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Experimental Evaluation of Effect of Leaves on Railroad Tracks in Loss of Braking

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Abstract: This study aims to comprehensively assess the lubrication effect of leaves on wheel–rail contact dynamics using the Virginia Tech-Federal Railroad Administration (VT-FRA) Roller Rig, which closely simulates field conditions with precision and repeatability. Railway operators grapple with the seasonally recurring challenge of leaf contamination, which can cause partial loss of braking and lead to undesired events such as station overruns. Better understanding the adhesion-reducing impact of leaf contamination significantly improves railway engineering practices to counter their effects on train braking and traction. This experimental study evaluates the reduction in traction and braking forces (collectively called "adhesion") as a function of leaf volume, using two leaf species that commonly grow along U.S. railroad tracks. The test methods rely on the chosen leaves' transpiration characteristics while ensuring the result's reproducibility. Leaves were symmetrically positioned on the wheel surface, centered around the mid-rib area within the wear band, and taped on the edges far from the wear band. The critical test parameters (i.e., wheel load, wheel velocity, and percentage creepage) are kept constant among the tests. At the same time, leaf volume is reduced from a maximum amount that covers the entire wheel surface (100% coverage) to no leaves (0%). The latter is used as the baseline. The percentage creepage is kept constant at an exaggerated amount of 2% to accelerate the test time. The results indicate a nonlinear relationship between leaf volume and the loss of braking. Even a small amount of leaf contamination causes a significant reduction in adhesion by as much as 50% compared with no contamination (i.e., baseline). Increasing leaf volume results in contact saturation, beyond which adhesion is not reduced. The minimum adhesion observed in this study is 20% of the maximum adhesion that occurs when no leaf contamination is present.

Keywords: leaf contamination; braking; wheel–rail interface; traction; railroad; VT-FRA Roller Rig

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1. Introduction

Amidst the dynamic realm of railroads, a remarkable phenomenon takes center stage—the unyielding grip of braking and tractive forces at the wheel–rail interface [1,2]. The study of these forces is essential, as a reduction in traction directly escalates the required braking distance, disrupting the adequate deceleration of trains [3,4]. This intricate cooperation of traction and adhesion forms the core of rail transportation, ensuring safe and efficient journeys. However, this symbolic relationship is far from unshakable, as many environmental factors intrigue to test its flexibility. From rain-drenched tracks [5,6] to grease/oil-slicked surfaces [7,8] and nature's confetti of fallen leaves [9–11], the braking and tractive forces face many challenges. Other than these environmental factors, vehicle speed, wheel slip, and contact pressure also play an essential role. The VT-FRA Roller Rig has been deployed to understand the resulting traction under various environmental conditions and factors, some of which follow the same background as this current study, available in [12,13]. Traction is generally quantified by normalizing the longitudinal force to the wheel load. This normalization is termed the Longitudinal Traction Coefficient. In simpler words, traction coefficients can be termed adhesion coefficients, which are essential for the smooth running of the locomotive. Loss of traction results in either braking of the train or slip, which arises at lower tractive coefficients. This case occurs when there are third body layers that cause reduced traction, such as in the case of leaves. Various traction enhancers are adopted by the railway to improve adhesion when the rail is contaminated.

Third body layers (3BLs) play a significant role in wheel–rail contact dynamics. The naturally generated wear debris in dry conditions results from oxidation wear at contact due to high pressure and temperatures [14,15]. The composition of these is iron particles and their corresponding oxides. Although this type of debris is generated during the wear process, it helps maintain/enhance adhesion between the wheel and rail. Under laboratory conditions, the thickness of this 3BL has been shown to play an essential role in traction and wear generated. Authors have identified that basic 3BL ranges from a few to several dozen microns, as iterated by Descartes et al. [16]. Meierhofer et al. [17] investigate how isotropic homogeneous properties of 3BL and thickness influence the traction coefficient. The authors use a twin disc setup to model and test various thicknesses of 3BL ranging from 5 microns to 100 microns with a basic 3BL thickness of 50 microns. Natural 3BL also includes dust, snow, humidity, and leaves resulting from the ever-changing natural environment conditions owing to the railroad's open system. Additionally, railway operators intentionally add substances at wheel–rail contact to control traction. These can be the flange grease, top-of-rail friction modifiers, sand, or water considered artificial 3BLs. Some materials like water, oil, snow, and flange grease reduce adhesion. Similarly, sand and specific top-of-rail friction modifiers display positive friction creep characteristics, thus enhancing traction [18]. Additionally, the authors state that there can be certain substances that can also provide neutral friction creep characteristics. Researchers have analyzed the influence of 3BL on adhesion. Several authors indicate the importance of 3BL at the wheel–rail contact interface. Niccollini et al. [19] state that the absence of 3BL limits the adhesion, creating an environment where the adhered third body is removed from the surface. Berthier et al. [16,20] provide adequate experimental data under low rail speeds and artificial 3BL to suggest the same. According to the author, a clean surface condition does not provide reliable data indicating the presence of 3BL to surge the life of the wheel–rail.

Current research on the effect of leaf contamination either focuses on traction recovery aspects, chemical and rheological characterizations, or combined effects of materials under various test scenarios [21,22]. Olofsson et al. [23] have statistically studied the effects of leaves and humidity with a pin-on-disk setup. The results of this statistical approach have shown a direct relationship between the coefficient of friction, percentage humidity, and the amount of leaves at contact. However, the ANOVA analysis performed by the researchers suggests no significant influence in the interaction between the amount of leaves and humidity but indicates individual factors alone have significance. Similarly, Guidoum et al. [24] have experimentally studied the tribological aspects of leaves in the presence of moisture. They have concluded that the slip rate and percentage humidity strongly influence adhesion. To remedy the low traction and braking induced by contaminants such as leaves at the wheel–rail interface, railroad companies invest in traction-enhancing materials such as sand to stabilize the traction. Omasta et al. [25] have focused on optimizing the sanding parameters needed for traction recovery in a contaminated rail. They use a twin disk machine to replicate the field characteristics. The results of their study indicate significant effects of sand needed for traction recovery. However, this is observed only at low rolling speeds and wheel slipcases—the impact of sanding increases with an increase in both these factors. While testing with 'wet' leaf mixtures, they have shown the lowest traction achieved. As a limited quantity of sand is added, there is only temporary improvement due to the formation of a hard-to-remove layer. Li conducted similar investigations. Z. et al. [26] examine the traction-recovering properties of various top-of-rail friction modifiers on leaf-contaminated rails. The authors use the SUROS test rig to perform these experiments. Using the same experimental setup, Cuevas et al. [27] investigated the particle size parameters of sand and its influence on adhesion recovery under a leaf-contaminated rail environment. Both these papers suggest the importance of adding traction enhancers of greater particle size of artificial 3BL to help faster recovery of the lost traction. Ishizaka et al. [28] have extensively analyzed the chemistry behind the black leaf film. They have shown that this Teflon-like layer on the rail reduces the traction in the presence of water or mild dew. To this end, they have used three kinds of leaf application: leaf powder, leaf extract (green and brown), and black precipitation powder. Friction tests were conducted with a ball-on-disk test rig, indicating no significant difference between the two leaf extracts. Little to no significant differences are observed in the friction tests under different green and brown leaf solution experiments. This allows researchers to test green and brown leaves to further enlighten them on their effects on traction. The authors have also focused on chemical characterizations to understand the low adhesion mechanisms, hypothesizing possible chemical reactions. Poole et al. [29] performed SEM/EOX and FTIR analyses for three leaf residues indicating similar chemical composition. This is helpful in the selection of leaves in our study to provide a generalizable result on leaves.

