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Electrostatics Safety Analysis and Controlling by Design of Experiment and System Thinking for a Railway Vehicle Carriage

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Keywords： Static electricity, Cause and effect diagram, Taguchi method, System thinking, Causal loop diagram analysis.

ABSTRACT

The human body is susceptible to static electricity shock due to movement or friction in dry environment. Static electricity affects the efficiency of train services and public safety in high-speed trains. This study determines the reasons for the accumulation of static electricity in newly purchased trains and the optimal design that prevents accumulation of static electricity. A cause and effect diagram is used to determine the principal factors for the accumulation of static electricity. The Taguchi method and an analysis of variance are used to determine the factors that most significantly affect the accumulation of static electricity and the optimal combination of parameters is derived. The results of the optimization experiment show that the electrostatic potential that accumulates on service personnel can be maintained at less than 1,000 volts, which represents an improvement of 37.7%, so the risk of shock due to static electricity is reduced. Because the humidity measured in carriages has a significant effect on the accumulation of static electricity, T-test is used to compare the humidity in new and old trains. System thinking and causal loop diagram analysis are used to devise strategies to decrease the risk of shock due to an accumulation of static electricity in railway vehicles of the future.

INTRODUCTION

Ride comfort is one of the most important service indicators for passengers. Vibration and noise and the quality of the environment in high-speed rail cars are also important. The temperature, humidity and the accumulation of static electricity in a train carriage affect the quality of service for passengers and attendants. When newly purchased trains were put into operation, a number of train attendants complained about shocks from static electricity in specific areas of the trains, which affects their performance and willingness to work.

The effect of the static electricity in vehicular systems has been the subject of several studies. Bulgin (1953) studied the static electric force that is generated when a tire is separated from the road. The force depends on the roughness of the road surface, the vehicle’s speed and the surface resistance of the tire. Gaćanović (2014) studied all conditions to eliminate the accumulation of static electricity when loading petroleum and oil products. Yu (2011) established a model for a tanker system and determined the degree of static electricity that is generated at each stage to determine the risk of ignition during fuel delivery. Frisina (1985) presented that the large modular habitats and small powered transport vehicles were protected with efficiencies several orders of magnitude over mass shielding against charged particle cosmic radiation. The electrostatic charging of vehicles in the dry climate of Spain was intensely investigated by Pidoll (2018). Besides the research of the electrostatic in the vehicle system, there were some applications for industry. The attributes of electric vehicles that give rise to concerns about electrostatic discharge (ESD) are determined by Krein (1996). Using the electrostatic finite-element model, Germano et al. (2004) determined the spatial distribution of the voltages in quartz watches. Greason (1998) investigated the possible ESD events involving the interface between the human body and an automobile. The effect of charge injection due to ESD on the operation of capacitive micro-electromechanical systems structures is presented by Greason (2008).

The accumulation of static electricity between the human body and a metal object has been the subject of some studies. Richman (1986) determined the effect of the human body on the electricity static discharge (ESD) Model for metal. The equivalent capacitance of the human body is about 100

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Pico-farads (pF). If the human body's potential reaches 3,000 volts and contacts metal, static electric discharge occurs, which can result in numbness. King and Reynolds (1981) determined the static electric waveforms between a finger-tip and a hand-held metallic object. Ohsawa (2011) performed a statistical analysis of accidents that are attributable to static electricity during operations by workers. A risk assessment of the issues of the accumulation of static electricity was performed by Ota (2018). Pavey (2004) presented a short overview of electrostatic hazards and discussed some of the basic concepts.

In this paper, a cause and effect diagram is used to determine the relevant control factors that affect the generation of static electricity in a train, including the temperature in a carriage, the effectiveness of air conditioning, the humidity, the duties of train attendants, and the configuration of items that are stored in the galley. The importance of each control factor is determined by measurement and an optimized design is derived using a Taguchi experiment and an analysis of variance (ANOVA) to determine the optimal parameter combination that controls the accumulation of static electricity. Vehicle measurements are then performed to verify that the electrostatic voltage is reduced. In order to compare the humidity in the carriage between new and old trains, T-test is utilized to present the relative humidity in the gangway near the new train's galley. Finally, the causal loop diagram analysis of system thinking is used to determine the cause of the accumulation of static electricity in trains.

STATICS IN A TRAIN CARRIAGE

Static Electricity Model

Static electricity occurs, if there is an imbalance in the charges on the surface or inside of a system. All matter is composed of atoms. The nucleus is composed of equal numbers of negatively charged electrons and positively charged protons to maintain an electrically neutral and stable state, Dhogal (1986). There are three types of electrostatic models: frictional charging, stripped charging and inductive charging.

(1) Frictional charging

Static electricity is caused by friction between the surfaces of two objects that are in contact with each other. Unevenness in the surface of the material means that the amount of electric charge that is generated by frictional charging is much greater than that due to contact charging. Uneven surfaces allow new areas of friction to increase and this increase in the contact area can result in a greater amount of charge.

(2) Stripped charging

The static electricity that is generated when objects that are in contact are separated, such as when tape is torn off or protective film is removed; cause a significant increase in charge. The closer the matter is in contact, the greater is the density of the charge and a discharge occurs. The amount of charge is determined by the speed of separation. If the speed of separation is slow, less charge accumulates and the static electricity discharge is smaller.

