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The Development and use of a Digital Twin Model for Tire Touchdown Health Monitoring

Andrew J. Zakrajsek[1,2]
United States Air Force, 96 TG/OL-ACL Landing Gear Test Facility, Wright-Patterson Air Force Base, OH, 45433

Shankar Mall[3]
United States Air Force Institute of Technology – ENY, Wright-Patterson Air Force Base, *OH, 45433*

Under performing aircraft tires can drive high program costs in addition to increasing the logistical and environmental footprint of that aircraft. Aircraft tire wear mechanisms are very complex and depend on a multitude of interdependent variables. Recent work has been completed showing that non-ideal touchdown (spin-up) landings can lead to potential tire flat spots and even mishaps. To enhance this tire touchdown wear prediction, a Digital Twin (DTw) model of a specific aircraft tire at touchdown was developed and utilized. This paper details the derivation of a physics based tire wear equation, *Slip Wear Rate*, for use in a nonlinear touchdown wear response model built from the high fidelity testing data. The response model was derived to be a function of variables that are easily visible in a field setting. A Monte Carlo analysis was used in conjunction with a Cotter sensitivity analysis to determine the uncertainty associated with the touchdown wear prediction. The DTw model was then used to determine Probability of Failure (POF) for varying distributions of sink rates, yaw angles, tire conditions (new to worn), and touchdown speeds. The DTw touchdown model results show future potential benefit for aircraft mission decisions that can assist in cost savings and health monitoring of tire's at touchdown. The initial DTw touchdown model is reviewed and future work is recommended to enhance the DTw touchdown model POF predictions. This initial DTw foundation is then extrapolated to show the future benefit of a DTw model for predicting the tire's full fielded life.

Nomenclature

DTw = Digital Twin
A1 = Aircraft 1
SR-1 = Lowest Sink Rate
SR-2 = Middle Sink Rate
SR-3 = Highest Sink Rate
SR = Sink Rate (General Variable)
E_{Spin_Total} = Total Spin-up Energy
E_{Wear} = Spin-Up Wear Energy
F_x = Drag Force
F_Z = Normal Force
t = Time
t_s = Time to Spin-Up Tire
TireC = Tire Condition (Tire Profile)
YAW = Yaw angle at touchdown (due to crosswind landing)
POF = Probability of Failure
n = Number of Monte Carlo Runs

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[1] R&D Engineer, 96 TG/OL-ACL Landing Gear Test Facility, 1981 5th Street WPAFB, OH
[2] PhD Student, Air Force Institute of Technology/ENY, 2950 Hobson Way, WPAFB, OH
[3] Professor, Air Force Institute of Technology/ENY, 2950 Hobson Way, WPAFB, OH

TW_{LM} = Touchdown Wear Equation (Linear Model)
C_i = Model Coefficients
R_w = Rate of Wear
A = Abradability (Tire Property Constant)
F_E = Frictional work per unit area
WR_{Flux} = Wear Rate
SWR_{Flux} = Slip Wear Rate
x = Distance tire travels
P = Tire inflation Pressure
γ = Tire slip percentage
TW_{NLM} = Touchdown Wear Equation (Nonlinear model)
R^2 = Coefficient of Determination
D = Tire Diameter
K_Z = Tire Vertical Stiffness
V_X = Touchdown Velocity
I_Y = Polar moment of Inertia
$SWR_{Flux,S}$ = Slip Wear Rate as function of Speed
CI = Confidence Interval

I. Introduction and Background

An aircraft tire spinning-up during touchdown is a very complex and dynamic process.[1,2,4] During touchdown the aircraft tire needs to accelerate to match the speed of the landing aircraft, which can result in tire wear that occurs in a highly localized area, causing non-uniform wear, informally referred to as a *flat spot*.[4,6-8] This *flat spot* can contribute to excessive wear during the remainder of the landing event, and potentially lead to in flight mishaps such as tire blowouts. Typically, touchdown wear has not been studied extensively due to initial findings, concluding that touchdown wear normally only accounts for around 5% of the typical aircraft tire wear spectrum.[2-4] Recent research performed focusing on non-ideal landing conditions showed that non-ideal sink rates, yaw angles (crosswind landing), and the tire profile can accelerate tire wear at touchdown.[9] The potential for a flat spot and the complex nature of predicting touchdown wear has yielded a need to develop an uncertainty based prediction using these empirical findings. This can be accomplished using the Digital Twin (DTw) process.[10-12]

Recently the US Air Force, in addition to other government organizations, have been developing DTw Models to attempt to address an increase in lifecycle costs and development timeline for the majority of new acquisition programs.[10-12] This DTw paradigm can be best understood as the “reengineering of structural life prediction and management”.[10] The DTw Model is a virtual representation of a system that is a combination of data and models that are intended to be continuously updated through the life of the system.[13] The models use multidisciplinary physics based approaches coupled with uncertainty simulations to provide failure predictions in addition to Structural Health Monitoring (SHM). To fully utilize these DTw models as intended, some major obstacles still need to be overcome. One of the major obstacles is that the high fidelity DTw models result in computationally expensive simulations, especially for Finite Element Methods (FEM) and Computational Fluid Dynamic (CFD) based DTw models.[10,11] To assist this, recent work has been completed using shape-memory sensing materials to assist in crack detection within a DTw model.[14] This type of research is increasingly important for DTw models as a potential way to reduce computational time without losing the high fidelity multiphysics based models. More work is needed to reduce computational time and create DTw models that are more easily integrated into actual fielded situations with a focus on variables readily available in these settings.

The majority of the available studies focusing on structures based DTw models have high analytical complexity and long life times associated with the structure. This results in few iterations of the DTw model. In this paper a different approach is taken, primarily based on high fidelity empirical results and the relatively short life time of aircraft tires. Utilizing recent experimental touchdown wear testing completed at the 96th Test Group/Aerospace Survivability and Safety Office (96 TG/OL-AC), Landing Gear Test Facility (LGTF), at Wright-Patterson AFB, a DTw model is developed and used. A nonlinear physics based wear prediction is derived based on key important variables that are both visible and potentially controllable in a fielded setting. Finally, the development and use of this DTw model for tire touchdown health monitoring (i.e. tire wear) is reviewed and linked back to the overarching DTw process.

II. Touchdown Wear Testing Results used for DTw Model

Experimental touchdown tire wear testing was previously completed focusing on non-ideal landing conditions. The experimental setup and results are briefly summarized here for convenience.[9] Testing was completed using an existing aircraft (denoted as Aircraft 1 (A1)) tire on the United States Air Force 168-inch (4.3meters) internal drum dynamometer (168i). It should be noted that A1's tire is a bias tire construction. The 168i is located at the 96 TG/OL-AC LGTF, at Wright-Patterson AFB, Ohio, and is available for military and commercial industry use.[1,5] An advantage of using the internal drum dynamometer, as opposed to a conventional external drum dynamometer, is that the tire footprint pressure distribution more closely resembles that of a flat runway. This provides shear stresses at the tread surface that are more representative of real world conditions. The dynamometer was fitted with a concrete surface which was cloned from an aircraft runway to properly simulate the runway micro and macro texture effects. This testing technique was developed at the 96 TG/OL-AC LGTF.[1] Figure 1 shows the 168i and the cloned concrete runway used for the touchdown testing.