Although various studies have evaluated the effects of leaves on the adhesion, they mostly do not adequately replicate the wheel–rail interface (WRI) because of the limitations of their test rigs, as iterated by Oscar et al. [30], and the experimental approach used for their testing. This study intends to bridge that gap by performing tests on a roller rig that nearly duplicates the WRI while maintaining repeatability and accuracy that is far beyond field testing, such as those in [31,32].

Any organic material, e.g., leaves, is unique. They differ in size, shape, composition, and thickness, which are extremely difficult to control. For this study, thorough research was performed to study rail ecology. Two species of leaves with different thicknesses that are (A) abundantly available and (B) spread across the railway lines are selected. Due to the vast railroad network, green leaves are also observed on the rail for several reasons. These can be the withering of evergreen trees or strong winds that can naturally displace the green leaves on the track. Leaves can easily adhere to the track if small traces of flange grease already contaminate the rail or other such contaminants that could hold the leaves on top of the rail. This paper tries to study and explore the effects green leaves (as is) may have on the traction coefficient at the wheel–rail interface; the testing parameters, including the wheel–rail relative position and wheel load, have been kept constant, replicating an actual wheel–rail contact scenario. For this study, the VT-FRA Roller Rig [33] is used to mimic the contact dynamics of the field with more precision and repeatability. This will help provide quantifiable results that can be directly related to the field conditions. It also serves as a means to compare with existing studies and eliminate the effect of other additives or contaminants added to the leaves. The results obtained from this study should be a medium for studying the material characterization of both wilted leaves and fresh green leaves and other traction-enhancing components that can have the best effect on traction recovery without causing much damage to the wheel and rail profiles. The terms 'tests', 'trials', and 'experiments' will be frequently employed interchangeably throughout this paper.

2. Test Setup

The tests are performed on the Virginia Tech—Federal Railroad Administration Roller Rig, as seen in Figure 1. It is a highly capable and controllable piece of machinery that can accurately measure contact forces, surface profile, and 3BL accumulation. The roller (shown in Figure 1) represents the rail and is made of AISI 1070 carbon steel. The running surface of which is scaled 1/4th of the US-136 rail profile. The cylindrical wheel used is made of 1063 grade steel with 0.1% vanadium and is oil-quenched hardened to achieve a hardness of 32–36 HRC [34]. The wheel diameter is approximately 1/5th the diameter of the roller, which is specifically set to keep the contact patch distortion to less than 10% of a flat rail. Six linear actuators govern the wheel load, angle of attack, and lateral position between the wheel and roller. Two AC servomotors rotate the wheel and roller with an accuracy of 0.1 rpm.

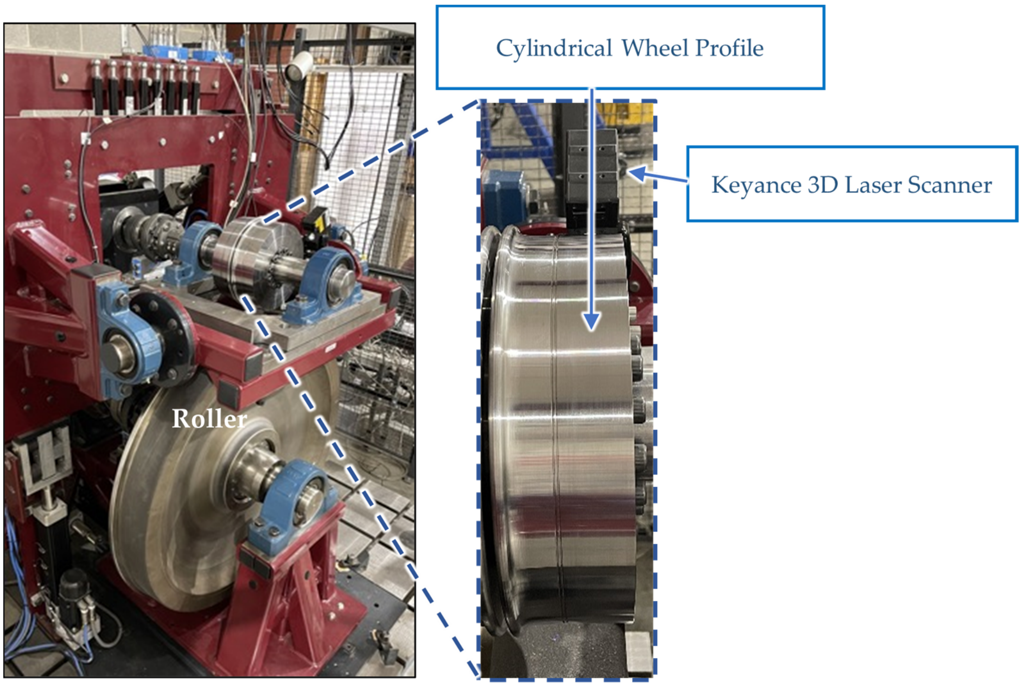

Figure 1. Virginia Tech—Federal Railroad Administration (VT-FRA) Roller Rig.

The rig is additionally integrated with a 3D laser surface measurement system that can measure the surface profile with micron-level accuracy. Detailed information on the VT-FRA Roller Rig is documented and is available in [35]. Since this study focuses on the effect of green leaves, other important contact parameters such as percent creepages, wheel load, and wheel speed are kept constant at 2%, 5000 N, and 3 kmph. Based on the scaling of the VT-FRA Roller Rig, the forces are scaled by a factor of 4^2 (=16) to correlate to a full-scale loading condition. Additionally, the scaling factor of wheel velocity is 1, thus making percent creepage also scaled by 1. This study focuses on the effect of leaves on traction. The tests are conducted at lower speeds, which are within the capabilities of the VT-FRA Roller Rig. It is estimated that the resulting change in traction coefficients is primarily due to percent creepages that are precisely controlled for the tests. For equal percent creepages, factors such as test speed affect the results to a far lesser extent. The testing parameters are shown in Table 1.

Table 1. Testing parameters used in the experiments with leaves.

Test Parameters	
Wheel Profile	Cylindrical
Roller Profile	US-136 rail
Wheel Velocity	3 kmph
Creepage	2%
Duration	1250 s
Wheel Load (Full Scale)	5000 (80,000) N
Wheel Condition	Clean/Dry

3. Materials and Methods

Railroad ecology is a term used to study ecological growth along railway tracks. Railroads are built over natural ecosystems, being contaminated by several materials, such as leaves. Over the years, non-native species have spread worldwide, especially near the railway ecosystem. These species have moved beyond their natural limits due to human activities and, therefore, are in a stage where it is too difficult to control. These species not only exist in animals but also in plants. One such prominent example is a variety of weeds that grow on roads, walls, and gardens, hindering useful plants' growth.

As discussed in the introduction section, the literature review reveals a divergence between the experimental methods and ingenious test setups used by previous authors and the practical realities of the railroad domain. To advance the study of leaves and their effects on traction, a critical evaluation of experimental data is warranted. Certainly, one can find past studies that elude the fact that a reduction in traction occurs due to leaves. However, such studies have either been based on empirical evaluations that do not offer any quantifiable data on traction or were based on field tests that affected the field conditions beyond traction. This approach embodies a proactive alliance between academia and industry, nurturing the development of strategies attuned to genuine challenges.

