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Optimization Analysis on Peeling of Iron Flakes from Wheel Tread Polishers by Experiment Design and Data Envelopment Analysis

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Keywords：Wheels tread cleaner, Polisher, Iron flakes, Data envelopment analysis, Taguchi method, T-test.

ABSTRACT

When the high-speed train brakes, the tread polishers in the braking system will contact the wheel tread and lead to the iron flakes scattering. The data envelopment analysis (DEA) was applied to define several polishers' characteristics and find the most efficient one in the study. Then through the Taguchi experiment method to find the optimized setting to reduce the peeling of iron flakes. The results showed that the peeling rate of the polisher surface dropped from 28% to 2%. It means that the iron fragments scattered on the track have significantly improved, and the risk of short circuits of the track circuit can also be reduced. According to the results of the T-test analysis, there is no significant difference between the optimized design and the original design of wheel tread roughness data.

INTRODUCTION

When trains run in normal conditions, a large amount of iron filings are scattered on the track. This has an adverse effect on the wheel treads and causes abnormalities in the track circuit, which result in train delays. Noise, abnormal vibration and environmental pollution are also generated when the wheels crush these iron filings. Multi-stage brakes are used on high-speed trains to increase stability and ride comfort by reducing the number of wear fragments that are produced during braking. To reduce the number of iron flakes from the wheel tread polisher, Saga (2010) used a control technique to reduce the number of wear fragments for railway vehicles, which was verified by tests. Using ADAMS/Rail software, Rezvani et al. (2009) determined the effect of a worn wheel profile on vehicle dynamics and the wear on wheels due to vehicle movements. Piechowiak (2010) used experimental measurements to validate a pneumatic train brake model. Using finite element modeling, Teimourimanesh et al. (2016) developed an advanced temperature-dependent material model that is used with fatigue analysis to quantify wheel performance.

Using VI-Rail and MATLAB software, the wear on a railway vehicle system was determined by Pradhan et al. (2018). Dirks et al. (2010) developed a lifetime prediction tool to predict the wear and the rolling contact fatigue for railway vehicle wheels using vehicle dynamics simulation. Most previous studies determine the effect of wheel profile on railway vehicle dynamics and rolling contact fatigue but few involve the wear fragments from railway vehicle wheels. This study reduces the number of iron flakes that peel from railway vehicle wheels and optimize the design using an experimental design method.

The High-speed trains are equipped with wheel cleaners. When the train brakes, many iron flakes are scattered on rails. This study uses a data envelopment analysis to determine the best polishers. The Taguchi method is used to identify the optimal design parameters that minimize the amount of iron flakes that are scattered on the track. Reducing the number of iron flakes that are scattered on rails, reduces the cost for cleaning using a night shift. Finally, the safety of trains is increased.

WHEEL BRAKE SYSTEMS

The brake system that is used for the study includes electric regenerative brakes, eddy current brakes and pneumatic brakes, as shown in Figure 1. When a train is running, the drag force for an eddy current brake is

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generated from the eddy current that is induced in the steel rail due to the relative motion between an electromagnet and the steel rail. The drag force that is exerted by an eddy current brake is not subject to the wheel-rail adhesive force, so braking distance is reduced. A pneumatic brake system uses the difference in pressure between compressed air and the atmosphere as the motive power. Air compressors and air storage tanks are installed on trains and the drag force is that is generated by transferring compressed air through the pipeline activates a booster cylinder to slow down the train. To prevent a decrease in wheel-rail friction and slippage due to oil stains, fouling or dampness, wheel tread cleaners are installed on trains as a part of the braking system to increase the wheel-rail adhesive force.

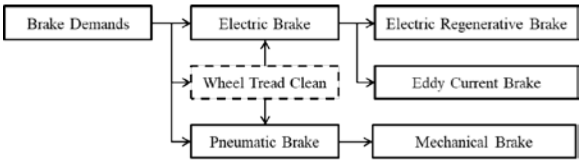

Figure 1: Tread Clean Polisher Function

Design of a Wheel Tread Braking Cleaner

A carriage with two bogies, with four wheel tread cleaners on both leading bogies, is shown in Figure 2. Wheel-rail friction decreases and slippage occurs if there are oil stains, fouling or dampness on the wheel treads and this adversely affects train safety. If disc brakes, electric brakes or electric regenerative brakes are installed on the train, without a wheel tread cleaner, the wheel tread becomes dirty and fouled, which decreases braking efficacy. If the wheel-rail coefficient of friction decreases to less than 0.15, the braking distance and time increase and the efficiency with which power is transmitted to the track decreases. Polishers for wheel tread cleaners and brake pads use an abrasive material with a high friction coefficient. When a braking command is sent, the brake booster cylinders on the bogies push polishers to clean the wheel tread and remove debris.

