

# Third-Rail Insulator Failure Causes and Mitigating Practices: A Comparative Study of Multiple Case Studies in the U.S.

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**Abstract** Rail transit systems are one of the most important and popular types of transit systems used daily in metropolitan areas all around the world. The third rail is one of the providers of traction power in electrified rail systems, but it faces several issues, such as insulator failures. The purpose of this study is to investigate the causes of insulator failures, which have not been comprehensively studied and presented in the literature. To accomplish this objective, eight transit systems with third rails were selected to (1) investigate the characteristics of third-rail systems, (2) determine the causes of insulator failures, (3) analyze the costs associated with insulator failures, and (4) determine mitigating practices to reduce the number and cost of insulator failures. After a thorough literature review, details of eight case studies were collected from different transit agencies, and their subject matter experts were asked to complete a survey and provide input. The results revealed that a build-up of dirt was the major cause of the 17 identified causes of insulator failures; carbon dust and dirt were identified as the most present particles in third-rail systems. It was noted that transit agencies often implement multiple mitigating practices such as cleaning

the insulator, performing visual inspections, and conducting regular maintenance to reduce the number and cost of insulator failures. The findings of this study will help decision-makers for transit systems make timely decisions to prevent third-rail insulator failures and adopt appropriate practices that best fit their transit system.

**Keywords** Third-rail system · Insulator · Failure · Mitigating strategy

## 1 Introduction

Rapid rail is used for transit in urban transportation systems globally. The electric power for this system is supplied by different methods, including a third rail [1]. Insulators are necessary for protecting electric railways, regardless of the source of the power supply [2]; however, they commonly fail and/or malfunction, negatively affecting the transit system's performance [3]. Since many urban transit tracks are adopting third rails as a power supply method, it is important to investigate the causes and consequent adverse impacts of the insulator failures.

Transit systems that implement a third rail often encounter insulator failures that are due to aging, water infiltration, severe weather conditions, mechanical stresses and impacts, contaminant accumulations, etc. [4, 5]. Any of these causes might result in erosion, flashover, deterioration, fire, and/or puncture of the insulators [6, 7]. These phenomena are dangerous to the people in the surrounding community, and precipitate the transit company's loss of operating time, workforce, and money. Thus, it is vital to develop and implement mitigation practices for insulator failures.

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A few researchers have investigated the reasons that insulators fail and have suggested practices to prevent and/or mitigate the failures [3]. Reddy [8] indicated that the most important of these are cleaning, preventive maintenance activities, and regular inspections, all of which are useful for detecting visible deficiencies [2, 9]. Conducting regular tests and developing predictive models for the service life of insulators are alternative methods that can be used to detect which insulators are prone to failure [7, 10, 11]. Verma and Reddy [6] examined the erosion of polymeric insulators by studying the impacts of contaminants and different environmental conditions, and they concluded that the contaminants present in acid rain cause the degradation of the insulators. Chughtai et al. [12] showed that the presence of contaminants on the surface of composite insulators can lead to fractures. Gorur et al. [1] analyzed the relationship between micro-cracks and environmental conditions in non-composite insulators and learned that severe weather conditions substantially affect the performance and reliability of insulators.

Although a few studies have analyzed the causes of failure and mitigating practices for third-rail insulators, their focus has been narrow. The present study aimed to address this gap by (1) investigating current third rail characteristics, (2) identifying the causes of insulator failure, (3) analyzing costs associated with insulator failures, and (4) determining mitigating practices. The findings of this research study will guide transit managers as they examine the current status of the insulators in their transit systems and adopt proper mitigation strategies to prevent/reduce further insulator failures.

## 2 Literature Review

### 2.1 Third-Rail Systems and Insulators

Third rails consist primarily of three types of materials: steel, aluminum, and aluminum/stainless steel (ALSS) [13]. Traditionally, steel has been the material of choice for third rails, and it is still used for many transit systems in the U.S. and elsewhere [4, 14] because of its several decades of service life. The next most often implemented material for third rails is aluminum, which is made of bonded aluminum strips and is used extensively in the U.S. Alternatively, ALSS third rails are composed of an aluminum extrusion and a steel cap [5, 15].