In summary, while valuable, the methodologies in the existing literature may benefit from closer alignment with railroad operations to optimize methods effectively. This process holds the potential to bring about solutions that genuinely resonate with the railroad sector's essential requirements. Leaves are utilized in isolation (as is), devoid of external substances, to ensure untainted outcomes in this study.

The first variety of leaf selected is 'Morrow's honeysuckle' (from now on, 'Type 1') with the scientific name of Lonicera morrowii, as shown in Figure 2A. Its native origins are from Japan and Korea. It is identified to cover the entirety of the US east coast, as seen in the mapped Figure 2B [36]. They are highly invasive shrubs that can develop complex root systems and adapt to any soil type. This species is also prominent in the railway ecosystem. The thickness of the leaf ranges between 300 microns and 500 microns.

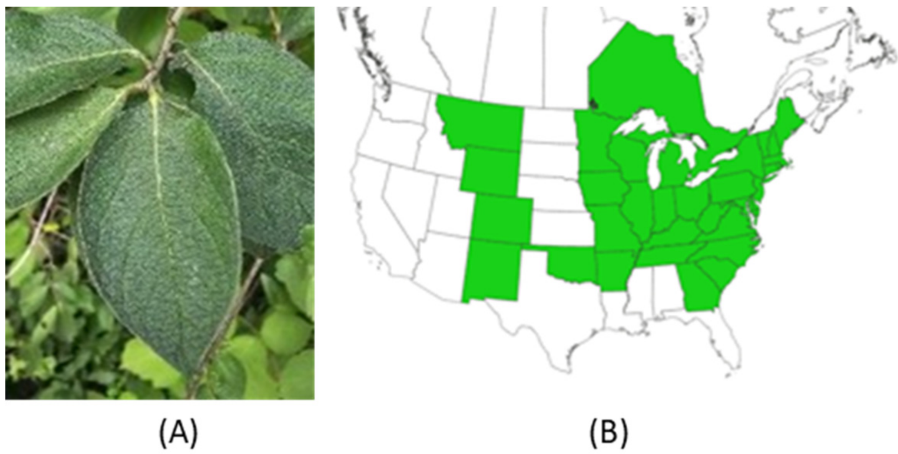

Figure 2. (**A**) Leaf: Type 1, 'Morrow's honeysuckle'. (**B**) Leaf distribution in North America.

The second variety of leaves is from the standard wild berry families or nontoxic raspberries (from now on, 'Type 2'). They can be seen as short trees and shrubs with similar leaves. They are considered larger weeds due to their highly invasive nature, spreading across North America, as seen in Figure 3. [37]. The leaves of this variety are more significant and broader in size compared to Type 1. The thickness ranges between 150 microns and 250 microns.

Significant differences in leaf thickness, size, and leaf varieties spread across North America are the main factors in selecting different types of leaves, helping to explain the broader implications of the results of this research on how thickness and natural 3BL generated affect traction.

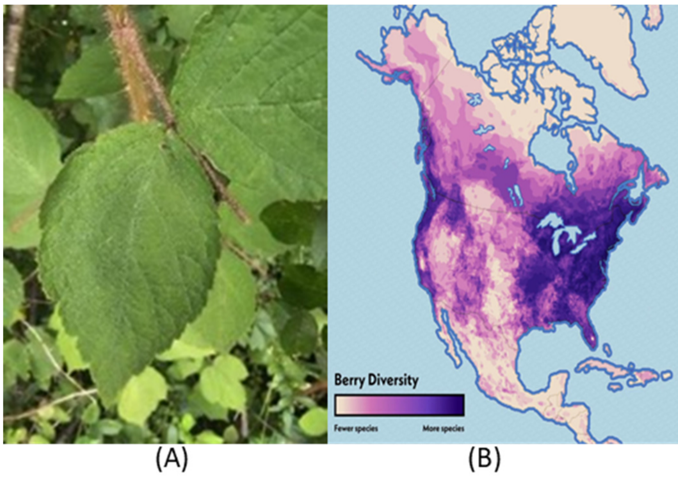

Figure 3. (**A**) Leaf: Type 2, wild berry families or nontoxic raspberries. (**B**) Leaf distribution in North America.

Transpiration is the natural process of water moving through the plant and evaporating through leaves, stems, etc. Water potential is the cause of this natural transpiration, affecting the experimentation procedure. To further understand the transpiration property of leaves, fourteen leaves of Type 1 were collected to monitor the natural transpiration rate and weight loss over time once cut from the stem. This is an essential step toward designing experiments with high degrees of repeatability and consistency in the leaves' properties during the tests. For the fourteen leaves selected, the weight was meticulously monitored and recorded every 15 min. This was conducted continuously in a 2-h window. A kernel density distribution plot, a method for visualizing the distribution of observations in a dataset (analogous to a histogram), was adopted to show the results of this study and the reason for establishing a meticulous step. Figure 4 illustrates the kernel density distribution plot for the leaf weight data collected in the first and second hours. The figure shows that the first-hour distribution is much more spread across the percentage loss, indicating higher standard deviations from the mean. Meanwhile, for the second hour, the distribution shows a higher amplitude, i.e., a more pronounced peak, which suggests the percentage loss of weight is much more concentrated with fewer deviations from the mean. In conclusion, resting the leaves for 2 h before performing the experiments will help provide much more reliable and repeatable results.

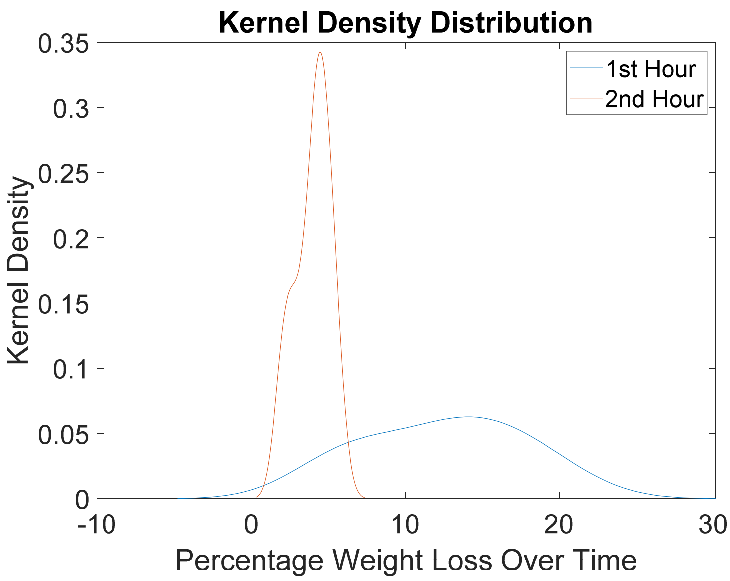

Figure 4. Kernel density distribution as a function of time to evaluate % weight loss during two hours.

The other controllable factor to ensure test repeatability is the leaf volume that comes into contact during the test. To this end, the weight of leaf pieces taped on the wheel surface (coverage) is considered the determining factor for the level of leaf contamination. The contributing amount of leaf weight to the wheel-rail interface is the difference between the initial weight of leaves before a test and the remaining leaf pieces after completing the test. Seven tests are performed with different contamination levels to evaluate the effect of light to heavy leaf contamination on the traction coefficient, reducing the leaves' weight successively by approximately 50%.