Several tests were conducted at different ideal and non-ideal landing conditions. These tests studied different sink rates, tire profile, and yaw angles (simulating crosswind landings). The different test conditions were chosen to simulate both ideal and non-ideal landings. Table 1 recaps the factors and associated levels tested. A full factorial test matrix was completed, with two repeats of each test point. The sink rates range from Sink Rate 1 (SR-1) resembling a very slow sink rate (touch-and-go landing) to SR-3, simulating a typical aircraft landing sink rate. The tire profile was studied by testing a new A1 tire and a worn A1 tire. Finally, the yaw angles tested simulate a mild crosswind event. The simulated 3º yaw angle (mild crosswind) at landing is similar to landings that can occur with both military and commercial aircraft. This can still be considered a non-ideal landing condition when compared to previous studies. The 3º yaw is held constant for a specific time interval throughout the tire touchdown, to match statistical trends observed in A1 flight data, and then transitioned to a 0 º yaw heading. Landing speed and final load were held constant for all of the test points at a speed and load reflective of typical A1 landings. The testing was initiated with the A1 tire slightly off of the 168i surface. The 168i was spun-up to landing speed, then the A1 tire was loaded into the flywheel following a specifically designed loading profile.


a) b)

Figure 1. 96 TG/OL-AC LGTF 168-inch internal drum dynamometer. a) *The 168i with a tire instrumented for comparative wear testing.* b) *Concrete surface cloned from selected runway.*

Table 1. Factors and Levels used for Touchdown Wear Testing

Factors	Levels
Sink Rate	3
Yaw Angle	2
Tire Condition	2

During the tire touchdown event there are a multitude of instantaneous changes to the aircraft tire's resulting drag force (F_x), wheel speed, slip percentage, and much more. A touchdown test result from a new A1 tire test at SR-3, with no yaw condition, is shown in Fig. 2.[9] In Fig. 2, the aircraft tire speed (wheel speed) rapidly increases from zero to match the flywheel speed. This transition is the entirety of the touchdown event. The event is completed in a fraction of a second. Wheel slip has been calculated as a function of the aircraft tire speed and the flywheel speed. Drag force, F_x, initially peaks during the touchdown event, and then rapidly decays to a sustained rolling resistance force. The experimental testing results can be easily understood by analyzing the material loss. The wear at the touchdown point is termed the peak material loss, and it represents the maximum material loss which typically occurs at the initial contact point of the tire during touchdown. This is the most important result for understanding non-ideal landing conditions' potential to create a "flat spot". Figure 3 shows the previously published results for peak material loss of a new and worn A1 tire at the three sink rates, and crosswind landing (Yaw) data shown.[9] Even with these high fidelity results, there is always a measure of uncertainty with experimental testing. For the initial development of the DTw touchdown wear model, the uncertainty associated with the experimental testing was assumed to be negligible.

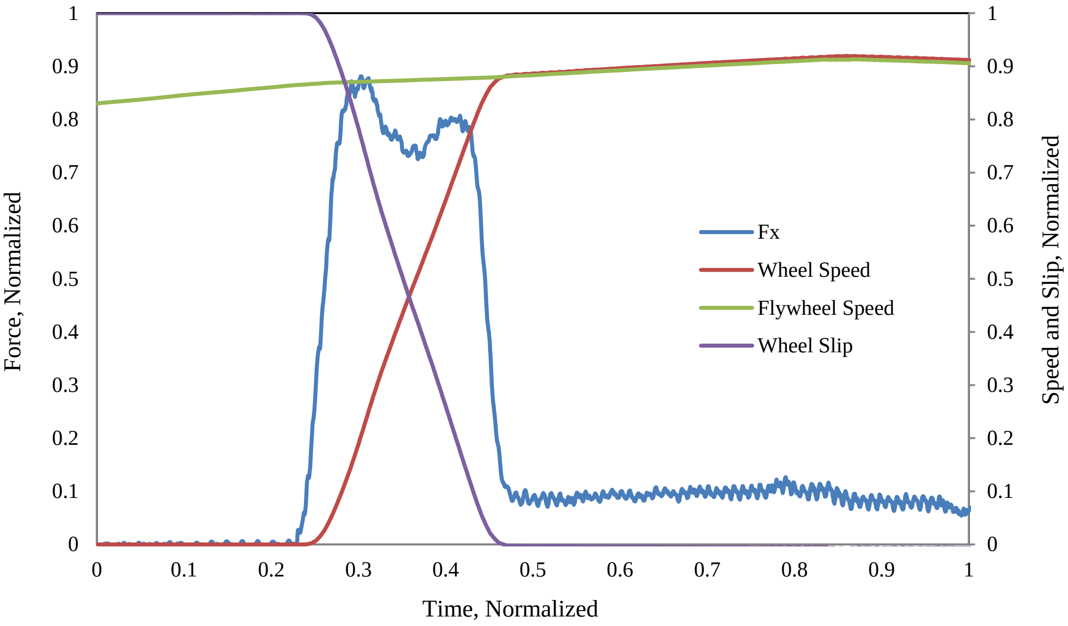


Figure 2. New A1 tire touchdown test at SR-3 with no yaw condition: resulting force, speed, and slip responses.[9] *The data presented has been normalized with respect to the maximum value.*

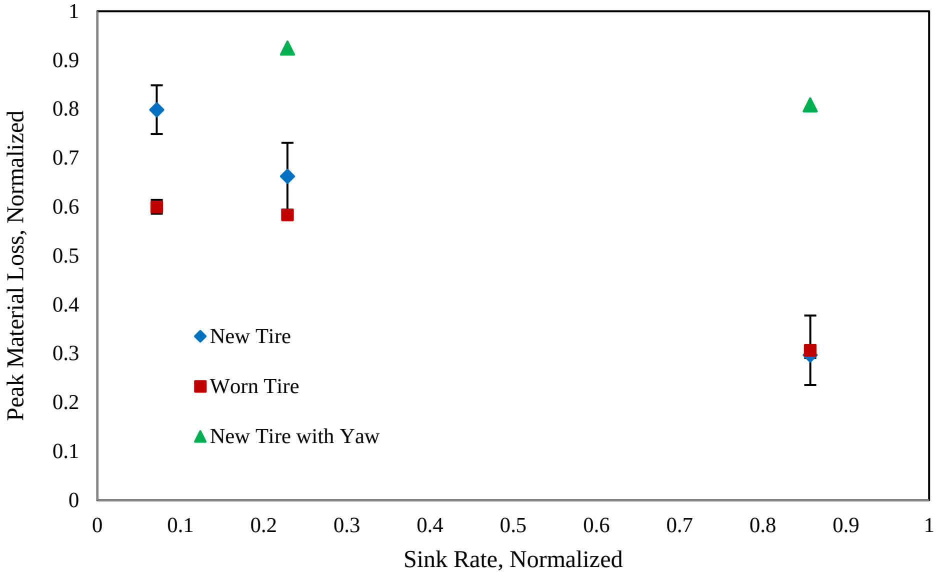


Figure 3. Peak material loss at different sink rates.[9] *SR-1, SR-2, and SR-3 flow from the left of the graph to the right, with SR-3 being near 0.85 on the normalized x-axis. The data presented has been normalized with respect to the maximum value. For all test points, standard error was calculated and shown above with error bars. In some instances the error was too low to visualize the plotted error bars.*