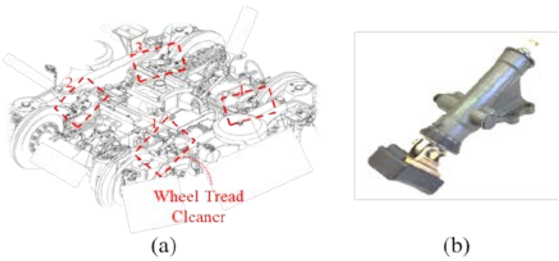

Figure 2: (a) 4 tread cleaners located on the bogie and (b) wheel tread cleaner with polisher

Working Mode for the Tread Cleaners

A train undergoes working tests for the polishers and the wheel-rail adhesive force is measured before it is run. If the cylinder for a tread cleaner is activated by air pressure, the polisher presses directly on the tread to prevent fouling and a decrease in the coefficient of friction between the wheel and the rail. To prevent peeling of a large amount of iron flakes from the polishers of tread cleaners due to continuous friction, the working mode for train brakes has developed from one-stop braking to multi-stage braking. The effectiveness of polishers depends on the brake system. When the brake system is started, tread cleaners clean the tread according to information from an on-board computer program and timer relay settings, as shown in Figure 3. The braking system combines digital control and mechanical braking system. When braking is applied, the tread cleaners begin the clean the wheel tread and do not stop until the speed is less than 25 km/h.

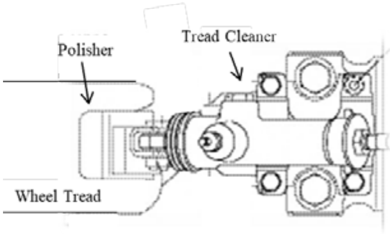

Figure 3: Wheel Tread Cleaner Configuration

Analysis of Iron Flakes and Polisher Type

Feedback from maintenance units (end users) show that a large amount of iron flakes are often found scattered on rails. The debris stretches to approximately 4 to 8 kilometers away from stations or railway sections where braking is required. These iron flakes have a shape that indicates that they peel from the surface of polishers, as shown in Figure 4. A comparison of the composition and weight percentage for these iron flakes shows that they have the same composition and weight percentage as polishers, as listed in Table 1. Currently, four types of wheel tread polishers are used: JA, JB, JC and LD. Iron flakes peel from each of the four types of wheel tread polishers to different extents. To ensure safety, night shift teams are used to remove the iron flakes that fall on train lines, which increase operating costs.

Table 1: Composition and weight percentage of polisher iron flakes

Fe, Mn	**Al, Cu**	**Al_2O_3, SiO_2**	**Aramid Fiber**	**Phenolic Resin**
40%	34.5%	11.5%	1.5%	12.5%

Figure 4: Iron flakes peeled off from the polishers

OPTIMIZATION OF WHEEL TREAD POLISHER EFFICIENCY

When many iron flakes peeled off from the wheel tread cleaners and scattered on the mainline, the track circuit may happen short-circuited, and the train will stop running. If night shift workers dispatch to clean the iron pieces, the labor cost will increase significantly. Therefore, this research uses data envelopment analysis (DEA) to determine which polisher has the best surface integrity for the four types of tread polishers currently available on the market. The Taguchi experiment method is applied to design the control factors and find the optimal setting to reduce maintenance costs further. In this way, the number of scattered iron flakes can be minimized, while human resource costs for night shifts also reduced, and train safety running can improve. Finally, a T-test determines whether the optimized parameter settings affect the wheel tread roughness and train braking efficiency.

Introduction to Data Envelopment Analysis

DEA is used to simultaneously process multiple input and output items. The result is an aggregative indicator. DEA is used to describe the concept of total factor productivity in economics. Production function and weight are not required and the process is free of subjective judgment so the process is rational and fair. Resource use is determined according to related efficiency and variables as a reference for decision making. DEA is used to determine service depot efficiency, hospital performance and on construction sites, but there are limitations to its application. The units must be homogeneous, so units with a different nature or scale cannot be compared. The analysis gives a relative efficiency, and not the absolute efficiency, of an evaluated unit, so the result cannot be used as an absolute value. This is a non-parametric technique that considers multiple variables to determine performance. Ji and Lee (2010), Weber (1996), Anouze and Bou-Hamad (2019), Maryam et al. (2019).

CCR Mode and BCC Mode

When DEA is used, the performance of a decision-making unit (DMU) is calculated for two modes: CCR mode and BCC mode.

CCR Mode:

The CCR mode is also called the Multiplier Form and was proposed by Charnes, Cooper and Rhodes in 1978. It calculates production frontier efficiency, which was proposed by Farrell. This mode assumes that the DMUs to be evaluated have a fixed scale. It is assumed that n DMUs are to be evaluated. The S input values are converted into m output values. To calculate the efficiency of the kth DMU, and respectively represent the unknown weights of each output value (i) and input value (j) and the output-input ratio is used to calculate the performance of each DMU. The formulae are: Charnes and Cooper et. al (1978).

$$\max\ h_k = \frac{\sum_{i=1}^{m} U_i Y_{ik}}{\sum_{j=1}^{s} V_j X_{jk}} \quad (1)$$

$$\text{s.t}\ \frac{\sum_{i=1}^{m} U_i Y_{ik}}{\sum_{j=1}^{s} V_j X_{jk}} \le 1 \quad (2)$$

$U_i, V_j \ge 0 \ge \varepsilon$, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, s$; $k = 1, 2, \ldots, n$

where,

k: A DMU to be evaluated.

h_k : The target relative efficiency of a DMU.