(3) Inductive charging

Inductive charging occurs only when an object is conductive. When a positively charged object approaches a conductor, the electrons inside the conductor move, so negative charge accumulates on the surface of the conductor that is closest to the charged object and a positive charge accumulates at the other end because the charge on the surface of the conductor must remain constant. This state is called induction.

Electrostatic Effect In A Train Carriage

Humidity affects the conductivity of the surface of an object, which significantly affects the loss of electrostatic charge. If the air is dry, or if water vapor condenses due to a low temperature, static electricity accumulates at a greater rate. Table 1 shows the charged state of the human body during different activities at different levels of humidity, IEEE (2007) and Greenwald (1991). If humidity is more than 30%, most insulators have a layer of moisture, which acts as a clearing path for electrostatic charges. However, if humidity is less than 30%, there is no moisture layer so electrostatic charge accumulates.

Table 1. Electric charge in human body for different activities at different levels of relative humidity

Activity	Relative Humidity		
	10%	40%	55%
Walking on Carpet	35,000V	15,000V	7,500V
Walking on a Plastic Floor	12,000V	5,000V	3,000V
Work Bench Operator	6,000V	800V	400V

If a human body walks and is not grounded, static electricity accumulates on the body. When thousands of volts of static electricity accumulate, it discharges to surrounding objects. If a train attendant walks through a dry carriage and accumulates a static charge, then when the train attendant touches a conductor such as a handrail in a galley, static electricity discharges and the train attendant receives a shock. Human cells are composed of particles and various substances in the environment move between them, which generates an electric field with positive and negative charges on both ends of the body and causes an accumulation of charges. Greenwald (1991) expressed the relationship between the electric potential of the human body and electric shock levels. If the potential in the human body reaches 3 KV and a static electric shock occurs, the person feels tingling, and when the voltage exceeds 10 KV, it can be quite painful.

CAUSE AND EFFECT ANALYSIS FOR STATIC ELECTRICITY

When the human body accumulates an electrostatic charge that exceeds 3,000 volts and comes into contact with other conductors, static electricity discharges, which to affects train attendants. When the potential difference is greater, the train attendant may feel pain. Service attendants note that static electric shock often occurs when they pass between the business-class carriage and the galley. This study uses a cause and effect diagram to determine the important factors that affect the accumulation and discharge of static electricity. A Taguchi design of experiment is used to optimize the design and an ANOVA is used to determine the optimal parameter combination. A T-test is then used to confirm the factors that affect the accumulation of static electricity. System thinking and a casual loop diagram are used to verify that the optimal combination of control factors limits the accumulation of static electricity in a train carriage within a specific range. The research process is shown in Figure 1.

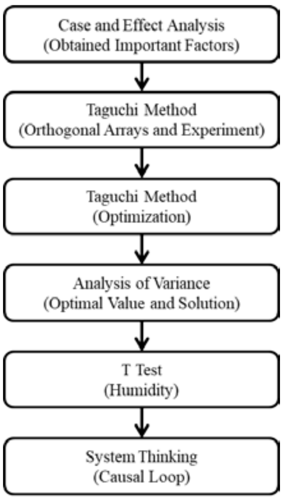


Fig.1. Process to improve design

Cause and Effect Diagram

A cause and effect diagram lists all factors that affect the results. These are then filtered to determine the control factor that is most likely to affect the results. The factors that affect the generation of static electricity in a train carriage include the weather, train temperature, humidity, clothing materials, and physical phenomena, air-conditioning equipment, floor materials and areas. These factors are included in the cause and effect diagram in Figure 2.

The cause and effect diagram shows that the saloon temperature, relative humidity and air output volume are important factors in the accumulation of static electricity. Without changing the design of the train, to reduce the accumulation of electrostatic charge, an electrostatic elimination device could be installed on the service cart's handlebar. Therefore, the control factors that affect the generation of static electricity in a train carriage are: air-conditioner temperature, humidity control, air-conditioner's air output volume and electrostatic elimination device.

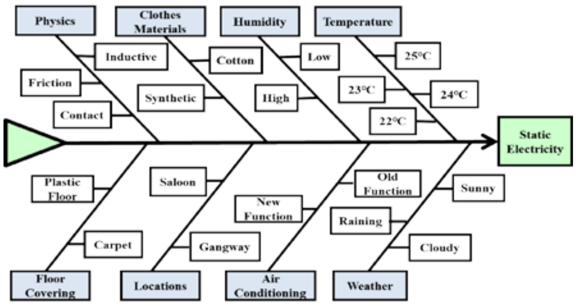


Fig. 2. Fishbone diagram for the analysis of static electricity

Preliminary Measurement Positions and Procedures

Interviews with several train attendants show that static electric shock occurs in specific sections of new trains, especially near the galley. This study terms sections that are prone to static electric shock as electrostatic hot zones. To confirm the control factors, a primary measurement is performed in the hot zone to determine the static electricity values, air-conditioning wind speed and temperature /humidity and identify the important factors. The primary measurement procedure is shown as follows:

Step1. Data Measure:

Temperature and Relative Humidity in the train carriage were measured. The same device was used for temperature / humidity measurement. Two types of values can be measured at the same time. Five sensors were placed in electrostatic hot zones and other places, as shown in Figure 3. Measurements were taken every 15 minutes and 5 sets of values were measured at one time. A total of 30 sets of values were taken. Using a WIFI connection, all values were displayed on a smartphone and recorded. The measurement system is shown in Figure 4.