With the help of the initial analysis performed with leaves, a meticulous methodology is curated to perform the experiments, the flow of which can be seen in Figure 5. During certain days of testing, rainy weather conditions were encountered, resulting in water droplets accumulating on the leaf surface. This can hinder the experimental results and portray the effect of leaves and water. To mitigate this interference, a pat-dry procedure was conducted to remove excess moisture and water as much as possible before conducting the experiments. The 2-h rest period is carefully retained considering the time needed to attach the leave pieces to the wheel surface, as shown in Figure 6.

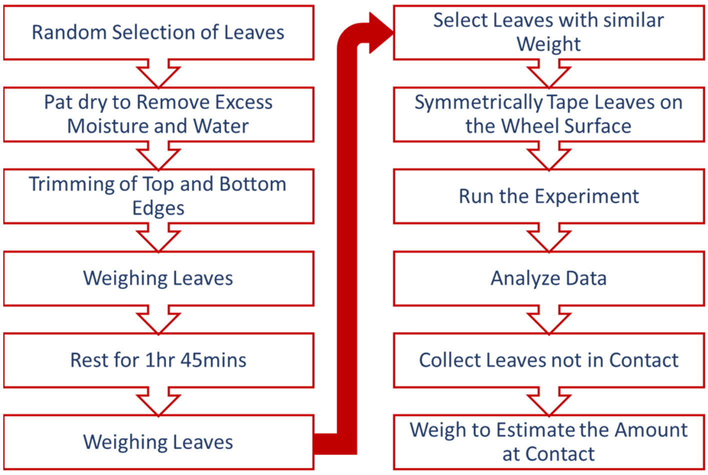

Figure 5. Experimental procedure flowchart.

Figure 6. Application of leaves to a clean wheel surface with adhesive tapes on the edges, away from the running surfaces.

For the Type 1 leaf, the first experiment is performed while covering the entire wheel circumference with leaves. This provides information on the sensitivity of traction on the volume of the leaves in contact. Subsequent tests are performed by reducing the weight of leaves by 50% compared to the last experiment. Table 2 lists the tests performed using each leaf type and the percentage of leaves added, denoting the wheel surface coverage. This systematic approach will help understand the pattern of reduced traction coefficient as the applied amount of leaves is reduced. A baseline test indicated as 'no leaf' in Table 2 is performed with the same testing parameters without leaves or contaminants. The baseline test will serve as a reference for comparison with all tests performed with leaves. A similar method was adopted to estimate the maximum amount of Type 2 leaves that can be added to cover the entire wheel surface. Since the second variety of leaves aims to understand the effect of a different leaf type with smaller leaf thickness on traction, selective experiments were performed. The check marks in Table 2 represent the experiments performed. The testing parameters mentioned in the previous chapter are kept at constant values to have results comparable with earlier experiments on the VT-FRA Roller Rig.

Table 2. Testing nomenclature and percentage leaf weight added.

Test Number	Quantitative Addition of Leaf Weight (%)	Type 1 [1]	Type 2 [2]
1	100	√	√
2	50	√	-
3	25	√	√
4	12.5	√	-
5	6.25	√	√
6	3.12	√	-
7	1.56	√	√
Baseline	0	√	√

[1] Type 1 corresponds to Morrow's Honeysuckle. [2] Type 2 corresponds to Raspberries.

4. Results and Discussions

4.1. Experiment Baseline

The Baseline tests are essential for providing an initial reference point against which the results can be compared. A baseline test with the data from the VT-FRA Roller Rig can establish the maximum traction coefficient achieved under clean, dry, and unlubricated wheel conditions. With the help of the Keyence laser scanner incorporated into the Roller Rig [13], the surface profiles before and after the experiments can be accessed with micron-level accuracy. This also serves as a point to compare wear generation after tests with leaves. The testing parameters used for this baseline test are the same as mentioned in Table 1. The baseline test is for 500 s. Figure 7 shows the maximum achieved traction coefficient of about 0.5 (-). Traction coefficient reporting in this study is the ratio of the longitudinal force over vertical force (wheel load) measured while testing. The maximum achieved traction coefficient was when no leaves were present, referred to as 'no leaf' or '0%'. This is used as the baseline for comparison among other conditions.

These parameters were selected because similar parameters were used to assess the effects of natural third-body layers on traction and wheel–rail interface dynamics [33]. Baseline tests ensure consistency in data acquired from the roller rig's continuously reprofiled wheel. Additionally, repeat baseline measurements help record all the data points, which allows observing any change in the data resulting from changing wheel and roller profiles.

The Keyence 3D laser scanner permits the ability to measure the wheel profile in situ. Figure 8 shows the images of the wheel along with their surface measurements at three intervals. Each figure presents 15 mm of the wheel surface with peaks and valleys differentiated by colors. Figure 8A shows the smooth redressed wheel surface prepared for testing. Figure 8B is taken when the test is completed without debris removal. The natural third-body layers are piled up on the wheel surface in an approximately 4 mm region, demonstrated using red/hot colors. Figure 8C is the cleaned version of the latter.

It clearly shows the depth of groove formed on the wheel surface due to the wheel–rail interaction via blue/cold colors.

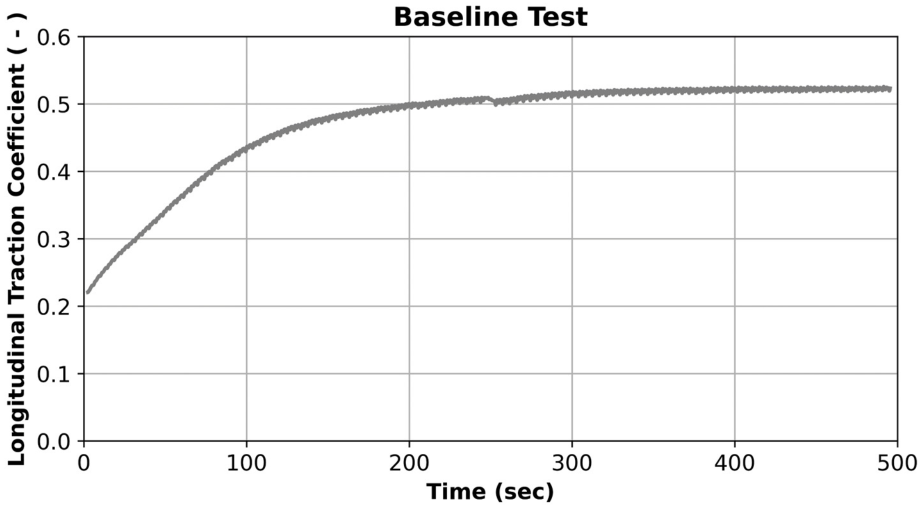

Figure 7. Longitudinal traction coefficient vs. time for baseline tests.