Y_{ik} : The i_{th} output value of the k_{th} DMU.

X_{jk} : The j_{th} input value of the k_{th} DMU.

U_i, V_j : Respective weights of the i_{th} output value and the j_{th} input value for the k_{th} DMU.

ε: Archimedes number.

BCC mode:

The CCR mode does not determine whether a DMU is within the scale inefficiency or technical inefficiency so the BCC mode was proposed by Banker, Charnes and Cooper in 1984. Applications of the CCR mode are expanded. The BCC mode is used to calculate the correlation between Pure Technical Efficiency, Scale Efficiency and the Returns to Scale for a DMU, in order to calculate the efficiency of the DMU and to determine the reason for inefficiency. Therefore, the BCC mode calculates efficiency by analyzing the Constant Return to Scale (CRS) and the Variable Return to Scale (VRS): Banker and Charnes et. al (1984).

$$\max\ h_k = \sum_{i=1}^{m} U_i Y_{ik} - U_k \quad (3)$$

$$\text{s.t}\ \sum_{j=1}^{s} V_j X_{jk} = 1,\ \sum_{i=1}^{m} U_i Y_{ik} - \sum_{j=1}^{s} V_j X_{jk} - U_i \le 0 \quad (4)$$

$U_i, V_j \ge 0 \ge \varepsilon$, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, s$; $k = 1, 2, \ldots, n$

The status of the Returns to Scale for each DMU depend on the value of U_k , as follows:

1. $U_k = 0$ represents a Constant Return to Scale (CRS), so a DMU performs production activities at the optimal scale.
2. $U_k > 0$ represents a Decreasing Return to Scale (DRS), so a DMU performs production activities at a scale that is greater than the optimal scale.
3. $U_k < 0$ represents an Increasing Return to Scale (IRS), so a DMU performs production activities at a scale that is smaller than the optimal scale.

DMU Definition and Pearson Correlation Coefficient

Input and output items for the four types of wheel tread polishers are defined in Table 3. Before applying DEA, this study confirms the isotropy and positive correlation between input and output items. The Pearson correlation coefficient, Rodgers and Nicewander (1988), Stephen (1989), is used to determine the effect and the direction of the effect between two sets of variables. The formulae are:
Pearson Correlation Coefficient is population data:

$$\rho_{XY} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y} = \frac{\frac{\sum\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{N-1}}{\sqrt{\sum\left(X_i - \overline{X}\right)^2 \times \sum\left(Y_i - \overline{Y}\right)^2}} \tag{5}$$

where,

ρ_{XY} : Population correlation coefficient.

σ_{XY} : Population covariance.

σ_X : Population standard deviation of *X*.

σ_Y : Population standard deviation of *Y*.

The sample correlation coefficient γ_{XY} is an estimated value of population correlation coefficient ρ_{XY}. The value of *r* for the Pearson correlation coefficient ranges from 1 to -1. $\gamma_{XY} > 0$ indicates a positive correlation between *X* and *Y*, $\gamma_{XY} < 0$ indicates a negative correlation between *X* and *Y* and $\gamma_{XY} = 0$ indicates no correlation between *X* and *Y*. The input and output items for this study are tested using Pearson's correlation coefficient and the results show a positive correlation between the two output items and the input item, as shown in Table 2.

Table 2: Pearson correlation coefficient between the output items and the input item

Item	Output	
	Rate of adhesion (%)	Durability (km)
Input Unit Price (NT)	0.935	0.545

The study uses two output items and one input item. Unit Price is the input item. Rate of adhesion and Durability are the two output items. Four wheel tread polishers were installed on the bogie of a train for the experiment. All of the test values are shown in Table 3. The test conditions for the DMUs (Decision Making Units) are described as follows:

1. Polisher adhesion Rate: 100 grids were adjusted according to the dimensions of the surface of each polisher. The surface of each polisher was covered with the grids to calculate the percentage of iron flakes that peel, as shown in Figure 5.

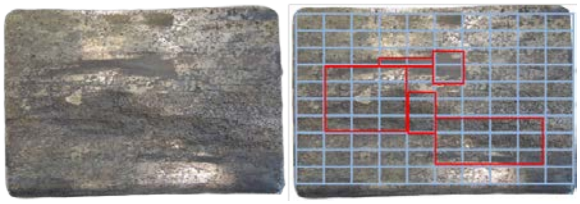

Figure 5: 28% Iron Flakes peeled from the current tread polisher

2. Durability: Durability represents the travelling distance for a train from the time when the four new wheel tread polishers are installed at the test points to the time when the polishers are worn out and must be replaced.
3. Polisher Price: This study uses unit price as an input item. If the unit price for a wheel tread polisher is NTD1000, the unit prices of other wheel tread polishers is determined relative to this price, in order to calculate the performance of each wheel tread polisher.
4. In this study, the name of each polisher is represented by a code: J means made in Japan and L is a local product. A, B, C and D are the serial numbers for each polisher. JA is the first test object, which made in Japan. This part is currently used for local trains. The remaining three are the objects for the optimization experiment.

