Investigation of Wear Rate of Passenger Airplanes Tyres During Landing

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Abstract

A real, functioning copy of one main landing gear wheel is used to show the landing impact of an aircraft. By minimizing abrasive sliding between aircraft tires and runway surfaces right after touchdown, this study seeks to identify possible tire-life improvements. An experimental investigation of size 22 X 5.5, type VII airplane tyres was conducted to evaluate the wear and related properties of temperature and friction caused while braking. One way to evaluate the tire's performance on surfaces with uniform slip ratios, including asphalt, concrete, and slurry seal, was to gear it up to the driving wheel of a ground vehicle. The range of slip ratios often attributed to an airplane's braking system was covered by the data gathered during dry runway operations. Our results show that cumulative tire wear is affected by runway surface features, increases with increasing slip ratio, and changes linearly with miles. The differing wear rates associated with the various surfaces may be used to rank runways based on tire wear.

Keywords: *Aircraft; Tyre; Wear rate; Landing.*

1. Introduction

The physical model predicts that a normal landing will take place in the sequence shown below: When the plane gets closer to the runway, its landing gear extends first. Even though the main wheels are not spinning at ground speed, they nonetheless establish first contact with the surface [1]. A skid occurs when there is a divergence between the tangential speed of the tire radius and the translational ground speed of the aircraft. The wheels pick up speed to match the aircraft's forward motion along the runway, which lowers the severity of the skid. Often, a little cloud of smoke is visible following the initial contact. Landing smoke is produced by a considerable friction between the tire and the runway surfaces, as stated by [2]. The softer surface might be burned by the heat produced by this friction (Tomita, 1964). The softer surface is the tire tread, which has excellent heat resistance and remarkably elastic dynamic qualities. For civilian aircraft, the tread is constructed of almost 100% natural rubber [20]. The primary landing gear of a Boeing 747-400 is considered a one-dimensional mass-spring-damper system in order to analyze forces in the short period of time that passes between touchdown and the wheels spinning up to the aircraft's ground speed. This case study has observed several tire dynamic states during landing, such as traction-limited sliding, free rolling, tyre spin-up, and touchdown [3].

2. Literature Review

The physical mechanism behind the vaporization of rubber in airplane tires under landing weights is not well explained in the literature, despite the publication of several research in the automobile industry. The result of material being lost due to abrasion between running tires and the asphalt runway surface is tire skid marks. According to Persson (2006), the internal friction of the rubber—a bulk feature—is connected to the friction force generated between the tire and asphalt surfaces. The rubber is held and moved across a rough surface in order to calculate the hysteretic friction component. Because of the energy lost as a result, these oscillating forces have the potential to heat the tire material to the point that smoke is produced [4]. The longitudinal tire dynamics during landings have only been partially simulated in research studies. An energy-balance model was created by Padovan, Kazempour, and Kim (1990) to determine the rate of work caused by interfacial friction between the runway and tire surfaces and how it affects the development of slip work and wheel spinning inertia. Calculations for the study were generated using the space shuttle model, with the assumption that each landing results in significant tire wear [5]. A constant friction coefficient, a simple Coulomb-friction formulation, and a non-linear curve fitted to experimental data were used to characterize the vertical tire load FR. Tire wear increased with horizontal landing speed, sink rate, and other factors, as demonstrated by many simulations conducted by Padovan, Kazempour, and Kim (1990) and surface friction coefficients [6] slide work and wheel rotational inertia growing. The study's computations, which were based on the supposition that each landing results in significant tire wear, were produced using the space shuttle model. A constant friction coefficient, a simple Coulomb-friction formulation, and a non-linear curve fitted to experimental data were used to characterize the vertical tire load FR. After running a number of simulations, Padovan, Kazempour, and Kim (1990) concluded that tire wear increased with horizontal landing speed, sink rate, and surface friction coefficients [7]. 1992's Slagmaat The Pacejka "magic formula" models, which are widely recognized in automotive literature, were shown to be unsuitable for replicating the rapid dynamics involved in airplane landings after research into suitable tire models for reproducing longitudinal aviation tyre dynamics. A multi-body nonlinear landing gear model was utilized to calculate the vertical tire loads, and significant simplifications were made to the Pacejka tire model (Slagmaat, 1992). Nevertheless, no comparisons with experimental results were made since there was a lack of trustworthy experimental data [8].