III. Development of Touchdown Wear Response Surfaces

The touchdown testing results provided a large set of empirical data that was imperative for the creation of the touchdown wear response surface. The response surface was initially selected to be a function of the same three independent variables: sink rate, tire profile (or tire condition), and yaw angle (simulating crosswind landings). Two separate response surfaces were created. The first response surface was created using a simple least squares fit to create a purely empirically driven model to predict touchdown wear based on the these independent variables. The second model incorporated more of a physics driven approach by deriving a nonlinear expression for tire wear based on the same independent variables.

A. Linear Response Surface (Empirically Driven)

An initial empirically driven linear model was created for the touchdown wear response surface. Touchdown wear is the response term in the model and shown in Eq. (1) with all coefficients values purposely excluded.

$$TW_{LM} = C_1 SR + C_2 TireC + C_3 YAW + C_4 \tag{1}$$

Touchdown wear is a function of three independent variables: sink rate, SR, tire condition, $TireC$, and yaw angle, YAW. The model coefficients, C_i, were created using the least squares fit of the empirical data. The model accuracy was then compared to the empirical results for the different test conditions giving a decent coefficient of determination ($R^2 = 0.83$). Figure 4 shows the response surface prediction versus the actual results. One of the major downsides of this empirically driven linear response surface is the lack of underlying physics that link the testing data to tire wear. To better incorporate the physics of tire wear into the response surface, a nonlinear physics driven response surface was created.

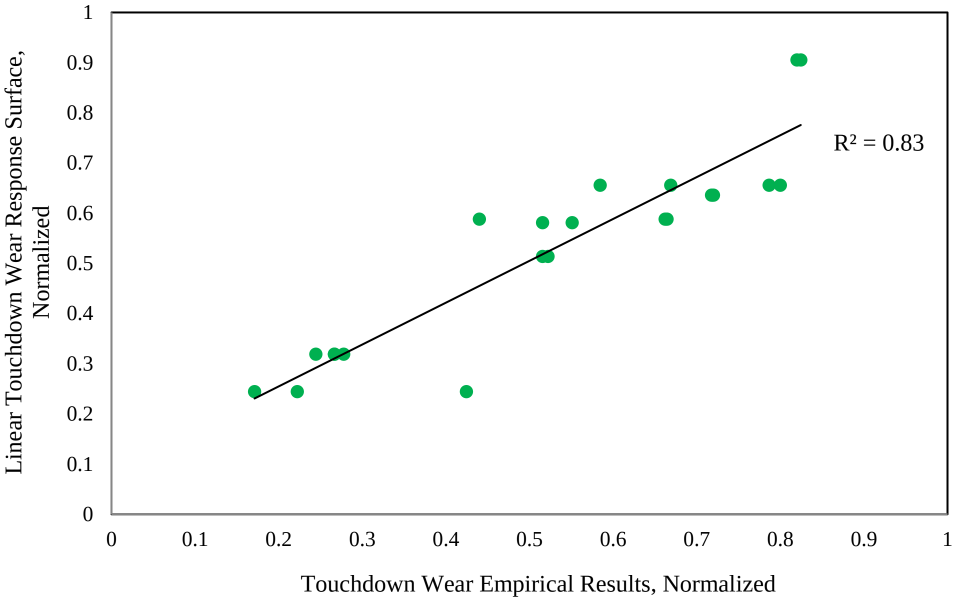


Figure 4. Linear Touchdown Wear Response Surface. *Compares linear touchdown response surface to empirical results previously presented in Fig. 3. The data presented has been normalized with respect to the maximum value.*

B. Nonlinear Response Surface (Physics Driven)

To better address the need of the DTw model to be built on underlying physics based models, a more detailed touchdown wear response surface was needed. Due to the complexity of aircraft tire wear, especially ablative-driven touchdown tire wear, a simplified physics based model was needed to link or bridge the difference between the variables available in the field and the physics-based variables that govern the wear process. There are few physics based predictions of spin-up wear. One of the most notable examples is an analytical-numerical simulation created by Padovan et al.[17] This simulation is based on several lower-level engineering inputs and data driven profiles that would not be easily obtained and tracked in the field. Therefore, in addition to the physics driven tire wear expression, an attempt was also made to bridge the gap between user level inputs (i.e. sink rate, yaw, speed, etc.) and the engineering inputs (i.e. force responses, tire deflections, temperature responses, etc.) needed for the physics based equations. One of the best ways to bridge this gap is using high fidelity testing data to develop these response surfaces.

Looking back farther into the literature gave more general closed form expressions for tire wear than the more developed numerical models of Padovan et al. One of the most fundamental physics-based expression for tire wear rate (automotive) was shown as a function of the frictional work generated in the interface between the tire and road per unit area, recently summarized by A. G. Veith and shown in Eq. (2).[18] The rate of wear, R_w, is the product of the abradability constant, A, and frictional work per unit area, F_E. Following along with this equation, recent research showed that aircraft tire life can be related to the ratio of the aircraft's maximum kinetic brake energy over the available surface area of the aircraft tires.[1] Both of these papers represent a similar concept that can be assumed and understood as a frictional energy flux, or just simply *Energy Flux*. This *Energy Flux* concept was useful for predicating tire wear based on both lower level engineering terms (abradability, force response, etc.) and upper level system variables (i.e. tire surface area, brake energy rating, etc.). To consider this an *Energy Flux*, we need to assume that all the frictional work enters the tire through the contact patch area. It should be noted that this assumption is less valid for the aircraft tire life ratio developed by Zakrajsek et al.[1]

$$R_w = AF_E, \tag{2}$$

A more general development of Eq. (2) was needed to better illustrate the *Energy Flux* expression. Focusing on what the tire sees, the substitution of response forces into the expression gives a more generalized *Wear Rate*, WR_{Flux}, equation, given by,

$$WR_{Flux} = A \int F_x(x) \frac{P}{F_Z(x)} dx \tag{3}$$

Here the integration of the drag force, F_x, over the tire travel distance, x, is used to obtain the frictional work going into tire. This is divided by the approximated contact patch area, which is the relationship of the tire's inflation pressure, P, and varying normal force, F_Z. The abradability term, A, can be better assumed to encompass all tire properties, not just abradability. Equation (3) can be used to compute the tire's *Wear Rate,* during actual testing or flight operations (determining on instrumentation limitations). It should be noted that the ability of the *Wear Rate* equation to predict aircraft tire wear for various aircraft is not well known, however, it still serves as a good physics-based starting point for this DTw model. In addition to the expansion of Eq. (2) to incorporate the response forces, there needed to be more physics added to relate the expression to aircraft tire wear. This is needed due to the aircraft tire having to undergo a higher variability of tire wear spectrums (landing and takeoff), when compared to automotive tires. Additionally, the high speeds and loads experienced by aircraft tires drive more of a dynamic wear situation, resulting in an increased slip for aircraft tires compared to automotive tires.[2-4,17] Therefore a simple, yet useful way to expand upon the *Wear Rate* equations is to add a slip term giving the following equation,