Table 3: Tread Polisher Types and DMU Conditions

Polisher	Output		Input
	Adhesion Rate (%)	Durability (km)	Price (Thousand)
JA	72.0%	2,100,000	1
JB	69.0%	1,400,000	0.889
JC	92.0%	1,700,000	1.111
LD	33.5%	1,500,000	0.796

Data Envelopment Analysis

It is assumed that the Constant Return to Scale (CRS) for the CCR mode is used to calculate the overall efficiency and that the Variable Return to Scale (VRS) of the BCC mode is used to calculate technical efficiency so DEA must be used in conjunction with the CCR and BCC modes to calculate Scale Efficiency (SE) and compare the relative efficiency between DMUs. In terms of the Product Efficiency (PE) for each wheel tread polisher, PE = 1 indicates that a wheel tread polisher is relatively efficient and PE < 1 indicates that a wheel tread polisher is relatively inefficient.

The Technical Efficiency (TE) of each wheel tread polisher is determined using the BCC mode. The SE for each wheel tread polisher is calculated by dividing PE by TE to determine the best wheel tread polisher, using the Return to Scale (RS) for each wheel tread polisher. Golany and Roll (1989).

SE and RS are calculated using DEA in conjunction with the CCR and BCC modes to determine the overall wear, durability and cost, as shown in Table 4. RS = 1 represents a Constant Return to Scale (CRS), so a wheel tread polisher has optimal input and output values. SE > 1 represents a Decreasing Return to Scale (DRS). SE < 1 represents an Increasing Return to Scale (IRS), so the acquisition cost must be reduced or the design of a wheel tread polisher must be changed, in order to increase the durability and adhesion rate for a wheel tread polisher.

Table 4: Efficiency and RS for wheel tread polishers

Polisher Type	DMU	CRS (PE)	VRS (TE)	SE	RS Status	Referred Times
JA	1	1.000	1.000	1.000	--	2
JB	2	0.961	1.000	0.961	IRS	0
JC	3	1.000	1.000	1.000	--	1
LD	4	0.897	1.000	0.897	IRS	0

Table 4 shows that the two sets of tread polishers showed satisfactory efficiency. DMU1 and DMU3 are the best efficient. DMU1 is the part currently used by the train and is used as a reference for the other two sets of polishers. DMU3 is also the best choice, and the adhesion rate is 22% better than DMU1. The purchase cost of DMU3 is very high, but there is no need for the night shift to clean iron flakes.

DEA provides a performance analysis of the surface peel rate for DMUs, and the results show that all kinds of tread polishers are inefficient. That is, every type of polisher needs further improvement. Since the train manufacturer provides the wheel tread polisher, the polisher cannot change its ingredients. As far as the options developed by the Taiwanese company are concerned, DMU4 is inefficient and cannot be verified for safety. The Taguchi experiment was designed for the polisher which the best one by DEA to minimize the iron flakes.

OPTIMIZATION DESIGN AND ANALYSIS

Montgomery (1997) and Taguchi (1986) expressed that the traditional experiment design methods include trial-and-error, full-factorial experiments and fractional-factorial experiments. None of these methods feature systematic application, reproduction, or simplicity. The Taguchi experimental provides an insight into a quality issue from the perspective of engineering and then allows an overall plan and design of experiment. A systematic method that allows experimental analysis uses an orthogonal array. The signal to noise ratio is used as a quality index to predict quality. The Taguchi experimental method gives integral and reliable experimental information using fewer experiments, reduces the impact of noise and interference on the result during operation and minimizes the variance between results and the target value.

To reduce peeling of iron flakes from wheel tread polishers, this study uses the Taguchi experiment method of experimental design and implements an experimental analysis with fewer parameter sets to identify the optimum parameter settings that minimize the number of iron flakes peel and fall on rails. This process gives a high-quality and cost-effective result.

Parameters Design

The peeling iron flakes are affected by several factors such as wheel deformation, polisher material, and operational duration of tread cleaners, train braking frequency, ambient temperature, and relative humidity. This study used three control factors and set levels according to the original design documents, as shown in Table 5. The three control factors are “Operation Duty Cycle,” “Bogie Wheels Truing Interval,” and “Polisher Position Exchange.” The “Polisher Position Exchange” factor can interact with the other two factors, so the interaction between factors A and C and between factors B and C are included. Each factor has two levels. These three control factors are used to optimize the peeling of iron flakes from wheel tread polishers. DMU3 identified the best one in the experiment.

Table 5: Control Factors and Levels

Factor	Explanation	Level 1	Level 2
A	Operational Duty Cycle Turn ON / OFF (Second)	10 / 75	22 / 22
B	Bogie Wheels Truing Interval (Mileage)	30	60
C	Polisher Position Exchange (Left & Right)	Performed	Not Perform

Factor A: According to Nonaka et al. (2006), friction between the polishers of the wheel tread cleaners and the tread affects the retardation efficiency of the train by just 1% so when a train slows, a change in the operational duty cycle of the tread cleaners has no significant effect on retardation efficiency. The Time Relay is adjusted to control the operational duty cycle of the tread cleaners. The operational duty cycle for the Level 1 settings uses the limit values that not affect the wheel / rail viscosity and which are established by the train manufacturer. Level 2 is the setting that is used currently on trains.