For usage on big aircraft, a simulation model for the anti-lock braking system (ABS) was created in (Li & Jiao, 2013). A contemporary LuGre tire model was used in that investigation to accurately simulate the extremely dynamic tyre forces [9].

In order to simulate the lateral "shimmy" oscillations of the main landing gear of a Boeing 747-400 aircraft, Besselink (2000) developed a detailed model. Although lateral dynamics are not within the purview of this study, some relevant experimental data were obtained, such as experimental wheel-speed time traces recorded during landing on a Boeing 747-400 aircraft, which are helpful in verifying our predictions. Within around 0.1 seconds of landing, aircraft tires accelerate from zero rotational speed to a free-rolling velocity, according to measurements made by Besselink (2000). A few instances of aircraft wheel spinner patents that attempt to lessen aircraft landing smoke are shown below. To our knowledge, no aviation firm has used these patents since there is insufficient evidence to support the claims made on how to reduce landing smoke and tire wear. There is a severe problem that has to be addressed in this job since aircraft landings continue to produce smoke, a screaming sound, flat patches on tires, and the need to repair the tires frequently. Beazley (1947) proposed patented remedies among other things.

A well-designed tire will last longer, improve landing safety, require less part wear and maintenance, require less cleaning of the tarmac, be less likely to blow out the tire, and have a lower chance of tyre debris getting into jet engines. The environment benefits from the decrease in tire smoke, noise, and air pollution brought about by tire disintegration (Beazley, 1947). Consequently, a number of hypotheses have been put out and have been around since the 1940s [11], some of which are detailed below.

Patents for aircraft wheel spinning systems and procedures include a wide spectrum of mechanically basic to rather complicated concepts. The literature indicates that certain pre-rotating systems are heavy, unreliable, or mechanically complicated. Consequently, a large number of patents centre on passive air flow systems, which call for modifying the wheels such that the descending wheels may be moved by the air stream prior to making contact with the ground. While some of them are wheel-mounted devices designed to use the air stream as leverage to get an aircraft's tires rotating before landing, the majority are intricate systems that make use of pressurized air and gas, hydraulic, magnetic, and other mechanical systems [12].

The main technique for getting the tires of an aerial plane to start spinning before it touches down on the runway is called pre-rotation. According to Khal & Khal (2013) [13], a flap system consists of a flexible resin plastic foundation, a layer that mimics Kevlar, and a top layer composed of the same material as the base. All of these layers are glued, stitched, or thermoplastically bonded together. Each disc-shaped component has passive, self-retracting flaps or vanes that open when they come into contact with the falling aircraft's airstream. The hinged flap shuts above the horizontal midline of the wheel; below the horizontal centerline of the tire, air forces the flaps open, pushing them to completely open at the bottom. This aerodynamic torque allows the wheel to rotate. When the flap is open, additional components prevent it from expanding above 90 degrees. One problem with this strategy is that the disc's outer circle could incorporate a weighted ring to provide centrifugal force to reset a disc that has been jostled by a hard landing;

But mounting the disc on the tires itself can damage them structurally, and as a result, this arrangement doesn't seem to be as functionally sound as some other designs [14].

Horvath and Szoke (2006), Instead of adding an assembly to the wheel, reshape the tire to include curved air foils that protrude from both sides of the tire. It is said that protrusion will be reduced by placing foils on both sides. The foils may be used to cover existing tires, according to the designers. They might be composed of "durable material" such as rubber, synthetic rubber, or closed or open cell foam. This part might then be coated in rubber or other synthetic materials and connected to "the carcas plies by nylon fabric or other methods." The concept of Horvath and Szoke has the potential to be very effective, but it hasn't been put to the test in practical settings. It would also probably be necessary to alter the tire's design, which would need the purchase of new wheel assemblies and enclosures—a move that is neither practical nor cost-effective. While pre-spinning airplane tires before to touchdown is a well-accepted concept, none of the patents that we looked up included estimates of the anticipated gains in tire life. Predicting the differences in tire wear between aircraft wheels that have undergone pre-spinning and those that have not is the aim of this study [15].

3. Simulation Model

The physical relationships that were utilized to construct a Simulink model that forecasts tyre wear under various initial circumstances as well as the forces operating on a tire during a typical landing event are described in the following subsections.

The following theories were applied to streamline computations; references were provided for each.