Insulators are important components of high-transmission tracks [5]. The insulators can be made of wood, porcelain, fiberglass, polymer, various composites, etc. [16, 17]. The insulators are important components of the third-rail systems since their failure can cause the whole system to fail [18]. In the following, the identified potential

insulator failure causes and mitigating practices from existing literature are presented and discussed.

### 2.2 Insulator Failure Causes

Table 1 summarizes the causes of insulator failure identified from the existing literature, along with the reference source. The accumulation of particles, pollutants, and contaminants on the insulator surface has been widely mentioned as an important cause of insulator failures [3, 6]. When insulators are covered by contaminants such as dirt, their performance is affected, and the likelihood of their failure increases [13]. For example, contaminants on the surface of insulators can lead to flashover, which halts the supply of electricity and is a dangerous and deadly phenomenon. Salma et al. [19] and Douar et al. [20] demonstrated that dirt build-up plays a critical role in the occurrence of flashovers in insulators. Sima et al. [21] revealed that a difference in the quantity of dirt accumulated above and below the surface of insulators can lead to a flashover.

Mechanical stresses are sources of cracks in insulators that may cause failure [13, 14]. Fournigue et al. [11] studied silicone rubber insulators under stress and revealed that thermal stress results in the insulator materials losing their properties, becoming hard, and failing. Electrical erosion is also a cause of insulators failing [1, 21]. Typically, this issue is a result of arcing that occurs between the third rail surface and the current collectors [7, 22, 23], as the insulator erodes when arcing occurs continuously at a specific location on a third rail [10]. Insulator corrosion is expected to occur inside tunnels, in locations where humidity/water exist [19]. The negative return current that is grounded by the rail is the major contributor to insulator corrosion [24]. Partial discharge, which occurs when insulators are exposed to high electric currents, is also an issue that can affect insulator performance [1, 17].

Aging is another cause of insulator failure in different types of insulators [12, 25]. Schneider et al. [10] simulated the effects of a coastal environment on the performance of insulators and learned that environmental conditions, specifically fog, significantly accelerate porcelain insulator aging [26]. Similarly, Sundararajan et al. [27] investigated the impacts of environmental stresses on polymeric insulators and concluded that aging is a main result of various environmental stresses. Xu et al. [4] analyzed the impacts of sunlight/ultraviolet (UV) rays on insulator function and concluded that sunlight/UV can result in degradation. Nekeb et al. [25] investigated the relation between UV and leakage current in polymeric insulators and concluded that leakage current substantially increases in insulators that are often exposed to UV. Kumosa et al. [3] and Venkatesulu and Thomas [28] indicated that heat, UV, and electrical

**Table 1** List of insulator failure causes and their sources

Failure cause	Reference source
Erosion	Cherney et al. [7], Chakraborty [37]
Aging	Verma and Reddy [6], Schneider et al. [36]
Vandalism	Verma and Reddy [6]
Water infiltration	Gorur et al. [1], Luder et al. [5], Verma and Reddy [6]
Sunlight/UV	Verma and Reddy [6], Ehsani et al. [17], Fourmigue et al. [11], Xu et al. [4], Nekeb et al. [25]
Saltwater	Reddy [8]
Lightning	Sun et al. [14]
Salt fog/air	Schneider et al. [36], Vohra [9]
Snow and ice accumulation	Vohra [9]
Defective product/material	Nyamupangedengu et al. [22]
Corrosion and fitting	Venkatesulu [28], Luder et al. [5]
Damage from impact	Jiang et al. [24], Vohra [30]
System voltage fluctuation	Reddy [8], Vohra [9]
Mechanical stress	Nyamupangedengu et al. [22]
Flashover/arcng	Verma and Reddy [6], Sun et al. [14], Schneider et al. [36], Chakraborty [37], Slama et al. [19], Douar et al. [20]
Cracking/fracture	Luder et al. [5], Vohra [9]
Dirt build-up	Sun et al. [14], Slama et al. [19], Douar et al. [20], Sima et al. [21], Cavallin et al. [23]

stress cause insulators to lose material properties and consequently fail.