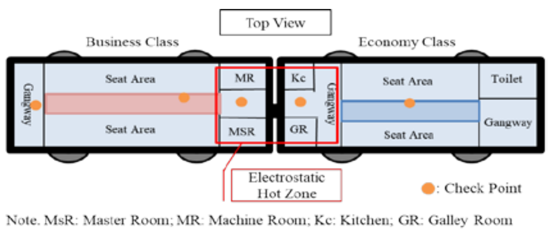


Fig. 3. Schematic diagram of the sensor distribution

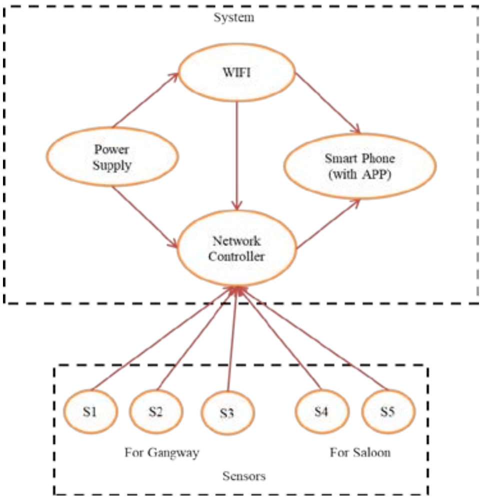
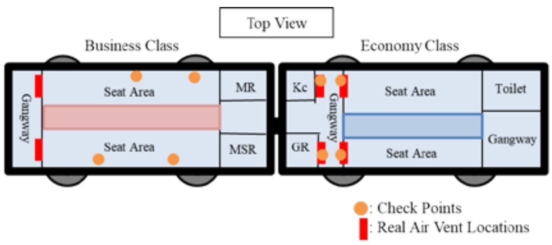


Fig. 4. Temperature and humidity measurement system in the train

Step 2. Electrostatic Voltage Measurement:
Measurements in the new train were performed every 5 minutes. The train ran 15 times in the north-south direction, so a total of 30 sets of values were recorded. The measurements were recorded on the train attendant's hand, as shown in Figure 5.

Fig. 5. Static electricity measurement positions on the service cart

Step 3. Measurement of the Wind Speed at the Vent:
Measurements were taken twice at four points in the carriage and four air outlets in the hot zone. The positions for measurement are shown in Figure 6.
The wind speed at the eight points is different, but the wind speed does not change with time, so only one set of values was recorded.



Note. MsR: Masterer Room; MR: Machine Room; Kc: Kitchen; GR: Galley Room

Fig. 6. Wind speed measurement positions

Measuring Equipment

In order to ensure the accuracy of the experiment, the experimental equipment for this study was within the validity period for annual calibration. The relevant contents and specifications of the main measuring equipment are described below.

(1) Measurement Sensor

The Temperature and Relative Humidity Sensor is small and easy to use. It measures temperature and humidity to the first decimal place. The specifications of the sensor are shown in Table 2. These sensors can be connected to the smartphone by Wi-Fi and downloaded its application software into smartphone. So, theses sensors can be used for monitoring and data logging.

Table 2. Specifications for measurement equipment

Device Name	Temperature and Relative Humidity Measuring Sensor	
Type	LYWSDCGQ / 01ZM	
Scope	Humidity: 0% ~ 99.9% Temp.: -9.0℃˜ 60℃	
Accuracy	60% RH ± 5% CRH / 0.3℃	

(2) Electrostatic Voltage Measurement Equipment

In determine the electrostatic voltage in a train carriage, hand-held static electricity measuring equipment was used. The temperature and the electrostatic voltage are measured at the same time using one measurement. This measurement equipment uses upper and lower laser focus to complete the measurement within 3 seconds. The specifications of the equipment are shown in Table 3.

Table 3. Measurement equipment specifications

Device Name	Handheld Static Sensor	
Type	SK-H050	
Scope	Temperature: 0~40℃ Humidity: 10% ~ 85 RH. Potential: ±2 kV / ±50 kV.	
Accuracy	Temp.: ±1℃. Humidity: ±5% RH. Potential: ±10 V / ±100 V.	

Impact Factors and Statics Measurement Results

Many control factors affect the accumulation of static electricity inside a train carriage. In this study the effect of relative humidity, train temperature, the air-conditioner's air output volume, and an electrostatic elimination device on the electrostatic voltage in a train carriage are determined.