$$SWR_{Flux} = A \int F_x(x) \frac{P}{F_Z(x)} \gamma(x)\, dx \tag{4}$$

With this addition, the *Wear Rate* can be re-termed as a *Slip Wear Rate*, SWR_{Flux}, being a function of the percent slip, $\gamma(x)$, the tire experiences. Since slip, unlike rolling is where the aircraft tire experiences the majority of wear, the slip term acts as a gate, allowing the potentially more accurate summation of the aircraft tire's *Wear Rate*. It should be noted that slip term,$\gamma(x)$, cannot equal zero, as would be expected for any rolling tire always experiencing some small slip. For example; if an aircraft brake system locks-up, the slip is ~100%, thus all of the *Wear Rate* is going into wear the tire. This addition attempts to compensate for the traditionally nonlinear wear rates the aircraft tire will see during the various landing and takeoff wear spectrums. The expression assumes that the energy going into heating the tire is negligible. This approximation initially neglects any temperature effects. A similar slip addition was used in a Drag Wear Energy expression; however, a constant value was assumed for the purposes of building test profiles and not for predicting tire wear, as is being proposed here.[5] The equation for *Slip Wear Rate* is noticeably still in terms of lower-level engineering variables, especially the integration with respect to distance. These lower-level engineering terms make the DTw process more difficult due to an increased level of engineering driven complexity on the user to update the DTw models. To better use the *Slip Wear Rate,* a relation to the known empirical testing parameters is needed. Therefore an effort was made to translate Eq. (4) into terms of the three important variables (Yaw Angle, Sink Rate, and Tire Condition), which are all readily available in a fielded setting. To complete this a detailed review of the data previously published was needed.[9]

To start this bridge to field visible variables, the frictional work the tire sees was approximated by the varying sink rates. From previous work the total frictional energy experienced by the tire was similar for all sink rates, however, the response of the frictional energy was vastly different.[9] Assuming the first time steps during the touchdown are the most critical for wear, then the higher sink rates had a larger frictional work initially than the lower sink rates. The higher initial frictional work seen by the tire at higher sink rates resulted in less tire wear versus the lower sink rates resulting in higher wear. Therefore the frictional work is approximated as a function of SR, shown in Eq. (5). For this initial nonlinear response surface development this approximation was used to be able to compare to the experimental results, however, it should be noted that this approximation is a major assumption and the frictional work would be better represented by including other variables such as landing speed and load, among many potential others.

$$\int F_x(x)\; dx \sim f(SR) \tag{5}$$

Following similar logic the tire profile was seen to be very relatable to the contact area. The A1 tire at the worn state has an increased contact area, which reduced the touchdown wear at the lower sink rates.[9] Therefore, following this we can approximate both the pressure and normal force, and subsequently the contact area as a function of the tire condition, shown in Eq. (6). Also, even though pressure and normal force are clearly better for contact area prediction, these variables, specifically normal force may not be readily available in the field versus a known tire condition, which is the reason for the relation.

$$\frac{P}{F_Z(x)} \sim f\left(\frac{1}{TireC}\right) \tag{6}$$

The final relation needed to complete the approximation of the physics-based *Slip Wear Rate* equation with field visible variables was the relation for the slip term. The slip is primarily a function of all three variables tested,

$$\gamma(x) = f(SR, TireC, YAW), \tag{7}$$

and many more. Due to the limited factors and levels tested, using all three variables to formulate the slip was not practical. For this initial approximation, slip will be determined as only a function of yaw angle alone. This simplification is given some credibility from the experimental findings that regardless of the sink rate or tire profile, test conditions with yaw (crosswind landing) showed a relatively similar touchdown wear.[9] It can be assumed that the similar wear was partially related to the initial tire offset (yaw angle) causing an increased slip during touchdown. Therefore slip can be approximated by Eq. (8). Rearranging Eq. (4) through (8) gives an expression for the *Slip Wear Rate* as a function of variables readily available in the field, shown in Eq. (9). A nonlinear fit of Eq. (9) using the experimental data previously referenced for spin-up (touchdown wear)[9], gave the final nonlinear response surface for touchdown wear, shown in Eq. (10). The nonlinear fit was performed using a fitting algorithm that estimated the model coefficients using an iterative least squares estimation, with initial values needing to be initially specified.

$$\gamma(x) \sim f(YAW) \tag{8}$$

$$SWR_{Flux} \sim f\left(A\frac{SR}{TireC}YAW\right), \tag{9}$$

$$TW_{NLM} = C_1 + \left(\frac{SR}{TireC}\right)^{C_2}(YAW)^{C_3}. \tag{10}$$

The nonlinear touchdown wear surface, TW_{NLM}, was fitted using an iterative procedure to estimate the model coefficients, C_i. The touchdown wear response surface is shown as a nonlinear function of the sink rate, tire condition, and yaw angle. The model accuracy was then compared to the empirical results for the different test conditions giving a decent coefficient of determination ($R^2 = 0.83$). Figure 5 shows the response surface prediction versus the actual testing results.