Factor B: The wheels l wear out as the train runs and treads gradually become deformed. A deformed wheel tread becomes beveled and does not completely fit the contact surface of the polisher, so the surface of the polisher is cut and iron flakes are generated. All of the wheels on a train bogie are trued every 600,000 km. For this study, intervals of 300,000 km and 600,000 km are used as optimized designs to decrease wheel deformation.

Factor C: The railroad track consists of two rails that run east and west. Rails that are laid on curves have different curvatures. Two locomotives move in fixed directions. The train runs against a sea wind on its west side so the two sides of the train are subject to different temperature and humidity conditions. Polishers on the left and right sides were exchanged during each monthly inspection to match environmental conditions.

Design of Experiment Using the Taguchi Method

Using the Taguchi method, this study reduces the number of experiments by using five control factors, which are placed on L8 orthogonal arrays. The peeling rate for iron flakes for each polisher was measured three times using 100 grids. The average rate of peel for iron flakes for each polisher is substituted into Equation (6) to calculate MSN and then into Equation (7) to obtain the S/N ratio. The results are shown in Table 6. A greater S/N ratio means that the quality feature is closer to the ideal value. The effect of a change in each control factor on the quality feature is shown in Figure 6.

Table 6: Orthogonal Arrays and Experimental Results

Number	A	C	A×C	B	B×C	y1	y2	y3	$\bar{Y}$	MSD	S/N
1	1	1	1	1	1	1.5%	1.7%	1.2%	1.5%	0.00022	36.59
2	1	1	1	2	2	2.0%	1.9%	1.6%	1.8%	0.00034	34.70
3	1	2	2	1	2	1.8%	1.8%	1.6%	1.7%	0.00030	35.21
4	1	2	2	2	1	2.0%	2.2%	1.8%	2.0%	0.00040	33.95
5	2	1	2	1	1	2.2%	2.5%	2.0%	2.2%	0.00050	32.98
6	2	1	2	2	2	3.8%	4.0%	4.5%	4.1%	0.00169	27.72
7	2	2	1	1	2	3.0%	3.5%	3.2%	3.2%	0.00105	29.79
8	2	2	1	2	1	6.5%	5.0%	5.5%	5.7%	0.00325	24.88

Taguchi (1986) expressed that In terms of the peeling rates for polishers and the optimization design using the Taguchi method, the target value is the smaller-the-better. The Mean Square Deviation (MSD) and S/N ratio are shown in Table 6. The formulae for calculating MSD and the S/N ratio are:

$$MSD = \left(\bar{y}^2 + S^2\right) = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{6}$$

$$S/N = -10\left[\log\left(MSD\right)\right] \tag{7}$$

where, y_i is an experimental value, $\bar{y}$ is the mean value of the quality characteristic, n is the number of samples and S is the standard deviation, which is calculated as:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}{n}} \tag{8}$$

The control factor response table uses the S/N ratios in Table 6. The control factors are presented in terms of the level of significance. The effect of each control factor is shown by the control factor response graph as the Figure 6. Table 7 shows that the two interactive factors are experimental errors, which are excluded in the optimization design. Therefore, A1, B1, and C1 are the optimum settings for the other three control factors. These are: timer setting to 10 / 75, wheel truing every 300,000 km, and the potion of polishers are changed. The ranking order for the control factors is A > B > C.

Table 7: Control factor response table

Item	A	C	A×C	B	B×C
Level 1	35.11	33.00	31.49	33.64	32.10
Level 2	28.84	30.96	32.47	30.31	31.85
Range	6.27	2.04	0.98	3.33	0.25
Rank	1	3	4	2	5

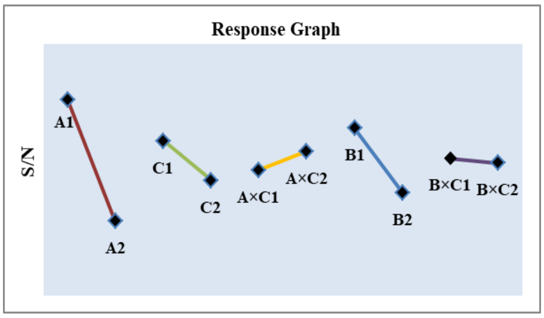

Figure 6: Control factor response graph

The experimentally derived optimum parameter set is A1, B1 and C1. The three polisher peeling rates measured for this set are 1.5%, 1.7% and 1.2% and the S/N ratio is 36.59 dB, which is greater than the S/N ratio for all other parameter sets in the orthogonal arrays. This is an improvement of 47%. This optimum parameter set gives the optimal design, as shown in Figure 7. In Figure 7, the peeling rate for iron flakes from polishers decreases from 28% to 2%. If one work party has 4 people and 10 work parties are required to clean all of the main lines every three days, the monthly cost is US$600,000. After DEA and using the optimized settings, only 5 work parties are required one night per month, at a cost of US$30,000. This solution eliminates 95% of the manpower costs to clean tracks on night shift and also eliminates the risk of a sudden short in a track circuit during a revenue service.