(1) Relative Humidity

When the relative humidity in a carriage is high, a layer of moisture forms on the surface of an objective, which inhibits the accumulation of static electricity. The new train's air-conditioning system has a humidity adjustment function so if the relative humidity is between 60% and 80%, the air-conditioning system automatically reduces the temperature by 1°C. If the relative humidity reaches 80%, the air-conditioning system reduces the temperature by 2°C to improve thermal comfort. The old trains do not have this function. A schematic diagram of the temperature / humidity control in the carriage is shown in Figure 7. The humidity in the carriage and the electrostatic voltage on the train attendants were measured. A total of 30 sets of values were taken to construct a scatter plot. If the relative humidity is high, the electrostatic voltage is relatively low. Figure 8 shows that these two sets of values are negatively correlated with each other.

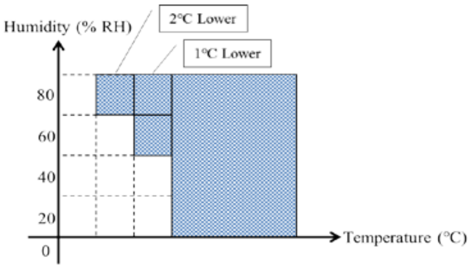


Fig. 7. Schematic diagram of the carriage's humidity control

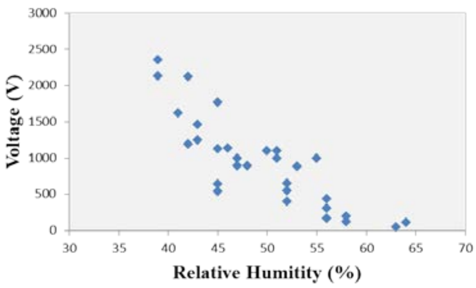


Fig. 8. Correlation between humidity and electrostatic voltage

(2) Train Temperature

The temperature and relative humidity (a total of 30 sets of values) were measured in the train carriage and a scatter plot shows that the temperature and humidity are positively correlated, as shown in Figure 9. When the temperature of the air-conditioning for the train is changed, the relative humidity in the train carriage changes and charge accumulates to generate static electricity. Using the ACCRP (air conditioning control relay panel), the temperature of the air-conditioning for the train can be set according to the experimental design. This ACCRP is used to independently control the temperature of each car.

(3) Air-Conditioner's Air Output Volume

The output volume affects the thermal comfort of the train but the wind speed affects air friction and results in the generation of static electricity. The average wind speed in the gangway is 2.875 m/s and the average wind speed in the train carriage is 2 m/s so the wind speed in the gangway is greater than that in the train carriage. Static electricity was generated by rapidly rubbing a plastic bag against a plastic ruler 25 times to determine the effect of different wind speeds on the accumulation of static electricity. Figure 10 shows that the electrostatic voltage in the gangway is higher than the electrostatic voltage within the passenger compartment, so wind speed is related to static electricity.

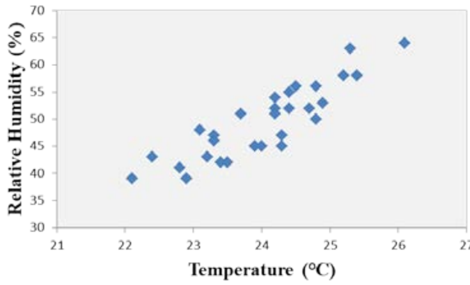


Fig. 9. Correlation between temperature and humidity

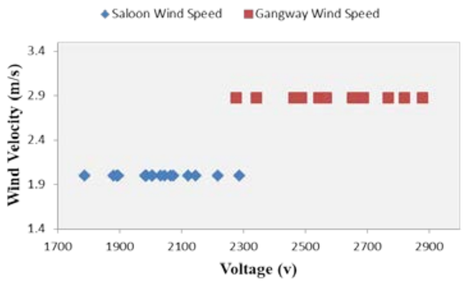


Fig. 10. Correlation between wind speed and electrostatics

(4) Electrostatic Elimination Device

Friction, peeling or induction between substances causes charge to accumulate on their surfaces, so static electricity is accumulated or discharges. This device reduces the charge that is accumulated. It was installed on the handle of a service cart, as shown in Figure 11.

Fig. 11. The electrostatics reduction equipment installed on the service cart

OPTIMIZED DESIGN AND ANALYSIS

Traditional experimental design methods include the trial-and-error method, full-factorial experiments and fractional-factorial experiments. No method is sufficiently systematic to ensure reproducibility and a lack of complication. Montgomery (1997) and Taguchi (1981) presented the Taguchi method is used to understand a quality problem from an engineering perspective and to plan the experiment. Orthogonal arrays and the signal-to-noise ratio are used as a quality index to predict quality. The Taguchi method gives complete and reliable experimental information with fewer trials and reduces the impact of noise and interference on the results. Variation between the results and the target value is also minimized.

In order to reduce the accumulation of static electricity in a train carriage, this study uses the Taguchi method for experimental design and experimental analysis using a small number of parameter combinations to obtain the optimal parameter combination that limits the accumulation of static electricity to a safe level. The results are achieved at low cost.

Parameter Design

The control factors and levels for this study are shown in Table 4. The four control factors respectively are the air conditioner (A/C) temperature, the related humidity (RH) control device, the air conditioner (A/C) louver block and the electrostatic elimination device. Each factor has two levels. These four control factors are used to determine the effect of static electricity in the train carriage.