Following touchdown, the pilot enters the spin-up phase without applying the brakes. Refraining from using the brakes abruptly will help you prevent locked wheels, excessive skidding, and tire flat spots—all of which worsen tyre and brake pad wear (United States Air Force, 2007)[16]. The aircraft, according to Jingzhe (2007) and Daidzic & Shrestha (2008), will land with all of its primary wheels engaged and no wing lift. With the tires and shock absorbers controlling the sink rate (vertical speed), the landing will be seamless. Furthermore, it will take the nose wheel two seconds after the main wheels to strike the ground. This second assumption is made because it's possible that the aircraft will land on the runway with some residual lift from its wings and because there's a chance that factors like crosswinds and pilot activity may cause the aircraft's weight to be unevenly distributed across all wheels at once. Furthermore, the aircraft may only touchdown on one tire, resulting in a rough landing and intense wheel pressure (FAA, 2004) [17]. A Lugre tyre model is used to determine the dynamic friction forces acting on friction since the static friction coefficients of the runway materials and tire remain constant during the landing process. The majority of very dynamic vertical forces are expected to be absorbed by shock absorbers in the landing gear structure, and tire deflection will change linearly with vertical load in accordance with a spring law.

The time interval between landing and the landing gear wheels starting to accelerate gradually to match the aircraft's ground speed is known as the wheel spin-up, or "skid" time.

4. Landing Gear Dynamics

The mass, spring, and damper system illustrated in Figure 1 was employed to explain the vertical forces exerted on the aircraft mass and tire contact area. The designs of the landing gear dynamics models of Tanyolac & Yasarcan (2011) and Lernbeiss (2004) are essentially the same.

Fz, which is equal to the aircraft weight less lift, represents the downward force that the landing gear structure will endure. After touchdown, it is expected that there won't be any lift, hence Fz is only the aircraft weight (Jingzhe, 2007; Daidzic & Shrestha, 2008). When forces are balanced vertically, the equation for the vehicle mass' oscillation is displayed in Figure 1.

$$F_z = m\ddot{z} + c\dot{z} + kz, \quad (1)$$

The vehicle's mass (m), the landing gear's damping coefficient (c), the suspension's linear stiffness (k), and the vertical displacement of the aircraft's lumped mass (z) are all represented in this equation. The datum for z is initially set to zero when the item touches down. Z represents the aircraft body's vertical acceleration (m/s2) after touchdown and Z represents the body's vertical velocity (sink rate) in meters per second [18].

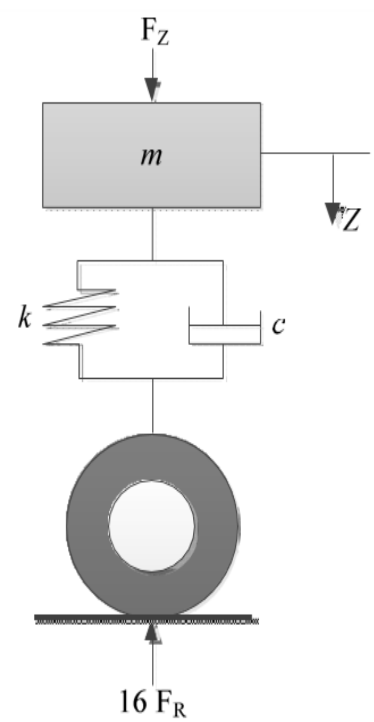

Fig 1. Modelling the landing gear structure's vertical forces using a mass-spring-damper system.

The vertical force that responded over the tire contact patches of all 16 wheels in the main gear was as follows, according to an inspection of the system in Figure 1 and (eq. 1): 16FR is equal to cz plus kz (2)The weight of the airplane times the displacement of the suspension springs times the landing gear spring constant equals the vertical force that the tire reacts to in a static situation, as demonstrated by equations (1) and (2).The damping component c in equation (2) states that greater sink rates, or the vertical velocity at which the wheel first meets the ground, would result in a larger vertical force being delivered to the tire at the time of impact. A Boeing 747-400's main landing gear, which consists of four oleo struts operating in tandem, has a damping coefficient of 5.473 106 N/m and a total spring constant of 5 106 N/m (Jingzhe, 2007). Boeing (2011) [19] states that because the airplane weighs 295,743 kg, the force FR in a static condition is equivalent to 181.33 kN (mg/16).