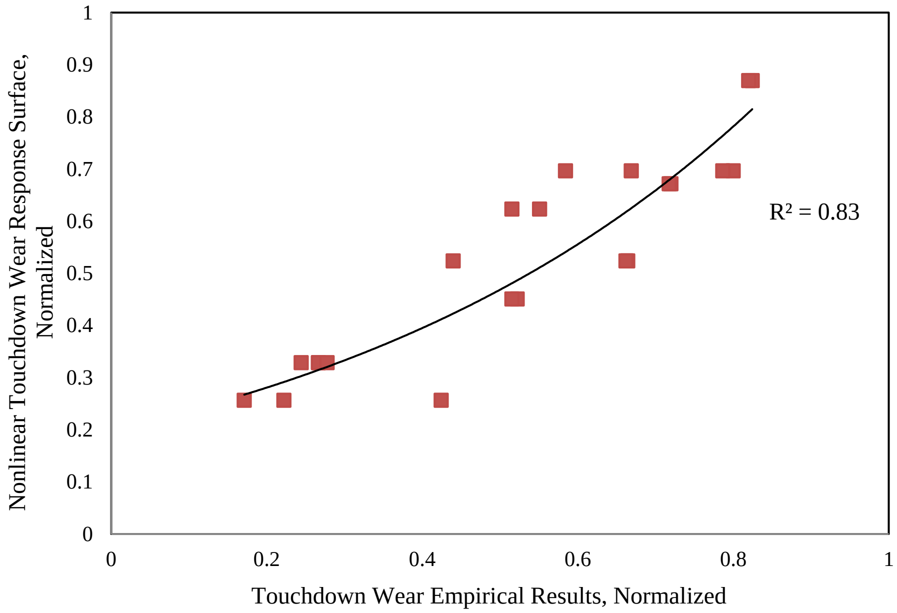
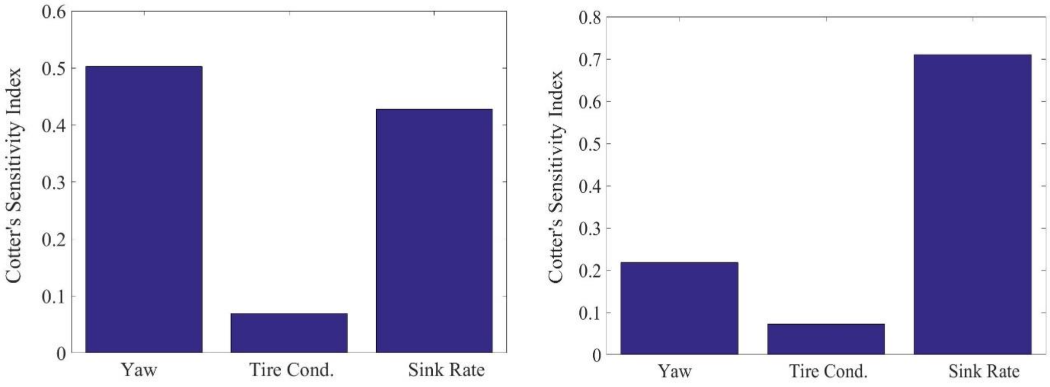


Figure 5. Nonlinear Touchdown Wear Response Surface. *Compares nonlinear touchdown response surface to empirical results presented previously in Fig. 3. The data presented has been normalized with respect to the maximum value.*

C. Comparison and Finalization of Response Surface for DTw Model

Two separate response surfaces were created to predict touchdown wear. The two response surface models were fitted to the empirical data set previously shown. The empirically driven linear response surface and nonlinear physics based response surface have the same coefficient of determination. This non-ideal coefficient of determination can mainly be attributed to the lack of levels and potential missing important factors in the experimental set used for model development. Without including additional physics in the model or collecting additional testing points there is a likelihood that the coefficient of determination will not increase further for any model built from this data. Even with this coefficient of determination, the physics based nonlinear response surface has more long term potential as it is based on a deeper understanding of tire wear. The usefulness of the nonlinear response surface prediction is best understood by completing a sensitivity analysis, and looking at the importance of each independent random variable.

A Cotter sensitivity analysis method was used to analyze the variables sensitivities to both response surfaces.[15] The Cotter sensitivity analysis is a useful analysis for experimentally driven data, and thus fit this need well. This analysis requires both maximum and minimum values of the test variables to compute the sensitivity. The maximum and minimum values were randomly selected for each factor following normal distributions that are representative of historic and field data. Figure 6 shows the sensitivity results for both response surfaces. A sensitivity analysis of the linear model reveals that the tire condition has little effect on tire wear. Additionally, seen in Fig. 6a, the yaw value is most likely over represented in the linear model. Contrary, the nonlinear sensitivity results, Seen in Fig. 6b, show a heavy reliance on sink rate versus tire condition and yaw angle. While the nonlinear model has a higher reliance on sink rate than would be desired, it is acceptable for this initial model, due to the largest number of levels tested having been for the sink rate. Additionally, even though tire condition sensitivity is still relatively low in the nonlinear model, it is more comparable to yaw angle, which is also substantially lower than in the linear model. The nonlinear model's lower sensitivity to both yaw angle and tire condition are not desirable, however, it is acceptable for this initial model development with the known need for future model improvements. Due to the physics based aspects of the nonlinear model, and ability to continue the development of the model easier than the linear model, it was selected and assumed as the *best* model for the remainder of the predictions.



a)

b)

Figure 6. Cotter's sensitivity of linear and nonlinear response surfaces. *(a) Cotter's sensitivity of factors with respect to the linear model. b) Cotter's sensitivity of factors with respect to the nonlinear model. All factors in the cotter's sensitivity index will sum to one.*

Selecting the nonlinear physics based response surface is important for the overall DTw process. Even with the selection as the *better* model, the nonlinear model still has some areas of uncertainty, one of these being a result of the lack of factors tested. One of the most important factors for predicting the tire's touchdown wear is the speed of the aircraft at touchdown.[17,19] An academic effort was made to use literature to update the *Slip Wear Rate* equation to encompass touchdown speed. To add speed to the touchdown wear response, a touchdown severity model developed by S.K. Clark is used.[20] This touchdown severity dimensionless equation is expressed as,

$$Touchdown\ Severity = \left\lfloor \frac{V_X^2 I_Y}{D^4 K_Z} \right\rfloor, \tag{11}$$

where the touchdown severity is related to the rolling direction (x component) velocity (speed), V_X, the polar moment of inertia, I_Y, the tire diameter, D, and the tire vertical stiffness, K_Z. Simply incorporating this dimensionless expression into the *Slip Wear Rate* gives,

$$SWR_{Flux,S} \sim A \frac{SR}{TireC} YAW \left\lfloor \frac{V_X^2 I_Y}{D^4 K_Z} \right\rfloor \tag{12}$$

Since the experimental testing was all completed with the same tire, Eq. (12) (*Slip Wear Rate* as a function of speed, $SWR_{Flux,S}$) can be re-arranged to put all tire constants into the tire property constant term, A, simplifying the expression. The tire property constant term was obtained experimentally for this work. The final nonlinear physics-based response surface used this relation in Eq. (12) to scale the results of Eq. (10) for inclusion of the touchdown speed factor. It should be noted that there was no effort to determine any potential error with this addition to the model, and any error quantification as will be discussed was with the base nonlinear touchdown wear model, shown in Eq. (10). The addition of speed was shown as a simple academic example of the importance of physics based models and the ability to continually update them to include more relevant factors. To use this updated model for actual touchdown wear predictions, additional testing points would be needed to account for varying speed at touchdown. The final nonlinear touchdown wear response surface, including the addition of speed, was assumed as the *truth* for the remainder of this work.

IV. Development of the DTw Tire Touchdown Model

For the development of the DTw model the nonlinear touchdown wear response surface is assumed as the *truth*. The coefficient of determination shows that there are physics and important factors (random variables) missing from this response surface, however, assuming this surface as the *truth* allows the development of the DTw model, and thus shows its potential benefit for fielded predictions. This nonlinear response surface was used as the physics based element of the DTw model. The ability to use high fidelity testing data to relate the physics based *Slip Wear Rate* expression to actual variables visible in the field is very important. This single response surface provided a robust way to look at the effect of multiple simultaneous variable changes in a fraction of seconds due to the analytical nature of the model. Thus, using experimental data from a real-world test environment proved as a very beneficial starting place for building a DTw model.