Table 4. Control factors and levels

Factor	Explanation	Level1	Level2
A	A/C Temperature	24℃	25℃
B	RH control device	Old	New
C	A/C louver block	Installed	None
D	Electrostatic elimination device	Installed	None

Design of the Experiment using the Taguchi Method

An experimental design using the Taguchi method is used to reduce the number of trials. This study uses 4 control factors and a L8 orthogonal array. Each set of electrostatic voltage values were experimentally 3 times. Table 5 shows the average values for the experiments. Equation (1) is used to calculate the MSN values for Equation (2) for conversion to a S/N ratio. The larger the S/N ratio, the closer the quality characteristics are to the ideal state, Taguchi (1981).

Table 5. Orthogonal arrays and experiment results

Number	A	B	A×B	C	D	y_1	y_2	y_3	$\bar{Y}$	S	MSD	S/N
1	1	1	1	1	1	176	208	154	179	27	32652	-45
2	1	1	1	2	2	992	2679	1902	1858	844	3926236	-66
3	1	2	2	1	1	367	493	112	324	194	130094	-51
4	1	2	2	2	2	3440	3385	2036	2954	795	9145707	-70
5	2	1	2	1	2	773	2988	1437	1733	1137	3863547	-66
6	2	1	2	2	1	124	673	226	341	292	173127	-52
7	2	2	1	1	2	2032	3147	898	2026	1125	4946346	-67
8	2	2	1	2	1	125	65	287	159	115	34073	-45
Original	1	2	–	2	2	3035	2899	2217	2717	438	7510172	-69

The mean square deviation (MSD) and the S/N ratio are calculated using the measured electrostatic voltage value and the target value (as small as possible) for the best design using the Taguchi method, as shown in Table 6. The MSD value and the S/N ratio are calculated as:

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

$$S/N = -10\left[\log\left(MSD\right)\right] \tag{2}$$

where y_i is a measured 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:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}{n}} \tag{3}$$

The S/N ratio in Table 5 is used to produce the control factor response table, which is Table 6. This table lists and sorts the importance of each control factor. The control factor response graph in Figure 12 shows the effect of each factor. Table 6 and Figure 12 show that the optimized parameters for the four controllable factors are A2, B1, C1 and D1, which respectively represent an A/C temperature of 25℃, the old train system, 50% of the A/C air blocked and the statics elimination device installed. The rank order for the control factors is D> C> B> A.

Table 6. Control Factor Response Table

Item	A	B	A×B	C	D
Level 1	-57.96	-57.33	-55.84	-57.27	-48.50
Level 2	-57.63	-58.26	-59.75	-58.31	-67.09
Range	0.33	0.92	3.92	1.04	18.59
Rank	5	4	2	3	1

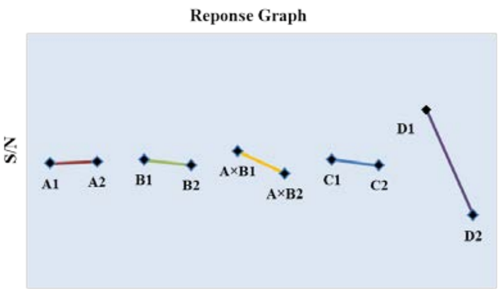


Fig. 12. Control Factor Response Graph

The optimal combination according to the control factor response graph is not in the orthogonal arrays (OA), so the experiment was run again using the best combination. The static voltage measurement results for the train attendants are respectively 101 V, 79 V, and 221 V, and the S/N value is -43 dB, which are is greater than the S/N values for all combinations in the orthogonal arrays. Therefore, this is an optimized and improved design. The improvement in the optimal design is shown in Table 7.

Table 7. Values and improvements for various phases

Phase	S/N ratio	Improvement rate
Original design	-69(dB)	–
Best Value in OA	-45(dB)	34.8(%)
Optimal design	-43(dB)	37.7(%)

Analysis of Variance

The relationship between experimental error and factor effects is determined. Using the Taguchi method, the interaction between factors is part of the experimental error and the experimental error is used to determine the effect of each factor on the experimental error. An analysis of variance uses the sum of squares as the mathematical method to determine the deviation in the average effect of each control factor in terms of the average effect on the entire experiment. Table 8 shows the four control factors for the analysis of variance for electrostatic voltage. The correction factor (*CF*), sum of squares (*SS*), *SS* of total variations (SS_{total}), *SS* of errors (SS_{error}), degrees of freedom (*DOF*), variance (*Var*), *SS* for factor effects (SS_{factor}), F-test and contribution ratio (*CR*) that are specified in Table 8 are calculated as:

Correction Factor (CF):

$$CF = N \times \bar{y}^2 = \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{N} \tag{4}$$

where N is the number of trials, y_i is the measured value and $\bar{y}$ is the average of y_i.

Total Sum of Squares (SS_{total}):

$$SS_{total} = \sum_{i=1}^{N}\left(y_i^2 - CF\right) \tag{5}$$

Sum of Squared Error (SS_{error}):

$$SS_{error} = SS_{total} - \sum_{i=1}^{n} SS_n \tag{6}$$

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

$$SS_A = \frac{sumA_1^2}{L_i} + \frac{sumA_2^2}{L_i} + \ldots + \frac{sumA_n^2}{L_i} - CF \tag{7}$$

Where $sumA_n$ is the sum of the level observations and L_i is the number of levels of n.

