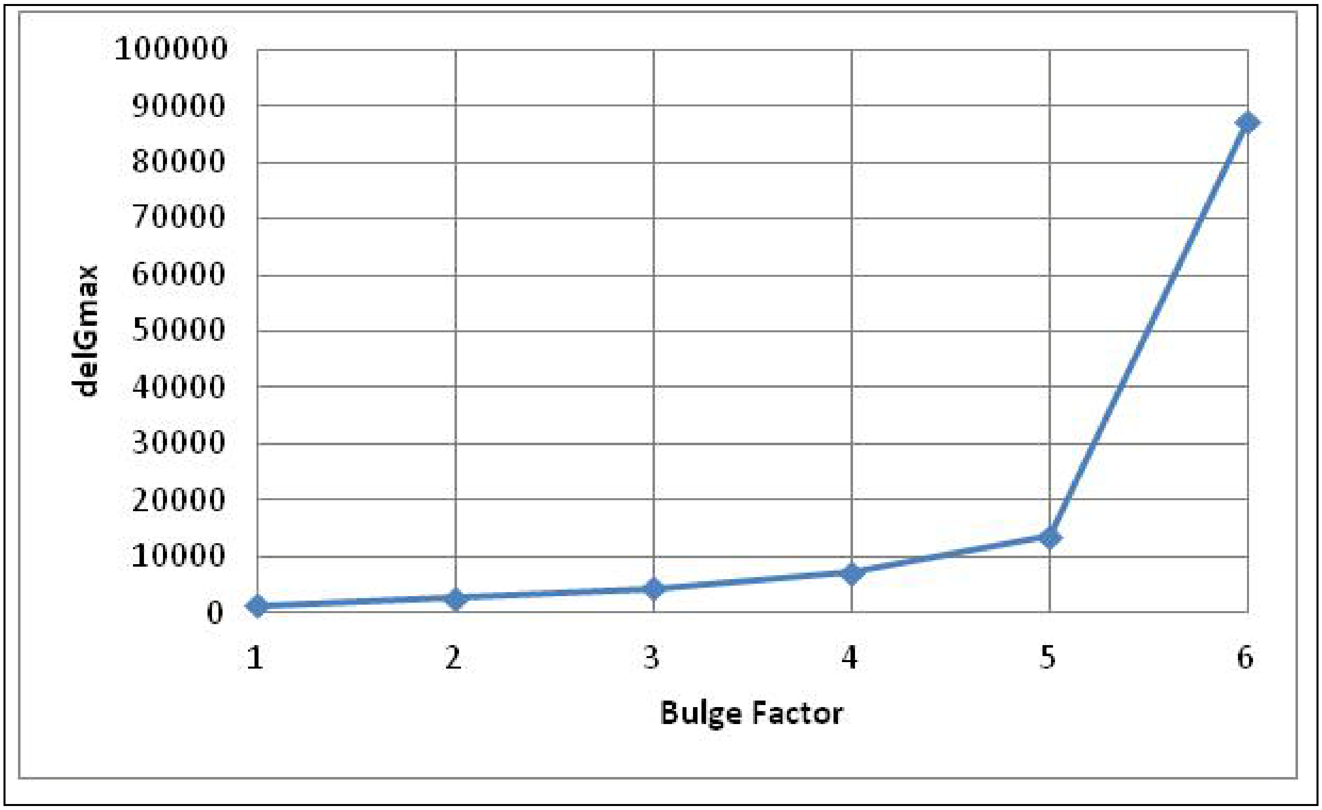

Figure 5. Values of ΔG_{max} required for solution at various bulge acceleration factors. With bulges, it is impossible to have a solution where the total mileage is less than the miles developed while $h < h_1$, and ΔG_{max} must increase without bound.