The analytical based response surface allows the use of a Monte Carlo sampling technique. This allows multiple simulations to be completed with the response surface in a quick timeframe when compared to either FEM or CFD based models. Therefore, starting from high fidelity test data provides a good initial foundation for the Monte Carlo analysis, where applicable. Since aircraft tire's wear out over several landings and takeoffs, a failure limit was needed. The failure limit can be understood as the user specified wear limit of the tire (not necessarily 100%). For example; touchdown wear typically doesn't account for more than 5% of full tire life at ideal conditions. Thus, for the purposes of this paper, a 10% wearing of the tread from the single touchdown event is considered failure as this would most likely cause a *flat spot* in the tire. Therefore the final DTw model is setup to allow any failure limit, however, a 10% failure limit was chosen for this work and reporting purposes. This failure limit was used with the Monte Carlo simulations and physics based response surface to generate the probability of failure (POF) for the tire to reach the failure limit.

An effort was made to include uncertainty in the Monte Carlo developed POF for this DTw touchdown model. A 95% confidence interval was created for the nonlinear touchdown wear response surface and used in this prediction. Prior to each Monte Carlo run four random variables were selected following their representative distributions. These random variables are sink rate, tire condition, yaw angle, and touchdown speed. Each of these variables was randomly generated following assumed normal distributions with both mean and variance values chosen initially from historical flight data. During the Monte Carlo analysis the random variables were stored to assist in the Cotter sensitivity analysis. The sensitivity analysis was performed for every model variable change (distribution, mean, and variance) showing shifts and changes in sensitivity of the important random variables related to the touchdown wear response surface. This coupled with the POF gives an idea of important variables to consider. Figure 7 shows the final DTw model schematic for a tire at touchdown following similar previous DTw type illustrations.[10] This developed DTw model can be used by varying the random variable means and variances for *n* Monte Carlo runs to determine the POF of the tire *flat spotting* during touchdown. This POF can assist with tire touchdown health monitoring prior, during, and after landings.

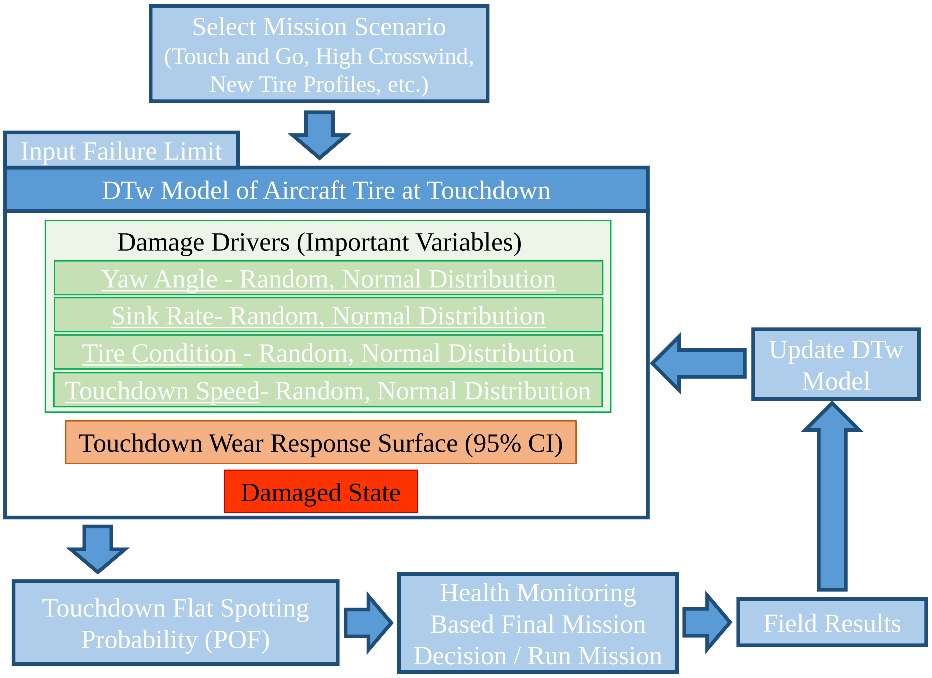


Figure 7. DTw tire touchdown model schematic.

V. DTw Tire Touchdown Model Results, Discussion, and Future Uses

Health monitoring of aircraft tires is comparable to both landing performance and wear monitoring. During every landing the tire wears, creating a new tire condition or profile. The new tire condition after every mission increases the already complicated wear prediction and resulting tire health monitoring. This preliminary DTw model for tire touchdown heath monitoring starts to address this health monitoring issue by predicting touchdown wear using probability and uncertainty. The DTw model can be used to predict if a tire will reach a user specified failure limit (i.e. wear limit), previously described to be considered 10% of tire life for this analysis. The DTw prediction is based on the previously derived nonlinear touchdown wear response surface and four important random variables. For the remainder of the discussion it should be noted that this DTw model was run with 10K Monte Carlo simulations, following established guidelines for Monte Carlo run selection.[16]

The DTw model was initially used to simulate a normal or average aircraft touchdown. To complete this normal prediction, historic flight data driven mean and variance values were chosen for the normal distributions of sink rate, speed, and yaw angle at touchdown. Tire condition was varied between new and worn tire conditions to simulate the variability likely to be seen in the field. The DTw model gave a ~21% POF for the A1 tire, which is a 21% probability the tire will reach 10% tread wear at touchdown. This prediction is higher than previous predictions for normal operation touchdown wear, and is a higher POF than what would be experienced in the field. The higher than anticipated POF continues to highlight the need for model enhancements, however, even with this overestimated normal touchdown POF, the DTw model still can be used to illustrate its future use and show how POF varies with sink rates, yaw angles, and speeds.

A. Touchdown POF for Varying Sink Rate, Yaw Angle, and Speed

During each touchdown the tire will wear, through an ablative wear process. The DTw model was used to predict the POF (for a specified failure limit) and monitor the tire's health in a simulated fielded condition. This was done by varying the mean values of the random variables (Sink Rate, Yaw Angle, and Speed). The variances were held constant for all random variable distributions. The ability to change the means of the independent random variable distribution clearly shows how this model could be used in a field setting to predict touchdown wear. It should be noted that for this prediction, some of the random values were selected outside of the testing data bounds (extrapolated from trends). The tire condition was randomly selected between a new and worn tire condition for all following simulations. The tire condition selection was performed this way to represent the random tire wear levels experienced in the field. The independent variable changes and distributions are extremely important for the POF predictions from the DTw model. Prior to each DTw run (Monte Carlo simulation) the random variables were selected from their respective distributions and the touchdown wear was computed from the nonlinear wear response surface. The results were compared to the failure limit which builds the POF.

Figure 8 shows the POF for the A1 tire to reach 10% wear at touchdown for varying sink rate means in addition to changes to landing speed means. First the sink rate was varied through several different mean values keeping the same variance. The yaw angle was kept at the same mean and variance values (using the normal distribution) based on historical flight data for the all of the runs. The average touchdown speed mean was increased and decreased by 10% for all the sink rate means. The POF at touchdown significantly decreases with increasing sink rate. The variations in speed show that at higher speeds there is an increased POF for the tire. This is expected based on the expression and incorporation of S.K. Clark’s expression into the enhanced physics based prediction part of this DTw Model. The results also clearly show how these random variables could be selected to give POF predictions for a specific mission or landing scenario.