Degrees of Freedom (DOF):

$$DOF = Level\ number - 1 \tag{8}$$

Variance (Var):

$$Var = \frac{SS_n}{DOF} \tag{9}$$

Pure Change (SS_n'):

$$SS_n' = SS_n - df_n \times V_{epooled} \tag{10}$$

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

F Distribution (F value): The difference between the averages for several groups.

$$F = \frac{V_i}{V_{error}} \tag{11}$$

where V_i is the variance for the sum of squares of each factor and V_{error} is the variance for the error value. Contribution Ratio (CR):

$$CR = \frac{SS_n'}{SS_{total}} \times 100\% \tag{12}$$

The each factor is confirmed, the less influential factors are pooled and the analysis results are shown in Table 8. The degree of contribution for factor D is more than 91 %. Moreover, the error of optimized parameters which degree of freedom is only 2 and its contribution to other controllable factors is extremely low and less than 0.1% as shown in Table 8. Therefore, it can be ignored. In terms of the S/N ratio, the effect of factors A, B and C is insignificant for the experiment so these are included in the experimental errors. Control factor D has a much greater effect on the electrostatic voltage greatly than other control factors so static electricity elimination equipment on the handle of the cart controls the accumulation of electrostatic voltage on the human body.

Table 8. ANOVA results

Factor	*SS*	*DOF*	*Var*	*SS'n*	F	Confidence	Contribution
A	0.2	1	Pooled				
B	1.7	1	Pooled				
C	2.2	1	Pooled				
D	691.5	1	691	682.7	78.81	99.99%	91.75%
A×B	30.7	1	Pooled				
error	17.89	2	8.95	0.3	1.02	58.43%	0.05%
e total	52.64	6	8.8	61.4	1.00	50%	8.25%
Total	744	7		744	At Least 99% Confidence		

T-Test

Using the results for the experimental design, the electrostatic elimination device and humidity are important control factors. Humidity sensing for the carriage improves the thermal comfort of the train carriage but it is not clear whether this affects the accumulation of static electricity. Therefore, temperature / humidity sensors (4 sensors) were installed in the train carriage and the gangway to measure and record the temperature / humidity every 5 minutes. Eight measurements were taken at each point, so 32 sets of data are used to confirm the deviation or variance. The measurement positions and methods are shown in Figures 3 and 5. F-test and T-test are used to analyzer the result.

The relative humidity in the train carriage has a significant effect on the accumulation of static electricity. A T-test confirms whether the humidity of the carriage and gangway of the new and old trains are the same and is used to verify the positions and range of the electrostatic phenomenon. To increase the accuracy of the T-test, this study performs the F-test on the measured values for the humidity in the new and old trains to confirm whether the difference between the averages for the group is less than a threshold value.

The F-test compares the square of the difference for the two groups of data to determine whether there is a significant difference in their precision, Richard (2012). A T-test uses T distribution theory to determine the probability of a difference. A T-test determines whether the expected value for one or more independent samples from a normal population is a specific real number to determine whether the difference between the two averages is significant.

The relative humidity measurement data and the F-test and T-test results for train carriages in the new and old trains are shown in Table 9. Table 10 shows the measurement data for the gangway and the relative humidity in the new and old trains, as well as the F-test and T-test results. Tables 9 and 10 are shown the data for humidity in the new and old trains. $\bar{X}$ is the sample mean and σ_s^2 is the sample variance. These are defined as:

$$\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{13}$$

$$\sigma_s = \sqrt{\frac{(n_1 - 1)\sigma_{s1}^2 + (n_2 - 1)\sigma_{s2}^2}{n_1 + n_2 - 2}} \tag{14}$$

Where x_i is the measured humidity, n is the sample size, σ_{s1} and σ_{s2} are the standard variance for the two sets of samples, n_1 is the sample size for humidity measurements in the new train and n_2 is the sample size for humidity measurement in the old train. The T-test and F-test values are calculated as:

$$F = \frac{S_1^2}{S_2^2} \tag{15}$$

$$|T| = \left| \frac{(\bar{X}_1 - \bar{X}_2)}{\sigma_s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \right| \tag{16}$$

Where S_1^2 and S_2^2 represent the respective variances for the two sets of samples. The larger is in the denominator. The degree of freedom for the numerator is $n_1 - 1$ and the degree of freedom for the denominator is $n_2 - 1$. If the value of the F-test statistic is greater than the threshold, the null hypothesis does not hold.

The T-test results show that there is no significant difference in the relative humidity in the carriages in new and old trains but the relative humidity in the new train in the hot zone in the gangway is lower than that in the old train so train attendants are more prone to static electric shock on the new train.

SYSTEM THINKING

System thinking is an overall dynamic thinking that uses causal feedback loops and time delays. It addresses the problems of intuitive thinking or judgment. It has been applied to investigate the safety and risk analysis, Fan et al. (2015), Goh et al. (2010), Cabrera et al. (2008), Leveson (2011).