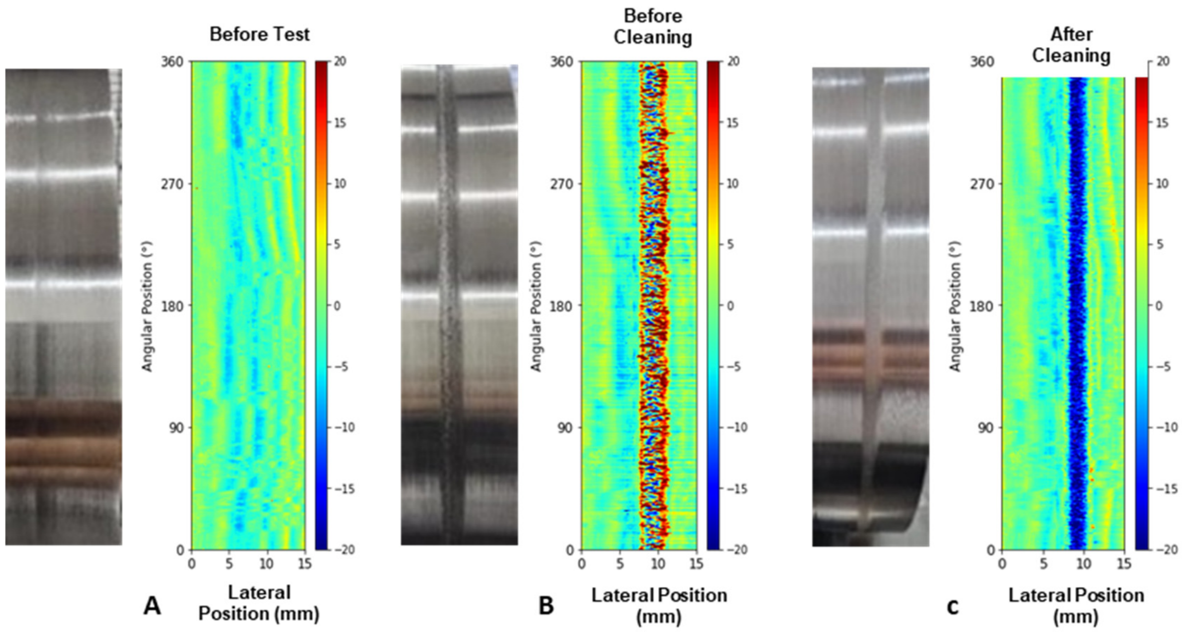

Figure 8. Wheel surface images and 2D laser measurements (**A**) before the test, (**B**) after the test with natural 3BL, and (**C**) after completing the test and cleaning.

Measurements taken using the laser scanner, shown in Figure 8, allow for extracting the wheel profile and analyzing the groove formed on the wheel surface, the natural third-body layer accumulated on the surface, and resulting wheel wear. Wheel profiles are the average of laser surface measurements along the wheel circumference. Figure 9A shows the wheel profiles obtained after the test before and after cleaning the debris. The region colored in blue indicates the accumulation of natural 3BL on the surface. Figure 9B, however, shows the wheel profiles before and after the test while the surface is clean without the presence of debris or contaminations. The area colored in green provides information regarding wheel wear that occurred during the test.

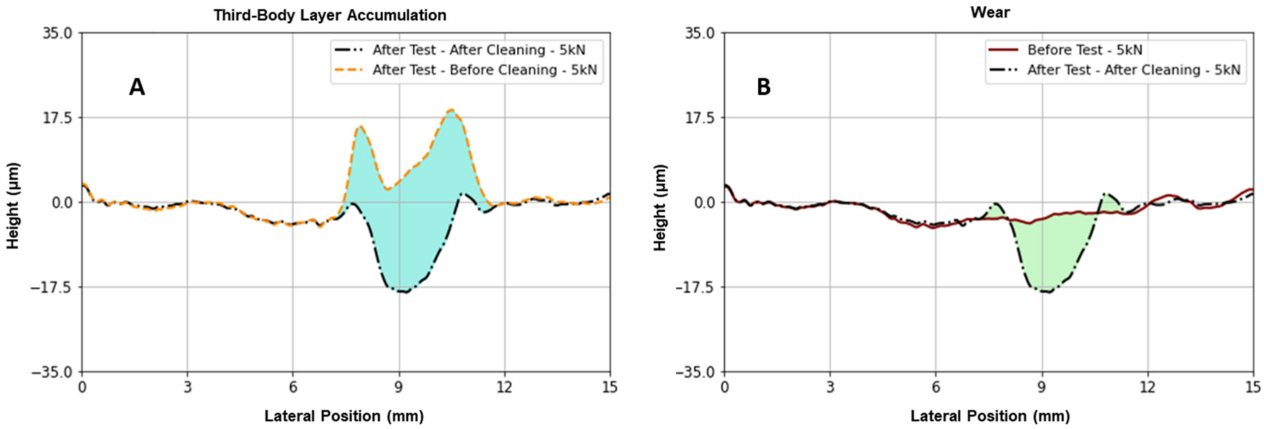

Figure 9. Third body layer and wear on wheel running surface after baseline tests; (**A**) third body layer accumulation; (**B**) wear.

4.2. *Leaf—Type 1*

By adhering to the curated methodology, different leaf weights have been categorized as test 1, which corresponds to the maximum amount of leaf weight that covers the circumference of the wheel, from now on termed as '100%', and test seven similarly represents the minimum amount of leaf that is added, termed as '1.56%', which refers to the small amount of leaf on the wheel (i.e., 1.56% of the maximum). The tests performed within the maximum and minimum range represent the intermediate amounts by systematically reducing the leaf weight by 50%, as iterated in Table 2. This standardized percent coverage strategy helps quantify the leaf weights much more conveniently.

The results of the tests performed with leaves—Type 1 are plotted as a traction coefficient vs. time plot, as seen in Figure 10. Two distinct regions can be visualized from the plot; one is transient, and the other is termed a steady state. The transient region's traction coefficient change rate for each test is considerable. The steady-state regions bring the understanding of natural recovery. The amount of leaves added plays an essential role in the outcomes of the curve in these two regions. Curves '100%', '50%', '25%', and '12.5%' have leaf quantity on the higher side. The results of this can be seen as a delay in the transient region. As the experiments proceed, this delay is not observed in the curves after '12.5%' leaf coverage. This observation indicates the lubricating effects of fresh green leaves on the wheel–rail interface. The natural lubrication is also visible in the steady-state region, as the traction coefficient is seen to plateau. No regain of traction is observed with time in the '100%', '50%', and '25%' curves. A prolonged rise in traction coefficient is observed in both '12.5%' and '6.25%' leaf coverage curves. Similarly, by further lowering the amount of leaves, the traction coefficient is regained to a new plateau region. This regain is much faster than the previous curves yet lower than the baseline. A clear pattern is observed when all the curves are plotted together.

All these tests were conducted under clean surface conditions, i.e., the wheel surface was redressed before and after each experiment using different grits of sandpaper ranging from 40 to 120. Redressing the wheel is essential to maintain the cylindrical profile within a certain micron tolerance, thus not hindering the experimental parameters. A clean surface profile also ensures repeatable results and provides a better direct comparison between tests with various amounts of leaves. In the field, however, rails and wheels are not always clean and in new condition. As mentioned earlier, several types of 3BL, naturally and synthetically, are present on the rail head. The presence of worn and said 3BL causes the traction coefficient to drop less at the beginning and have a steeper increase. Similar observations and conclusions were made by the authors who have tested the traction recovery aspects of a leaf-contaminated rail environment [24–26]. This makes it essential to understand traction recovery in the presence of wear and naturally generated 3BL. This test performed is referred to as 'maximum + wear'. A 10-minute dry cycle with the conditions of the baseline test was conducted to generate natural 3BL and wear on the wheel and roller surface. To the wheel surface, '100%' leaves of Type 1 were added, covering the entire circumference (time zero for the maroon curve in Figure 11). The experiment was continued to study the results of a worn profile on traction recovery. The plateauing behavior observed in the 'clean surface' curve from Figure 11 disappears, showing a slow rise of traction in the 'worn surface' curve throughout the rest of the experiment. This experiment suggests that wear plus natural 3BL helps natural traction recovery, decreasing the traction drop as hypothesized.