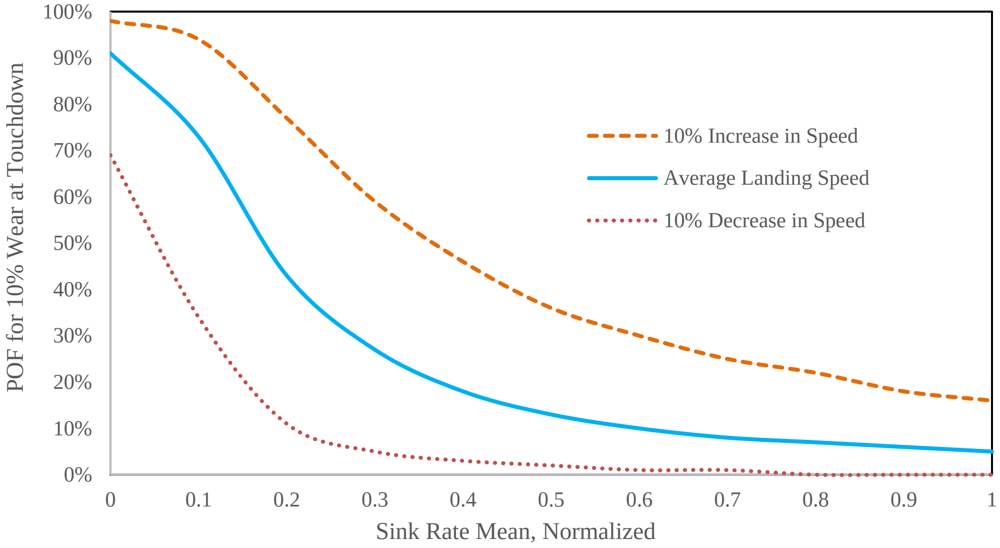


Figure 8. Tire touchdown POF for varying mean sink rates and speeds. *The sink rate and speed mean values were varied for their respective normal distributions. The data presented has been normalized with respect to the maximum value.*

The same POF prediction was completed for varying mean yaw angles. The yaw angle was varied through several different mean values keeping the same variance (based on historical flight data) for the random normal distribution selection. Additionally, the sink rate was randomly selected from its normal distribution based on mean and variance values chosen from historic flight data. The touchdown speed mean value was varied following the same logic as in the previous section. The DTw model was run giving a POF for varying mean yaw angles, shown in Fig. 9. The POF increase is initially nonlinear, however becomes linear farther into the POF response. The linear response may be attributed to the lower sensitivity of the nonlinear response surface to yaw angle when compared to sink rate. This may also be attributed to the extrapolation of the yaw mean distribution values as well. The effect of the speed mean increase and decrease on the POF follows what would be expected in a fielded setting. The POF results for varying mean yaw values highlight some potential needed model additions to better encompass the nonlinear yaw behavior.

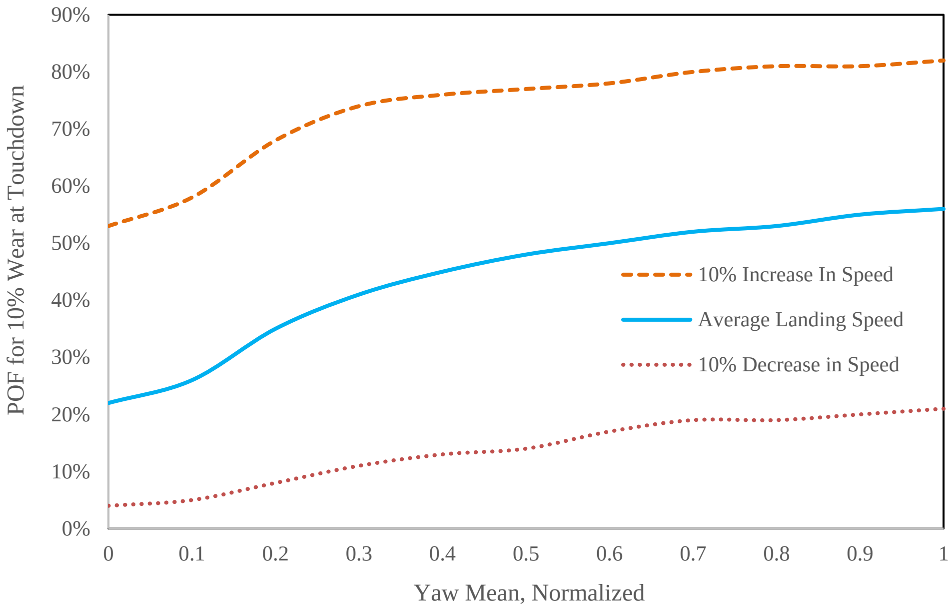


Figure 9. Tire touchdown POF for varying mean yaw angles and speeds. *The yaw angle and speed mean values were varied for their respective normal distributions. The data presented has been normalized with respect to the maximum value.*

B. DTw Tire Touchdown Model Potential Benefit for Field Operations

The DTw tire touchdown model results clearly show how this model could be useful for assisting real-time flight operations and mission risk assessments. Specifically with this model focusing on *flat spotting* potential at touchdown. The current DTw model, with additional model updates, could be used for field wide decisions (global decisions). A specific example can be seen by using the DTw model to potentially change landing procedure (i.e. increasing sink rate in certain landing conditions to cut down on touchdown related wear). Similarly, if there is high crosswind on a day with non-critical flights, the POF could assist in quantifying the risk of landing and any potential landing mitigations that could take place to avoid excessive touchdown wear. Figure 8 and 9 give an initial idea of how these DTw results could be used to vary all four random variables to understand a tire's touchdown POF based on the user specified failure limit. Not shown above are the results from varying all of these random variables at once. The POF is very high for high yaw angle and low sink rate landings. In addition, more detailed understanding of the variables interactions can be examined using this DTw model. Another additional benefit of the model is the tire condition can also be specified for new or worn tires if a random selection is not desired. This type of tool can be increasingly important for programs with poor performing tires in a flight test and training environment. Likewise this information can be utilized to inform decisions as to acceptable levels of risk when planning missions and or changing flight operations. The results can also be used to continually monitor the tire's health (for touchdown wear) after each mission. Another benefit of the model is that it is a physics based analytical model fitted to empirical data and thus can be run with 10K Monte Carlo simulations or more in a matter of seconds. Finally, the model is linked to field visible variables and can be used in a fielded setting during mission planning, without any in-depth engineering understanding. With more development of this DTw model, there is a clear potential use and benefit for the field and touchdown health monitoring.