Table 9. Results for the F-test and T-test for humidity in the passenger compartment

Items	1	2	3	4	5	6	7	8	$\bar{X}$	σ_s^2
Humidity in the new train (%)	57	52	54	53	52	45	47	50	51.3	14.8
Humidity in the old train (%)	57	60	56	56	56	55	50	50	55.0	11.7

The test result:

F-test value is 1.26 <threshold 4.99 ($F_{0.05,7,7}$), $\sigma_1^2 \approx \sigma_2^2$

T-test is 2.06 <2.145 ($t_{0.05,14}$), it's not the distinct deviation.

Table 10. Results for F-test and T-test for Humidity in Gangway

Items	1	2	3	4	5	6	7	8	$\bar{X}$	σ_s^2
Humidity in the new train (%)	50	57	52	50	49	48	51	49	50.8	7.9
Humidity in the old train (%)	59	56	56	52	53	60	49	52	54.6	14.3

The test result:

F-test is 0.56 <threshold 4.99 ($F_{0.05,7,7}$), $\sigma_1^2 \approx \sigma_2^2$

T-test is 2.33> 2.145 ($t_{0.05,14}$), it's the distinct deviation.

It generally considers the causes and effects of the event, so events or data that seem to be independent and fragmented can be integrated to determine an overall interactive relationship. The three factors that best describe the system are time, the interaction between elements and the goal. The three elements are the main core of system thinking, Senge (2018).

Effect of Service Procedures

When a train moves away from a station, business-class crew members must push a cart to provide onboard services for the newly boarded passengers and then return to the galley or the gangway. As shown in Figure 13, the business-class crew members move from point A to point B and point C and then return to point A. If a train stops at multiple stations, the attendant must perform multiple service walks, so the crew-member must push the cart across the carpet multiple times and a large amount of static electric charge accumulates. The results show that train attendants are more prone to static electric shock as the number of stops increased.

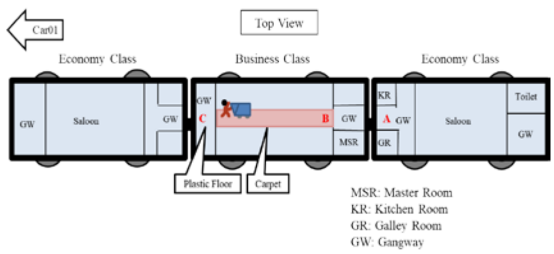


Fig. 13. Schematic diagram of service procedures on a train

If 3000 volts of static electricity accumulates, discharge may occur. If the service procedures are changed (for example, a local train makes multiple stops), a single journey with the service cart is possible. The service cart is stopped at the other end of the business-class and then returned from the other end when the train reaches the next stop so less static electricity accumulates on the human body. The Negative Feedback Loop for the passenger compartment's electrostatic state for Changes in Work Procedures is shown in Figure 14.

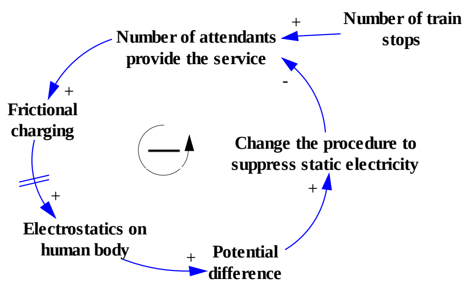


Fig. 14. Negative feedback loop for changes in work procedures

Effect of Storage Configuration in the Galley

When or customer service items are placed in the galley room, friction between the items can easily occur due to the limited, crowded space in the galley, which causes charge to accumulate. If a paper cup is placed next to a coffee pot, the plastic packaging on the paper cup and the coffee pot rub against each other due to vibration of the train and a charge accumulates. Improving the way items are stored in galley room reduces the amount of static electricity. The negative casual loop diagram for the electrostatic state of the galley is shown in Figure 15.

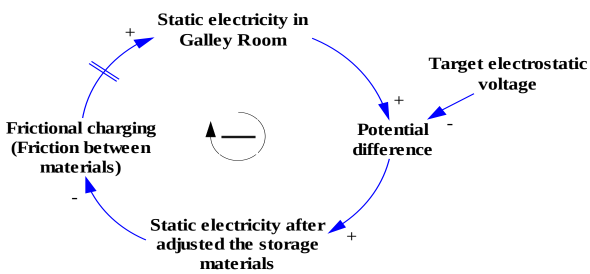


Fig. 15. Negative feedback loop for the improvement of item storage in the galley

Effect of Climate

On rainy days or humid conditions, if an electrostatic charge is generated, the charges disappear immediately. An insulator or a conductor that is insulated from the ground can store charge. The rate at which electrostatic charge is generated and the rate at which it is discharged depend on environmental conditions. Relative humidity is higher at room temperature and there is less accumulation of electrostatic charge. If the relative humidity reaches 55%, the electrostatic charge on the human body is about 5-20% of that at a relative humidity of 10%. If the relative humidity is 60-70%, the accumulation of static charge is significantly reduced. Humidity has a significant effect on the accumulation of static electricity.