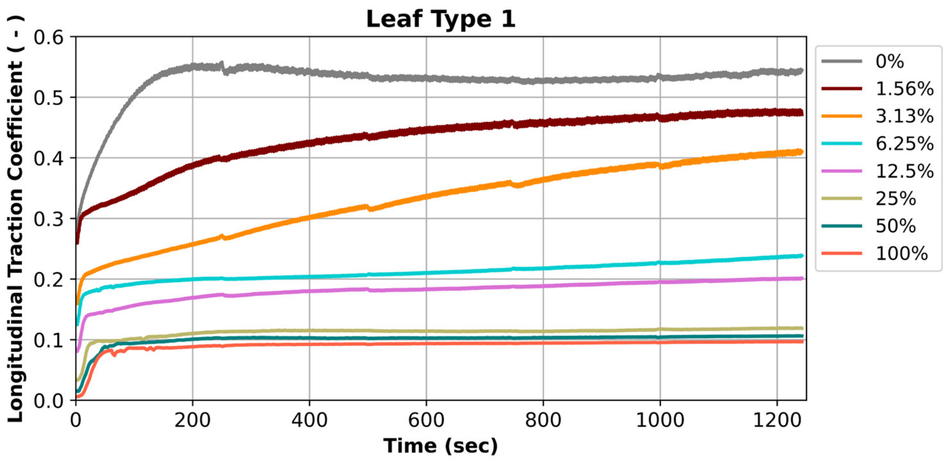

Figure 10. Effect of leaf volume on reducing adhesion (Longitudinal Traction Coefficient) for leaf Type 1.

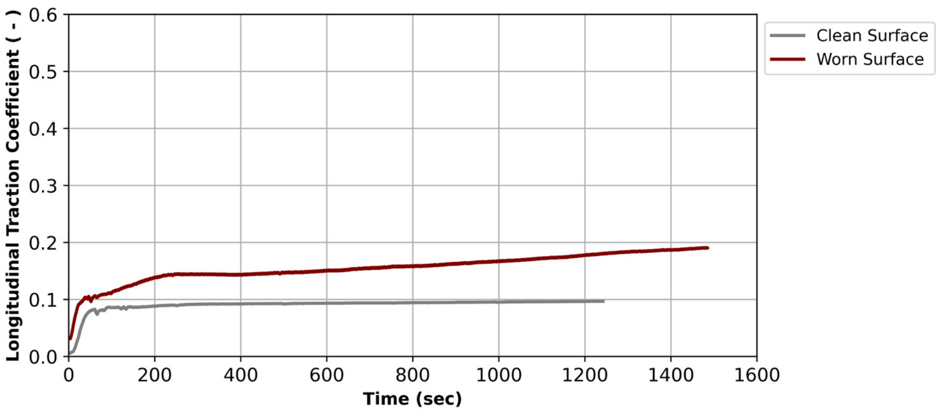

Figure 11. Adhesion (Longitudinal Traction Coefficient) reduction due to maximum leaf contamination when applied to a wheel with cleaned (redressed) and worn (with worn material present) surfaces.

4.3. Leaf—Type 2

The Type 2 leaf selected is much thinner than the Type 1 leaf. Since studying the leaves of varied grades was vital, four distinct weights of leaves were chosen for testing. Like the measurements considered in Type 1, test 1 represents the maximum weight that can be added to cover the entire wheel surface and is hereinafter mentioned as '100%'. The test with the minimum amount of leaves also follows similar naming standards, such as '1.56%'. The remaining tests correspond to intermediate weights added on the wheel surface referred to as '25%' and '6.25%'.

Figure 12 represents the traction coefficient vs. time plot for all four categories of tests as well as the baseline plot. The trend observed is slightly different when matched with the results with leaf Type 1. For the '100%' and '1.56%' categories, the traction coefficient seems to increase gradually and does not tend to reach a steady state during the test duration.

Interestingly, in the curve of 25% leaf weight covering the wheel circumference, the traction coefficient plateaus and reaches a steady state. Despite conducting the test multiple times, the outcome remained consistently unchanged. Further lowering the weight to about 6.25% of the 'maximum' for the category yielded a similar result to the other categories. The trend of slow increase in traction coefficient is observed as it does not saturate as observed in the previous case.

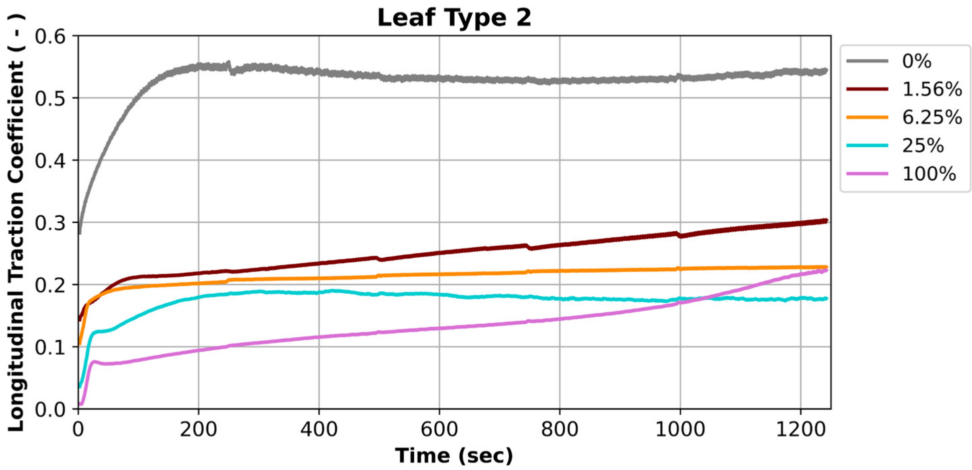

Figure 12. Effect of leaf volume on reducing adhesion (Longitudinal Traction Coefficient) for leaf Type 2.

4.4. Repeatability

Repeatability tests are significant for experimentalists because they ensure the reliability and validity of tests. By conducting these repeatability tests, researchers can assess the consistency of the findings made with the VT-FRA Roller Rig. Figure 13 shows the repeatability tests performed with the categories '100%' and '1.56%' coverage tests conducted with leaf Type 1.

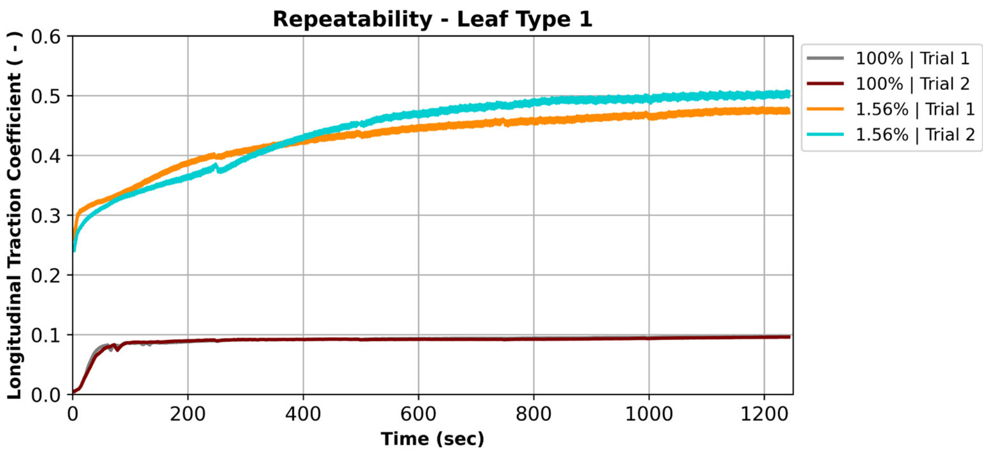

Figure 13. Repeatability tests for minimum and maximum amount of leaf contamination for Type 1.