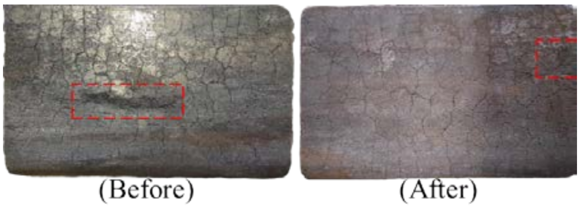

Figure 7: DMU3 peeling rate before and after improvements to the process

Analysis of Variance (ANOVA)

The correlation between the experimental error and the factorial effect is calculated. The Taguchi method considers the interaction between factors as part of the experimental error. This is used to calculate the significance of each factorial effect to the experimental error. An ANOVA is a mathematical approach that uses the sum of squares to calculate the deviation in each control factor's average effect from the experiment's average effect. Table 8 shows the results of the analysis of variance for the five control factors, in relation to the peeling of iron flakes from polishers. The formulae for calculating the Correction Factor (*CF*), the Sum of squares (*SS*), the *SS* of the Total variations (SS_{total}), *SS* of errors (SS_{error}), the Degrees of freedom (*DOF*), the Variance (*Var*), the *SS* of a factor effects (SS_{factor}), the F-test and the Contribution Ratio (*CR*) are:

Correction Factor (CF):

$$CF = N \times \bar{y}^2 = \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{N} \tag{9}$$

where, N is the number of experiments, y_i is an experimental value and $\bar{y}$ is the average of y_i

Total Sum of Squares (SS_{total}):

$$SS_{total} = \sum_{i=1}^{N}\left(y_i^2 - CF\right) \tag{10}$$

Sum of squares of error (SS_{error}):

$$SS_{error} = SS_{total} - \sum_{i=1}^{n} SS_n \tag{11}$$

where, SS_n is the sum of squares of a factor (SS_{factor}): the formula for calculating the sum of squares for factor A is:

$$SS_A = \frac{sumA_1^2}{L_i} + \frac{sumA_2^2}{L_i} + \ldots + \frac{sumA_n^2}{L_i} - CF \tag{12}$$

where, $sumA_n$ is the sum of the *n*th level observations and L_i is the level number of *n*.

Degrees of Freedom (DOF):

$$DOF = Level\ number - 1 \tag{13}$$

Variance (Var):

$$Var = \frac{SS_n}{DOF} \tag{14}$$

Change (SS'_n)

$$SS'_n = SS_n - DOF_n \times V_{epooled} \tag{15}$$

where, DOF_n is the degree of freedom of a factor and $V_{epooled}$ is the variance of the sum of errors.

F distribution (F Distribution)

F value: Average variance among groups:

$$F = \frac{V_i}{V_{error}} \tag{16}$$

where V_i is the variance of the sum of squares of each factor and V_{error} is the variance in errors.

Contribution Ratio (CR)

$$CR = \frac{SS'_n}{SS_{total}} \times 100\% \tag{17}$$

When the significance of each factorial effect to the experiment is confirmed, the factors that have no significant effect are pooled and analysis results are shown in Table 8. These have no effect on the experiment so factors C, A×C, and B×C are included in the experimental error.

Table 8: ANOVA Result

Factor	*SS*	*DOF*	*Var*	*SSn*	F	Confidence	Contribution
A	78.56	1	78.56	75.26	23.763	99%	64%
B	22.18	1	22.18	18.87	6.709	95%	16%
C	8.33	1	Pooled				
A×C	1.91	1	Pooled				
B×C	0.12	1	Pooled				
error	6.17	2					
e (total)	16.53	5	3.31	23.14			20%
Total	117.27	7		117.27	At Least 95% Confidence		

This result shows that control factors A and B have the most significant effect on the polisher peeling rate, with respective contributions of 64 % and 16 %. The polisher peeling rate is optimized by using a timer relay setting for the WTC of 10-seconds of operation and 75-second of non-operation and by performing wheel truing every 300,000 km.

VALIDATION OF THE WHEEL ROUGHNESS

Wheel roughness affects the efficiency of train braking. The wheel roughness and tread cleanliness have a causal relationship to each other. If the wheel cleaner operating frequency is unilaterally changed, the braking efficiency may be affected. This chapter determines the difference in the wheel roughness using the original and the optimized parameters. The test continued until the polisher was replaced. The deformation in the shape of the wheel flange was determined and the wheel roughness was measured. The process was monitored to ensure that the optimized parameters do not reduce the wheel roughness below the accepted standard.

Measurement Equipment and Procedure

To ensure experimental accuracy, this experiment used two devices: a wheel flange shape gauge and a surface roughness measurement instrument. The wheel flange shape gauge was used to check for profile deformation, using a scale for marking measurement points, as shown in Figure 8. The surface roughness measurement instrument was within the validity period for annual calibration during the experiment. Wheel profile and tread roughness was measured using the following three steps:

1. A bogie has 4 wheels, each of which was measured at 4 points. Each measurement point extends to 4mm from the lateral direction.
2. The critical value (λc) for wheel roughness for each point is 0.8μm. If the measured value for a single point exceeds the standard, but the average value (Ra) for the 4 points is less than 1μm, the result is acceptable.