5. Wheel Geometry

It is anticipated that the wheels will begin to accelerate as soon as the plane touches down, reaching the jet's forward speed before decelerating as it slows down. The stiff wheel forces at touchdown (t = 0) are shown in Figure 2. Under the weight of the aircraft, the wheel radius, R, will bend and transform into the deflection radius, rd. The deflection's magnitude is (= DB). The tire footprint ABC will be created by compressing the arc ADC. Since the main landing gear has 16 wheels, the vertical force pressing one wheel downward is equal to Fz/16. This force results in an instantaneous friction force Fx (=FR), where FR is the force produced in response to the weight on the wheel. The angular displacement of the wheel and the aircraft's landing speed (v) are both shown. Milwitzky, Lindquist, and Potter (1955) [20] is the source of the geometric correlations displayed below.

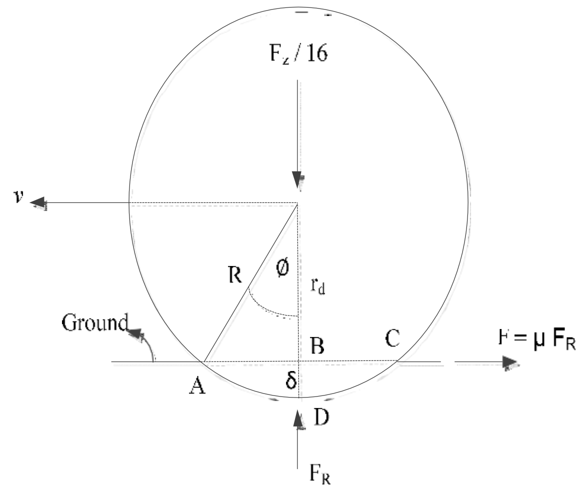

Fig 2. Force applied by a wheel as it collides with a runway. Milwitzky is the source of 1955, Lindquist & Potter. The equation for the tyre deflection is: rd = R - (3) (3).

6. Aircraft Landing Path and Speed

The plane's trajectory throughout approach, flare, touchdown, skidding, and deceleration is depicted in Figure 3. The aircraft wheel will skid throughout the spin-up (rotation phase), as seen in the illustration, until it achieves free rolling, at which point the brakes will apply.

An airplane will normally approach by keeping a constant speed to cross the runway's threshold at a distance of fifty feet (15 meters) before performing the flare manoeuvre. The purpose of the flare is to produce a gentle touchdown by lowering the vertical speed during the landing roll.

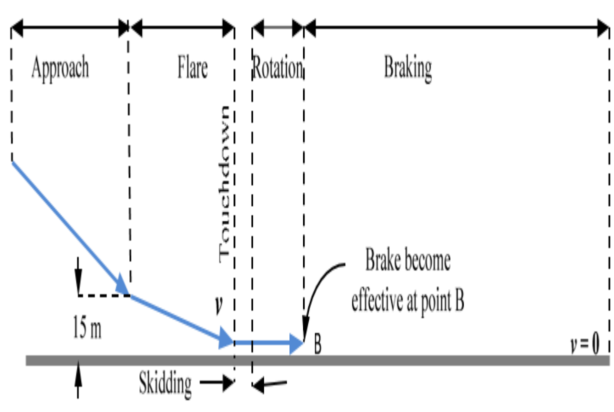

Fig 3. Typical Aircraft Landing Process (not to scale). Modified from Mair & Birdsall, 1992.

During the flare manoeuvre, the aircraft's vertical speed is changed while the pitch angle is raised in order to create drag and slow the aircraft down by around 10 knots.(1999; Kanai & Ochi). The vertical sink rate of a landing Boeing 747-400 typically varies from 1.5 m/s to 3 m/s, according to Li and Jiao (2013). The study's sink rate is 2 m/s at the beginning of each landing simulation, and the horizontal speed during touchdown is set at 75.6 m/s. These values are the same as Boeing (2011)'s approach speed of 80.78 m/s, less 5.14 m/s due to flare deceleration (Ochi & Kanai, 1999). The whole simulation revolves around that negligible horizontal speed, which occurs during the presumptive two-second window prior to the pilot using the brakes.

7. Simulation Model Details

A flowchart of the simulation model's computations may be seen in Figure 4. The computation of the vertical landing gear dynamics is done first, using equations (1-2) and starting with a non-zero sink rate of z and a non-zero landing gear strut compression of z. The vertical acceleration z with respect to time is then integrated to determine the vertical speed z for the next time step.