C. DTw Model Limitations and Next Steps

The DTw model presented in this paper has several areas which are not fully complete and can benefit from further model enhancement. One of the major areas for improvement would be increasing the levels and additional factors tested. This need is understood by analyzing both the linear and nonlinear model's coefficient of determinations, which are currently not sufficient for a predictive model. In addition to more high fidelity testing data, more derivation and development of the *Slip Wear Rate* equation is needed. The yaw angle's nonlinear influence on tire wear needs to be better incorporated into this equation. Likewise the importance of touchdown speed should be better incorporated into a final touchdown response surface through more testing data and physics driven models. More development of the tire property constant term, A, is needed to give users a way to use known tire property data to build this constant.

Other factors to consider are updates to the tire condition, surface characteristics (runway properties), more tire properties, environmental conditions, among many others that are needed for more robust predictive models. The addition of most or even some of these items will allow further development of the physics based response surface, giving a better coefficient of determination and more robust DTw model.

In addition to the enhancements of the physics based equations and testing data, a better understanding of the random variable distributions, including the mean and variances are needed. This model and paper assumed the distributions from limited historical flight data and assumed that each distribution, excluding tire condition, was a normal distribution. The important random variables, especially variables like yaw angle, would not be expected to follow normal distributions and might follow more skewed distributions. Several papers could be written on this topic itself due to the more uncertain field conditions of these and other independent variables. Another reason why these independent random variables are extremely important, are the ability to link the DTw model to the field for continued updating. Understanding these variables and being able to incorporate the field visible variables will assist this DTw model and all DTw models in general. This is a very important point because even if a DTw model was capable of predicting field results with perfect accuracy, if the inputs to the model are not readily available or easily measured, the model will not be used.

The final, and potentially most important model limitation is the inability to easily compare the results to the field, as the field landings encompass more wear spectrums than just touchdown wear. Thus, a comparison to the field would be subjective at best for updating this model, and it can’t fulfil the full DTw paradigm. The tire touchdown DTw model, while showing some initial benefit, will eventually need to be expanded on. The next step in building a DTw model of an aircraft tire should focus on overall tire life. This next step, full tire life DTw model is shown in Fig. 10. It should be noted that the inputs in Fig. 10 need to be eventually updated to encompass more readily available user inputs, once more information is available on this future DTw model. The idea is to build a more robust DTw model focusing on the full wear spectrum, not just touchdown wear. This full tire life DTw model can be accomplished using a similar approach as in this paper, with a nonlinear physics based model fit to high-fidelity testing data. One of the clear major benefits of this type of DTw model is the relatively very short aircraft tire life when compared to general structure lifetimes. This would allow the model to continually be iterated upon and updated. Doing this will not only quickly create a more refined DTw model for aircraft tire life, but also better define and add understanding to the overall usefulness and possibilities of the DTw process.

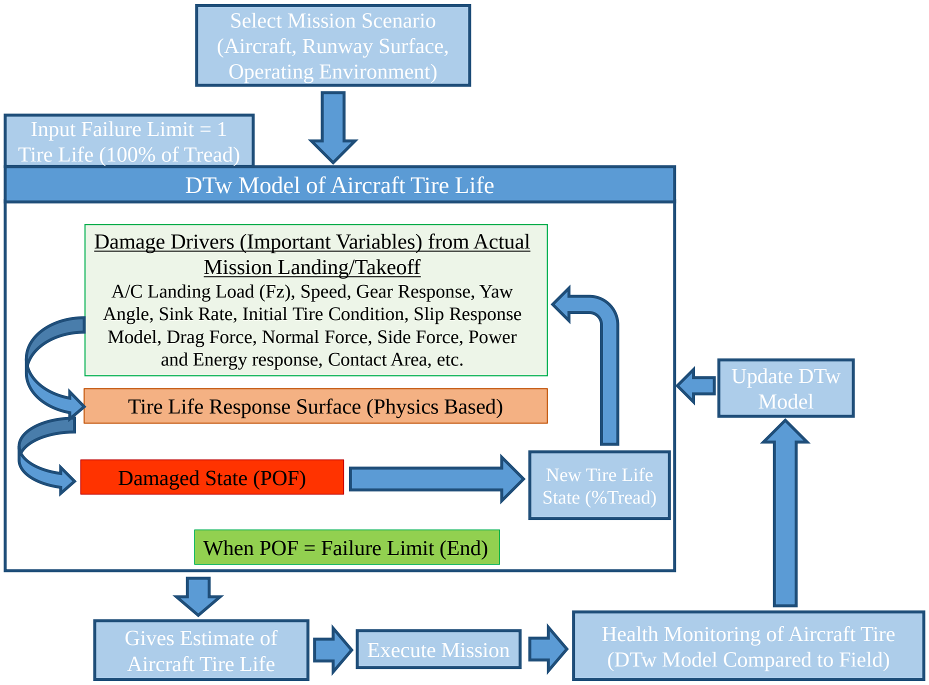


Figure 10. Future DTw Model of Tire Life for Health Monitoring

VI. Conclusions and Future Work

Aircraft tire wear at touchdown can lead to excessive wear (*flat spots*) and potential landing mishaps due to non-ideal landing conditions. Previously published experimental tire touchdown wear results were used to develop a DTw model to enhance the prediction of tire touchdown wear and associated health monitoring. The DTw model was built using a derived physics based equation, *Slip Wear Rate,* to predict touchdown wear. The *Slip Wear Rate* equation in conjunction with the empirical results were used to create a nonlinear touchdown wear response surface. A link or bridge between lower-level engineering variables and those variables more visible in a fielded setting was completed to make the final DTw model more applicable to the field. A Monte Carlo simulation technique along with a Cotter sensitivity analysis was used to complete the DTw model. The DTw model was then used to predict POF of a touchdown landing while varying the mean sink rate, yaw angle, and speed, following their respective random normal distributions. The results clearly showed the potential benefit of this DTw tire touchdown model for assisting flight operations by computing POF (tire touchdown wear) for specific missions. A detailed discussion on ways to improve the model was completed showing needed steps to make the final DTw model more robust. Finally, a need to move beyond one aircraft landing spectrum (touchdown wear) to a full tire life DTw model was discussed. One of the major benefits of a DTw full tire life model is the ability to easily compare the model results to the field. This would allow the model to continually be iterated upon and updated creating a more refined DTw model for aircraft tire life, but also better defining the overall usefulness and possibilities of the overarching DTw process.

The creation of this DTw model also yielded additional observations about the overall DTw paradigm. Through the development of this DTw model, the importance of a DTw model to bridge the gap between lower-level engineering terms and variables visible in a field setting was shown. This allows the DTw model to be more easily used and updated. Another potential area for DTw process improvement would be the development of DTw models focused on non-traditional structures, like aircraft tires (subsystem of the aircraft). The lower life of aircraft subsystems compared to the aircraft structure allows multiple model iterations and a potential better overall understanding of the general applicability of the DTw processes. A final consideration for the DTw process is to leverage high fidelity testing results where applicable to build and update physics based response surfaces. This allows select variables to be studied and assists in bridging between the physics of the actual failure conditions and the field visible variables.

Overall the DTw tire touchdown health monitoring model demonstrated potential benefits for predicting tire touchdown wear in the field, while also providing general improvements and observations to the overarching DTw process.

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