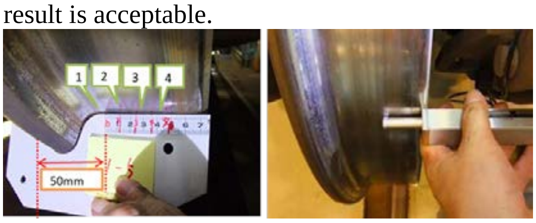

Figure 8: Four measurement points

3. Measurements were repeated 3 times for each wheel.

After the on-board tests, the tread roughness of the four wheels on each of the two bogies was measured using the measurement process and the results are shown in Table 9. The overall average for wheel tread roughness is 0.58μm for Car 1 and 0.61μm for Car 2. The design specification for the train states that wheel tread roughness must be greater than 0.5μm so the measured values meet the requirement and the optimized parameter settings do not affect wheel roughness.

Table 9: Wheel Tread Roughness Data

Train	Wheel	Roughness (μm) 1	2	3	Average (μm)	Overall Average (μm)
Car1	W1	0.56	0.54	0.58	0.56	0.58
	W2	0.59	0.62	0.58	0.60	
	W3	0.58	0.60	0.62	0.60	
	W4	0.58	0.58	0.56	0.57	
Car12	W1	0.62	0.60	0.61	0.61	0.61
	W2	0.62	0.60	0.63	0.62	
	W3	0.59	0.61	0.58	0.59	
	W4	0.61	0.60	0.62	0.61	

T-Test

As shown in Table 9, the optimum parameter set maintains satisfactory wheel tread roughness. Wheel tread roughness significantly affects wheel-rail viscosity so to ensure train safety and the robustness of the experimental design, tests used multiple measurement points and a T-test, Box (1987), was performed to verify that wheel-rail viscosity is not affected. To ensure accurate T-test results, the wheel tread roughness data for the original and the optimum parameter sets is tested using an F-test, in order to confirm that the average variance between the two sets is less than the threshold.

An F-test (Joint Hypotheses Test) for a null hypothesis is a test to determine whether statistics comply with the F distribution. It is used to test a hypothesis in terms of whether t the variance for a normal population is equal to the variance for another normal population. An F-test typically determines whether t there is a significant difference in the precision of two data sets by comparing the sums of their squares. A student's T-test uses a t-distribution to calculate the possibility of variance. It determines whether the expected value of one or more sets of independent samples from a normal distribution population is a real number, in order to determine whether the variance between two averages is significant.

F-test and T-test results for the roughness data using the original and optimum parameter sets are shown in Table 10. There are 16 sets of measured data for each of the two parameter sets, where $\overline{X}$ is the sample average and σ_s^2 is the sample variance, which are calculated as: Lomax (2012).

$$\overline{X} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{18}$$

$$\sigma_s = \sqrt{\frac{(n_1-1)\sigma_{s1}^2 + (n_2-1)\sigma_{s2}^2}{n_1+n_2-2}} \tag{19}$$

where, x_i is the measured roughness, n is the number of samples, σ_{s1} and σ_{s2} are the standard deviations of the two sample groups, n_1 is the number samples for the measurement of tread roughness using the original parameter set and n_2 is the number of samples for the measurement of tread roughness using the optimum parameter set. The T-test and F-test values are calculated as:

$$F = \frac{S_1^2}{S_2^2} \tag{20}$$

$$|T| = \left| \frac{(\bar{X}_1 - \bar{X}_2)}{\sigma_s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \right| \tag{21}$$

where, S_1^2 and S_2^2 are the respective variances of the two sample groups. The greater variance is used as the denominator. The degree of freedom of the member is n_1-1 and the degree of freedom of the denominator n_2-1. The null hypothesis is invalid if the result of the F-test is greater than the threshold.

When debris collects on the wheel tread, the tread roughness decreases and the wheel-rail viscosity decreases. Factor A for this optimization experiment reduces the operational ratio of the wheel cleaner to a critical value and the T-test results in Table 10 show that there is no significant difference between the value for the optimized parameters and that for the original parameters in terms of wheel tread roughness. It is concluded that the optimized parameter settings do not reduce wheel-rail viscosity.

Table 10: Results of the F-test and T-test for Wheel Tread Roughness

Wheel Tread Roughness (μm)								
Items	1	2	3	4	5	6	7	8
Original	0.75	0.53	0.67	0.74	0.69	0.81	0.75	0.67
Optimum	0.57	0.51	0.73	0.64	0.53	0.57	0.54	0.66
Items	9	10	11	12	13	14	15	16
Original	0.62	0.75	0.7	0.82	0.83	0.85	0.8	0.78
Optimum	0.83	0.73	0.68	0.63	0.89	0.58	0.56	0.75

Test result:

F-test value is 1.26 < threshold 2.86 ($\boldsymbol{F_{0.05,15,15}}$), $\sigma_1^2 \approx \sigma_2^2$

T-test is 2.45 < 2.4573 ($\boldsymbol{t_{0.01,30}}$), it's not the distinct deviation.