To calculate the vertical force at the point where the tire contacts the ground, use equation 2. The rolling radius and vertical tyre deflection are determined, respectively, by equations 3 and 8. Next, utilizing the aircraft's horizontal speed along the runway and the initial wheel rotational speed, the wheel slip-ratio (eq. 10) is computed.

The longitudinal friction force FX acting between the tyre contact patch and runway surface (eq. 14) and the Normalized Archard wear volume (eq. 26) are computed using the slip ratio and vertical tire-load.

Wheel inertia is reduced by the product of the tire friction force (FX) and the instantaneous rolling radius (eq. 21) to determine the wheel's rate of rotational acceleration. The wheel speed in the next time step is obtained by adding the wheel rotational acceleration over time using Equation 22, and this wheel speed is then used to determine the amount of wheel slip. In the post-processing stage, the history of normalised Archard wear volumes for each time step is combined together to determine the total wear seen throughout a landing simulation.

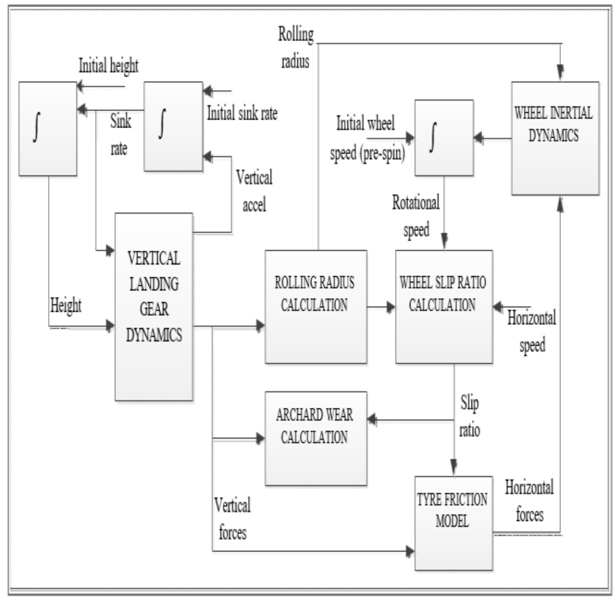

Fig 4. Diagram of the simulation model's calculating flow.

The model described above was built using Simulink, a data flow graphical programming language tool for designing, simulating, and analyzing dynamic systems. The model's ordinary differential equations were solved via the Runge-Kutta Dormand-Prince (RKDP) method. It was allowed to use a variable time-step of between 1x10-6 and 1x10-3 seconds. If the absolute and relative errors exceed a tolerance of 1x10-3 units, the time step would automatically be decreased. The model was first set up with a sink rate of 2 m/s and a horizontal speed of 75.6 m/s in order to undertake baseline calculations. To estimate the sensitivity of tire wear to initial aircraft speed, the starting sink rates and vertical speeds were later adjusted. Numerous separate simulations were conducted with varying starting wheel rotational speeds at touchdown for each combination of initial vertical and horizontal airplane speeds in order to investigate potential advantages on tire wear from technologies that pre-spin an aircraft tire before touchdown. The vehicle mass was adjusted at 295,743 kg for the simulations.

(Boeing, 2011), and FR calculated the vertical force on a single tire using (eq. 1). The longitudinal tire force was initially set to zero and was then accrued using the tyre dynamics of the LuGre model.

8. Discussion

In around 0.35 seconds, the slowest settling variable (vertical load), whose simulations were run for up to two seconds after an airplane touched down, reaches a stable state. The wheel accelerates at an essentially constant pace until t = 0.07 seconds after the friction coefficient is saturated at a maximum value of 1.0 up to 0.04 seconds. Two things contribute to the first fast acceleration: the first is the longitudinal friction that results from internal tyre material deformation within the tyre contact patch; the second is the strong vertical force that the tyre responds to and is attenuated by the landing gear's shock absorbers (Eq. 2).

There is a "traction-limited" sliding condition with the tire and its coefficient of friction. When the tire acceleration becomes close to constant and the aircraft's initial sink rate is zero. When the tire spins up to free-rolling velocity, the friction force pulling on it diminishes as the slip ratio rises. After a slight overshoot at about 0.07 seconds, the wheel has stabilized at a speed where the slip ratio is less than 0.1 within 0.08 seconds after contact. The plane's forward speed as it approaches the runway corresponds with the tangential speed of a point on the tire surface, thus when the wheel eventually reaches the point where re = v, the slip ratio is zero. After the wheel spin-up phase is over, the tire essentially rolls freely until the wheel is subjected to braking force.