Figure 14 represents two repeatability tests with added 25% and 100% leaf coverage. Some differences are observed at the beginning of the repeatability tests for the '25%' of leaves. It is hypothesized that the difference in the transient region is due to the initial positioning of the leaves on the wheel surface.

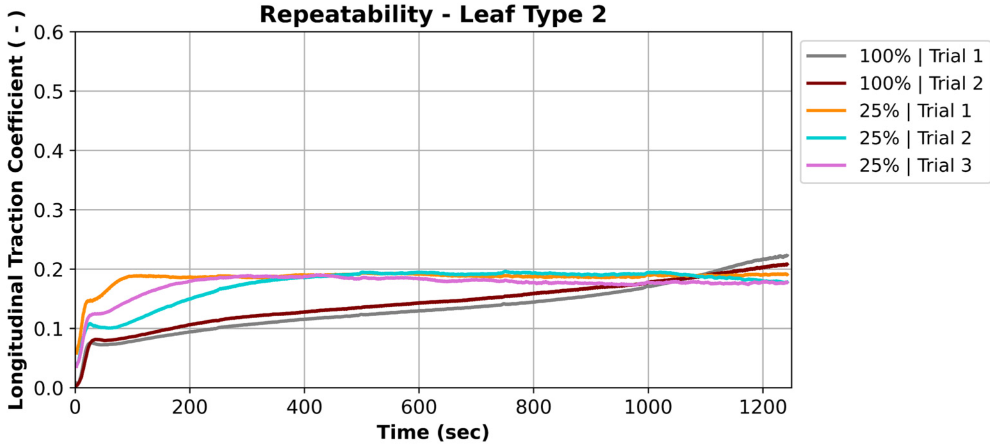

Figure 14. Repeatability tests were done with maximum and minimum categories for leaf Type 2.

These figures suggest that the experiments performed on the VT-FRA Roller Rig are highly repeatable following the meticulously chosen methodology.

The relation between leaves and traction is critical for railway safety. The bar plot in Figure 15 visually represents this intricate correlation, illustrating the inverse relationship between the number of leaves that have come in contact and the traction coefficient. The blue bars show the percentage of the number of leaves at contact concerning the maximum number of leaves at contact for test 1, '100%'. The orange bar, however, shows the percentage of the traction coefficient finally achieved during each test concerning the maximum traction coefficient obtained in the baseline, 'no leaf' test.

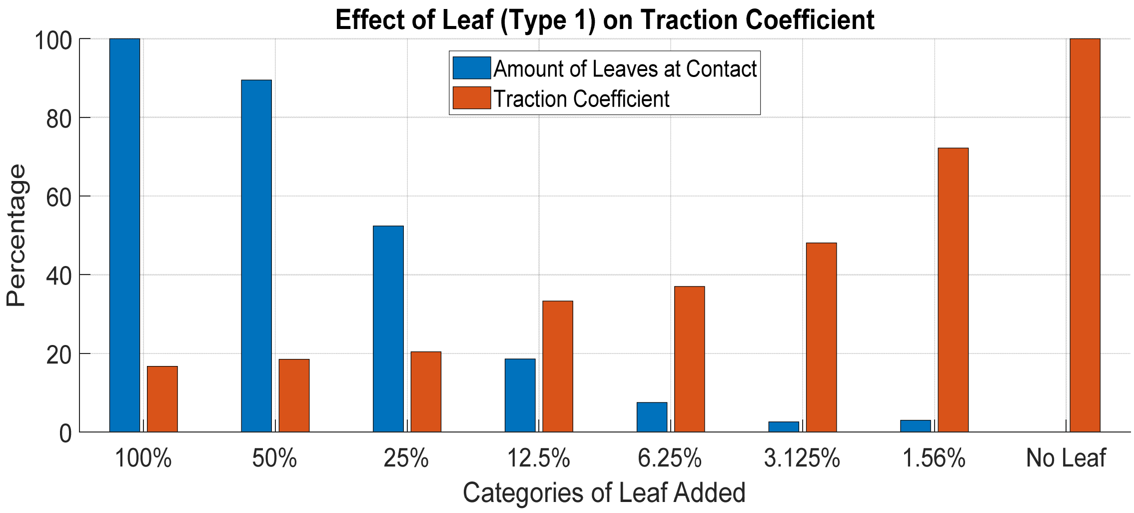

Figure 15. Statistical analysis on the effect of leaf Type 1 amount on traction coefficient.

From the plot, a clear trend emerges as leaves are reduced. At the outset, the 'maximum' leaf category exhibits a substantial reduction in the traction coefficient, indicating a significant reduction in adhesion between the wheel and the roller. This '100%' is noteworthy as the achieved traction coefficient drops by about 84%, highlighting the detrimental effect of excessive leaves on surface adherence.

Additionally, it is essential to note the '1.56%' category, indicating that the mere presence of leaves significantly affects the traction coefficient, decreasing it by 27.8%. Also, as observed in the baseline 'no leaf' test (Figure 7), it takes about 200 s to reach the peak traction coefficient; however, in the case of '1.56%', it takes about 1000 s to reach a peak much lower than the baseline. Even though the amount of leaves added is reduced by 50% for the '100%' and '50%' categories, the amount that has come into contact is very close. This indicates a saturated amount of leaves in contact with which the experiments are performed. Similar observations are made in the '3.12%' and '1.56%' categories.

As mentioned earlier, leaf Type 2 is thinner than the latter, expressing different tribological behavior. From the bar plot in Figure 16, the '100%' category of leaf Type 2 added has a similar reduction in traction coefficient, indicating a drop of about 81.5%, a value slightly lower than leaf Type 1.

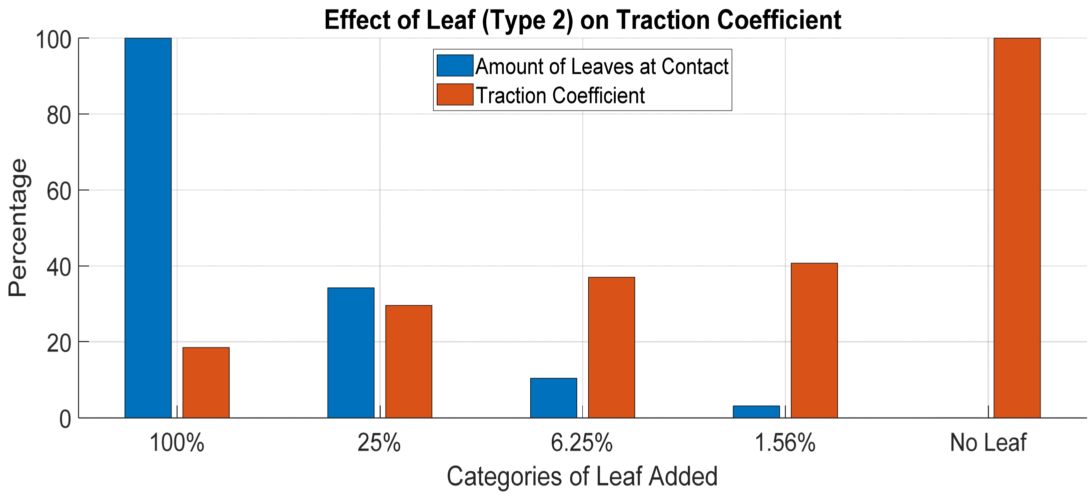

Figure 16. Statistical analysis on the effect of leaf Type 2 amount on traction coefficient.