During rainy days, half of the fresh air containing moisture should be input into the carriage through the train ventilation system to neutralize the frictional static electricity that is generated when attendants move the service cart across the carpet and reduce the risk if electrostatic shock. When the dehumidifying systems on the train keep operating, the humidity is eliminated slowly. The electrostatic charge will be accumulated, when the service cart continues working. The climatic negative feedback loop is shown in Figure 16.

Effect of Parameter Optimization

Using the Taguchi method analysis, the factor that most significantly inhibits the accumulation of electrostatic charge is identified as the electrostatic elimination device. Through systems thinking, two distinct loops are generated by electricity static. When statics charge accumulates, it is suppressed by another loop to minimize the risk of static electricity shock to the attendants, as shown in Figure 17.

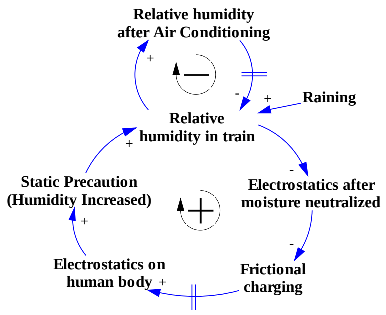


Fig. 16. Negative feedback loop for rainy days and the accumulation of static charge

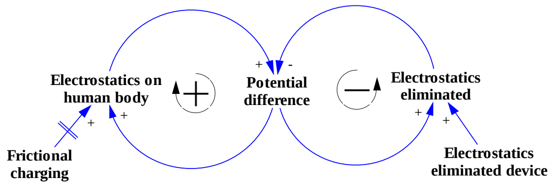


Fig. 17. Feedback Loop for Optimization of the Air-Conditioning

Improvement Analysis for Static Electricity in the Train Carriage

The factors that affect the accumulation of saloon static electricity are integrated into the causal loop diagram for overall static electricity generation and control. Figure 18 shows that when each impact factor is improved, a negative loop is formed, so less static electricity is accumulated. During this period, static electricity measures are added through the Taguchi method to optimize parameters. The cause of static electricity is identified and the electrostatic voltage is maintained at a safe level.

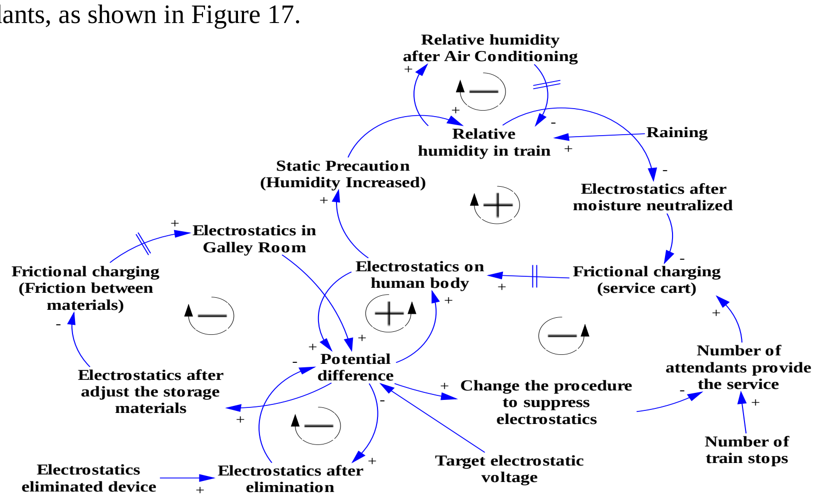


Figure 18. Overall causal loop diagram for the control of static electricity

CONCLUSION

This study uses a Taguchi design of experiment and system thinking to determine the cause of the accumulation of static electricity in a train carriage and the optimal design. The results provide a comprehensive view of the system whereby static electricity is generated in a carriage. The experimental design uses a factor analysis to determine the four important factors that affect the accumulation of static electricity in a train carriage: the temperature setting, the air-conditioning function, the relative humidity and an electrostatic elimination device. A design of experiment using the Taguchi method and an optimization analysis gives the optimal solutions. Using this setting, the static electricity that is accumulated by attendants is limited to 1,000 volts so the risk of electrostatic shock is reduced. Finally, each causal loop diagram shows that static electricity accumulates because a frictional charge is generated when train attendants move the cart in a dry and cold environment during the on-board service, followed by friction between items. When the factors that affect the system are improved, each loop forms a balanced cycle that inhibits the accumulation of static charge.

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應用實驗設計與系統思考安全分析高速列車靜電與控制

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摘 要

人體在乾燥環境中容易因運動或摩擦而受到靜電衝擊。靜電會影響高速列車的列車服務效率和公共安全。本研究發現新購列車產生靜電積聚的原因以及防止靜電積聚的最佳化設計。因果關係圖用於瞭解靜電積累的主要原因。使用田口實驗法和ANOVA 分析來確定影響靜電積累最顯著的因子，並推導出參數的最佳組合。最佳化實驗結果顯示，能將人員身上積聚的靜電維持在 1000(v)以下；改善 37.7%之靜電觸電風險。由於車廂內測量的相對濕度對靜電的積累有顯著影響，因此採用 T-test 來檢定新舊列車間的濕度差異性，發現新購列車車廂較為乾燥。系統思維和因果循環圖分析可幫助列車的改善設計，以降低未來鐵路車輛中由於靜電積累而引起的電擊風險。