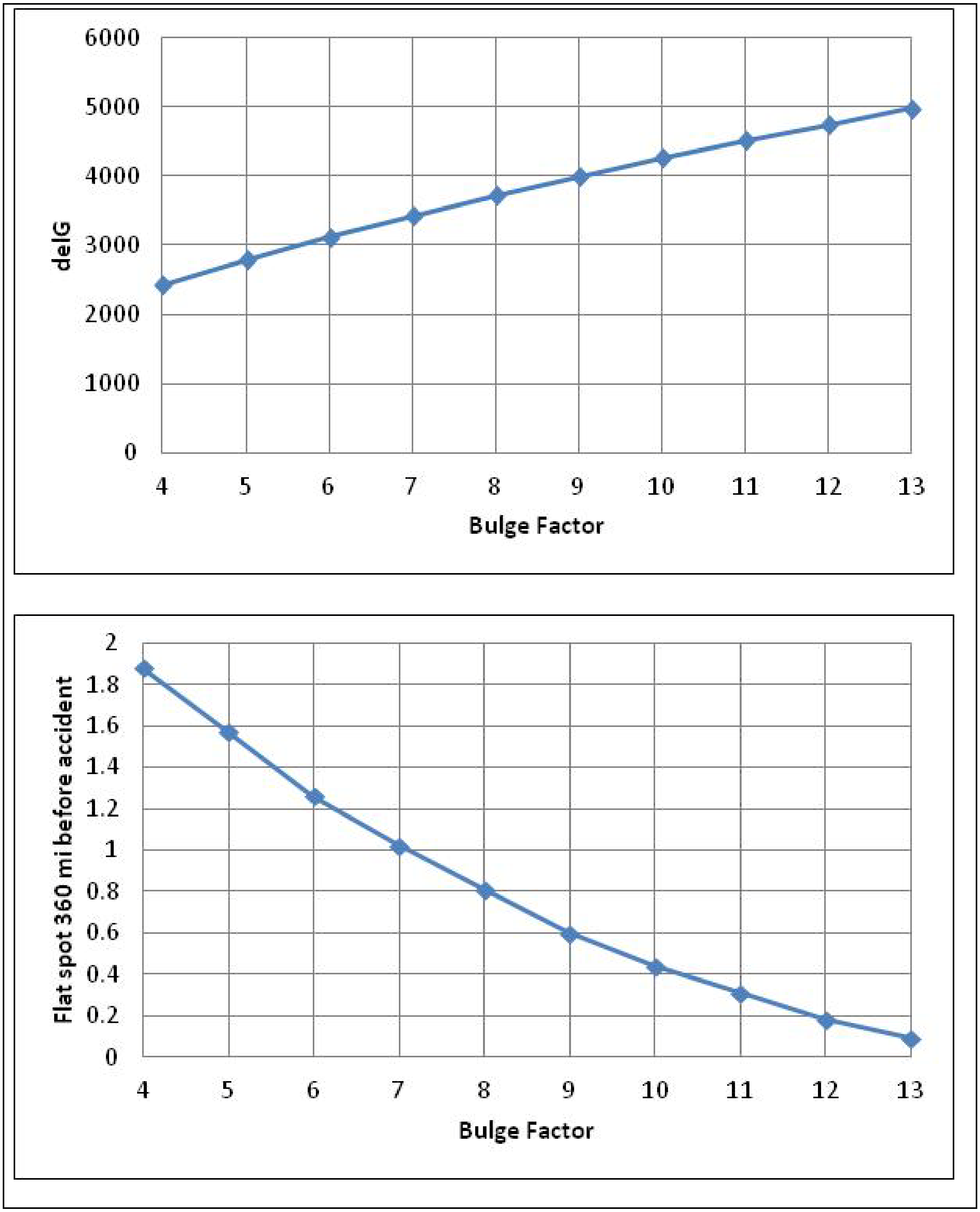

Figure 6. Simulation results using constant ΔG for a separation of size 3.5" x 16.7", nominal tread depth = $^{4}/_{32}$", Flat spot tread depth = $^{0.5}/_{32}$", and a wear rate of 4000 mi/32nd". A range of bulge acceleration factors bracket the likely flat spot depth 360 mi before failure.