CONCLUSION

This paper presents the optimization design analysis on the peeling of iron flakes for the wheel tread polisher. Apply data envelopment analysis to four groups of tread polishers to confirm that DMU3 is the best one. To further optimize the peeling rate of the polisher surface, the best parameter combination was designed through the Taguchi experiment method. The results showed that the iron flakes peeling rate of the best parameter design dropped from 28% to 2%. This solution eliminates 95% of the labor cost of night shift cleaning the track and removes the risk of a sudden short circuit of the track circuit during the business period.

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REFERENCE

Anouze A.L.M. and Bou-Hamad I., "Data envelopment analysis and data mining to efficiency estimation and evaluation,"; International Journal of Islamic and Middle Eastern Finance and Management, Vol. 12, No. 2, pp.169-190 (2019).

Banker, R. D., Charnes, A., & Cooper, W. W., Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis,"; Management Science, Vol. 30, No. 9, pp.1078-1092 (1984).

Box J. F., "Guinness, Gosset, Fisher, and Small Samples," Statistical Science, Vol. 2, No. 1, pp. 45–52 (1987).

Dirks B. and Enblom R., "Simulation and Measurement of Wheel on Rail Fatigue and Wear," 16th International Wheelset Congress, Cape Town, 14-19 March (2010).

Charnes, A., Cooper, W. W. and Rhodes, E., "Measuring the Efficiency of Decision Making Units,"; European Journal of

Operational Research, Vol. 2, No. 6, pp. 429-444 (1978).
Golany B. and Roll Y., “An Application Procedure for DEA,”; Omega Vol. 1, No. 3, pp.237-250 (1989).
Ji Y. and Lee C., “Data envelopment analysis,”; The Stata Journal, Vol. 10, No. 2, pp.267–280 (2010).
Lomax R. G. and Hahs-Vaughn D. L., Statistical Concepts: A Second Course, Taylor and Francis Group, New York (2012).
Montgomery D. C., Design, Analyses of Experiments, 3rd; John Wiley & Sons, Hoboken, USA (1997).
Maryam J., Mahnaz M. and Hadi B. V., “Classifying fuzzy flexible measures in data envelopment analysis,”; Journal of Intelligent & Fuzzy Systems, Vol. 36, No. 4, pp.3791-3800 (2019).
Nonaka T., Nakazawa S., Endo Y., Ohyama T. and Yoshikawa H., “Improvement of Control Performances of Anti-lock Braking System for Train Sets in Railway Systems,”; RTRI Report, Vol. 20 No. 7, pp. 17-22 (2006).
Piechowiak T., “Verification of pneumatic railway brake models,”; Vehicle System Dynamics, Vol. 48, No.3, pp.283-299 (2010).
Pradhan S., Samantaray A. K. and Bhattacharyya R., “Prediction of railway wheel wear and its influence on the vehicle dynamics in a specific operating sector of Indian railways network,”; Wear, Vol. 406-407, No.1, pp.92-104 (2018).
Rodgers J. L. and Nicewander W. A., “Thirteen ways to look at the correlation coefficient,”; The American Statistician, Vol. 42, No. 1, pp. 59-66 (1988).
Rezvani M. A., Owhadi A. and Niksai F., “The effect of worn profile on wear progress of rail vehicle steel wheels over curved tracks,”; Vehicle System Dynamics, Vol. 47, No. 3, pp.325-342 (2009).
Saga S., “Restraint of the Scoring Phenomenon in Abrasive Blocks Using Control Techniques,”; Quarterly Report of RTRI, Vol. 51, No. 3, pp.122-124 (2010).
Stephen M. S., “Francis Galton's Account of the Invention of Correlation,”; Statistical Science, Vol. 4, No. 2, pp.73-79 (1989).
Teimourimanesh S., Vernersson T. and Lundén R., “Thermal capacity of tread-braked railway wheels. Part 1: Modelling,”; Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 230, No. 3, pp.784-797 (2016).
Taguchi, G. Introduction to Quality Engineering: Designing Quality into Products and Processes. Asian Productivity Organization, Tokyo (1986).
Weber C. A., “A data envelopment analysis approach to measuring vendor performance,”; Supply Chain Management, Vol. 1, No. 1, pp. 28-39 (1996).

應用實驗設計和資料包絡分析法於高速列車之踏面鐵屑剝落最佳化分析

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摘 要

當高速列車執行煞車時，車輪踏面將與製動系統中的踏面研磨子接觸並引起鐵屑散落。本研究應用資料包絡分析(DEA)，定義數種研磨子的特性並找出效率最高者。再透過田口實驗找出降低鐵屑剝離的最佳化方案。結果顯示研磨子表面的剝離率從 28% 降到 2%。表示軌道上散落的鐵片大幅減少，同時也可降低軌道電路短路的風險。根據 T-test 分析結果，最佳化設計與原始設計的車輪踏面粗糙度之數據無顯著差異。