Since the slip ratio is significantly more than zero, it is assumed that the tire will be sliding throughout the spin-up phase. Figure 5 below shows the three previously mentioned stages of tire behaviour.

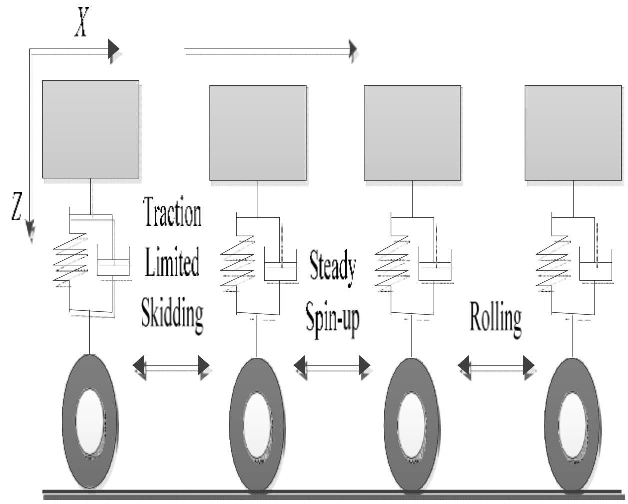

Fig 5. When the wheel is not rotating when it touches the ground, it might land, skid, spin up, and roll on the runway.

While simulating a landing, internal dynamic effects on tire forces cause a substantially damped oscillation in wheel speed while the wheel is already spinning at a speed that provides low slip. The oscillation ends after 0.07 seconds, when the slip ratio reaches zero. According to the Archard wear hypothesis, the minute fluctuations in tire speed would result in wear, but the amount of material lost from the tire would only be 1.07% of what was seen in the simulation that began with a static wheel.

The starting sink rate and horizontal speed were adjusted for the sensitivity research in 5% steps up to 30% higher than the default values of 2 m/s and 75.6 m/s, respectively. Figure 10 displays the findings of the sensitivity analysis performed on the data in tables 3 and 4. Increases in aircraft horizontal speed have a greater impact on tyre wear than do modifications in vertical sink rate upon touchdown. For slip ratios larger than 0.2, a 1% increase in horizontal speed at touchdown is expected to result in an increase in tire wear of 0.59% to 0.83%. The sensitivity of tire wear to horizontal landing speed decreases with lower initial slip ratios.

When the wheel is spinning at the free-rolling speed, the wear volume at such slip ratios is already very small, and the change in wear volume at zero slip in cubic meters per second is practically nonexistent. However, simulations revealed that at an initial slip ratio of zero, tyre wear actually decreased by 0.6% for every 1% increase in landing speed. Consideration of a particular measurement of wear volume results in nearly zero sensitivity to landing for starting slip ratios of 0.6 and higher, and nonzero but fundamentally modest sensitivity for lower slip ratios. The sensitivity of tire wear to slightly negative sink rate values indicates that, in comparison to lighter landings, heavier landings enhance tyre spin-up efficiency by increasing spin-up torque.

9. Conclusions

To evaluate the tire wear of a main-gear wheel that is initially stationary and a spinning wheel after touchdown, a simulation model has been constructed. A tire that has been pre-spun to match the forward speed of the airplane usually loses just 1.07% of its material to abrasive wear prior to touchdown.

The increase in tyre wear for unspun tires is less than 1% for every 1% increase in aircraft horizontal speed. The sensitivity to longitudinal speed decreases if the touchdown wheel slip ratio is brought down to less than 0.2 using a pre-spinning mechanism. Tire wear is less impacted by landing sink rate changes than by changes in horizontal speed.

It was possible to examine the relative tyre wear of different simulations without taking into account the properties of the runway materials or the tires themselves since the Archard wear was reduced to a normalized wear volume. According to the Archard wear theory, the amount of tire material lost during a landing is inversely proportional to the square of the velocity difference—that is, the kinetic energy required by the wheel to achieve zero slip and free rolling—between the aircraft's forward speed and a point on the tread of the tire at the moment of touchdown.

By modelling landings with different beginning wheel rotational speeds, this idea was created. The Archard wear hypothesis states that tire life could be greatly increased and wear might be decreased if the wheel was pre-spun to the free-rolling speed prior to touchdown.

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