The measured quantity of leaves recovered and weighed may contain some margin of error attributable to the challenging nature of collecting residue. Not all leaf residues can be retrieved due to their fragile and delicate nature, which can adhere to the wheel and roller surfaces. Retrieving these minuscule layers of residue with precision can be particularly challenging due to their adhesive nature. All the values have been approximated to the best of scientific judgment.

4.5. Understanding Wear

Lubricants are used to reduce wear, and as several authors have mentioned, the presence of 3BL helps slow the process of natural wear. Figure 17A shows the wear band generated when no contaminants are in contact. Both physically and with the help of the laser scanner, we see the wear caused by the test parameters on a clean and dry surface.

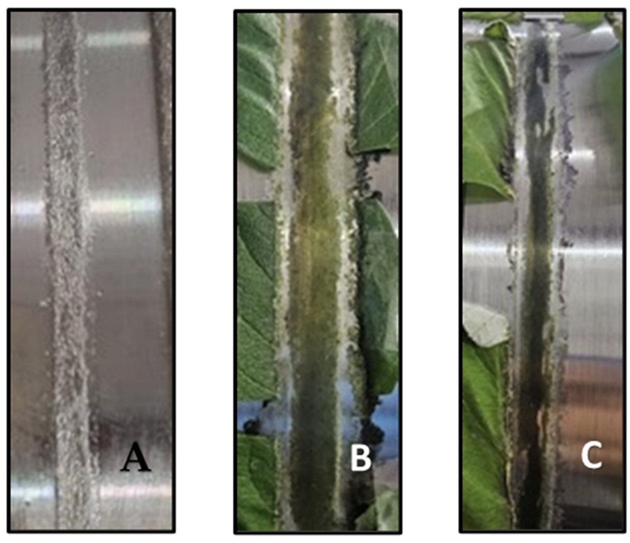

Figure 17. Images of wear band after (**A**) No Leaf, (**B**) 100% Leaf Type 1, and (**C**) 100% Leaf Type 2.

The same is not observed with the 'maximum' category in leaf Type 1. As mentioned, the thickness of the first variety of leaves is about 350 microns on average. From Figure 17B, the wear band is seen to have a green paste-like consistency, which adhered to the wheel surface and was hard to remove once the test was concluded. Once this generated 3BL was removed from the surface, no wear was observed, which can also be logically interpreted as no dark or blackish residues were observed in the band. On comparing the observations made to the wear band seen in Figure 17C, the darker presence of worn iron and its corresponding oxides show a much thinner 3BL. Additionally, as the experiment was being performed, some of the generated 3BL fell off the surface, which was not true in Type 1 leaves. These properties of leaves make them lubricate in nature without any presence of water or oil.

Once the leaf residue was removed and cleaned from the wheel surface, there was little to no wear observed. This can be seen in Figure 18. Comparing this figure to Figures 8B and 17A indicated the lubrication effect of the wheel on reducing wheel wear under the testing parameters used. The leaf layer formed at the end of testing is at the micron level scale and shows extremely adhesive properties. This layer was removed only using high grit sandpapers. The irregularities formed from sanding made it difficult for the laser scanner to provide accurate wheel profile data. For this reason, the scanned wheel profiles after the test have not been reported.

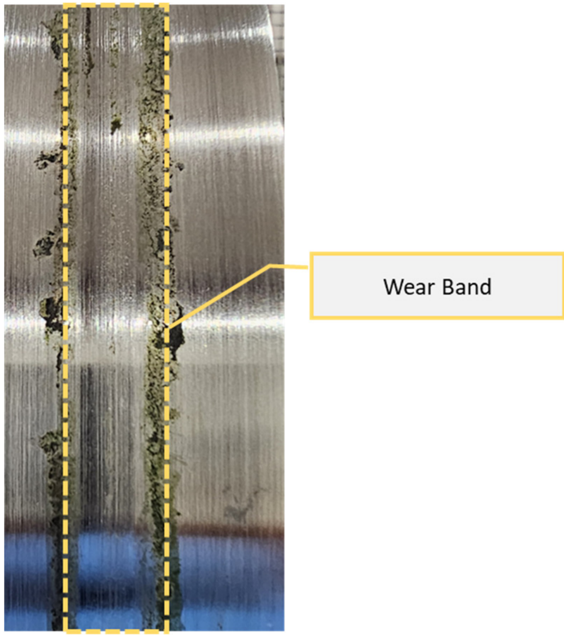

Figure 18. Wheel surface wear after removing leaf residues from the running surface.

5. Conclusions

This paper experimentally investigated the lubrication effects of leaf contamination of railroad tracks, focusing on reducing the ability to stop a train, along with the associated impact on wheel wear, using the Virginia Tech—Federal Railroad Administration (VT-FRA) Roller Rig. Two leaf species were investigated to understand their contamination effects better, using a comparative analysis that included varying the number of leaves from fully saturating the contact surface (100%) to a fraction of it by successively reducing the leaf weight by 50%, from 100% to zero (i.e., 50%, 25%, . . .). The percentages were determined proportionately to the total saturation (maximum) weight. For instance, the 50% condition implies 50% of the weight of the leaves for full saturation (called "100%" or "maximum"). To accelerate the tests significantly, the tests were performed at 2% creepage, an order of magnitude or more significant than the creepage experienced in revenue service.

The condition with no leaf and no debris (cleaned wheel) was chosen as the baseline for comparison with all other cases. Key findings from the tests include the following:

- Morrow's Honeysuckle (Type 1) leaves are approximately 56% thicker compared to wildberry (Type 2) leaves.
- A larger drop in traction is observed for Type 1 leaves. The traction saturates and does not naturally regain owing to the thick leaf residue generated upon contact.
- A similar drop in traction is observed for Type 2 leaves, but a slow and steady natural recovery is observed owing to the thinner thickness of the leaves. This results from generating more steel-to-steel wear upon contact.
- No wear was observed under 100% coverage of leaf Type 1, and a contrasting darker wear band was observed for Type 2.
- A minimal contamination of leaves has a significant reduction of adhesions; the presence of water or grease has a multiplying effect on braking.

Although most tests were performed with a redressed wheel to maintain higher repeatability, some tests used wear and debris at the running band to better emulate field conditions. When present, the wear debris (called here as "natural third body layer" or "3BL") resulted in a quick adhesion of recovery. The worn surface roughness and 3BL increased the wear of the leaves at the contact, causing them to have a shorter-lasting lubrication effect. For both types of leaves, the results indicate that even a tiny amount significantly affects the loss of adhesions when present on the track. This results in longer braking distance and reduced ability to generate traction to pull a train. The results of this study show that Longitudinal Traction Coefficients are higher than those observed in other literature, which leads to the conclusion on the large effects of various additives employed in their experimental approach. It is also interesting to see that both green and brown leaves result in a similar drop in traction, which has a future scope in understanding the tribology or material characterization of leaves. It was impossible to correlate the roller rig test results with field data because of their lack of availability; such a comparison is highly recommended to further validate the findings. In the future, the results of this study will provide empirical data to test with various traction enhancers, which can help regain the lost traction without causing wear or damage to the wheel and rail profiles.

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