### 2.3 Mitigating Practices

Every transit agency adopts its own mitigating practices to lessen the number of insulator failures in its third-rail system [29, 30]. Some of these practices include internal inspections, rail-walking inspections, regular maintenance, cleaning, etc. [16, 22, 31]. Cleaning is one of the most common mitigating practices because it prevents the accumulation of dirt on the insulator's surface [32–34]. Cleaning can be performed both manually and automatically, although, the latter is more accurate, less time-consuming, and safer [35–37]. Cleaning the surfaces, insulators, and other components is extremely useful for avoiding issues in third rails.

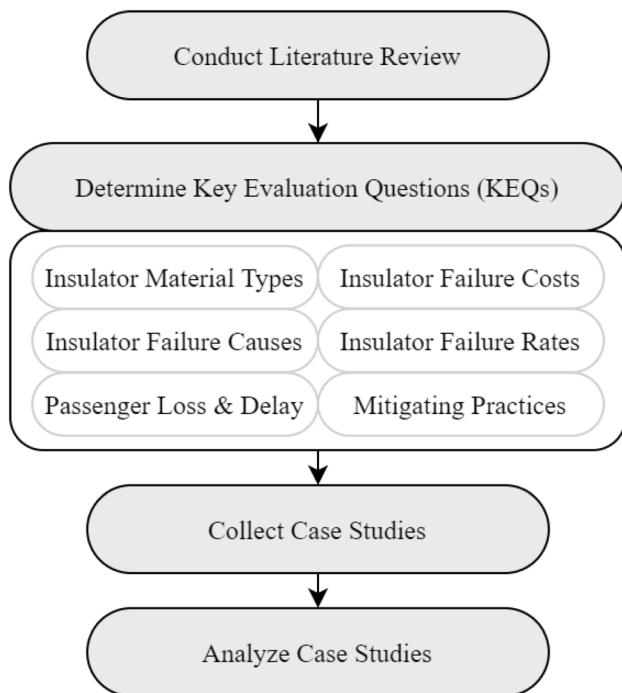
Inspections are needed to determine whether insulator caps are in place by a lug hole, the insulators need to be cleaned, and/or broken or chipped insulators need to be replaced [6, 38]. Implementing predictive models that employ statistical methods and historical data helps identify the insulators that may fail in near future [38]. Cathodic protection is a method that is useful for insulating the third rail components from weather effects such as erosion, corrosion, salt fog, sunlight, water infiltration, and saltwater.

### 2.4 Knowledge Gap

As the causes of third-rail insulator failures and the corresponding mitigating practices have been rarely studied, the focus of this study was to identify the causes of third-rail insulator failures and their corresponding costs, determine third rail characteristics, and develop practices to mitigate their adverse impacts. The results of this study can aid decision-makers of third-rail systems in understanding the status of the insulators in their transit networks and implementing sufficient mitigating practices to reduce the rate of insulator failures.

## 3 Research Methodology

A four-step methodology, shown in Fig. 1, was developed to accomplish the objectives of this study. In the first step, literature relating to the failure causes and mitigating practices of third-rail insulators was collected and studied. In the second step, the key evaluation questions (KEQs) for data collection were determined. In step three, based on the KEQs, the data from selected case studies was collected and categorized by (1) transit system characteristics, (2) features of insulators, (3) insulator failure causes, (4) insulator failure costs, and (5) insulator failure mitigating practices. Subject matter experts (SMEs) from eight active transit agencies with third-rail systems were asked to



**Fig. 1** Research methodology

provide additional information for the data collection. Finally, the data was statistically and descriptively analyzed and compared through synthesis of similarities and differences.

#### 4 Key Evaluation Questions

The literature was comprehensively studied to establish a rationale for comparing third-rail insulator case studies and their status synthesis. The following KEQs were determined:

- Insulator material types
- Insulator failure causes
- Insulator failure costs
- Insulator failure rate
- Passenger loss and delays
- Mitigating practices

Investigating the insulator material type is important, as each material has its own issues, advantages, and disadvantages. There may also be some environmental and financial limitations to implementing insulators made of various types of material in different geographic areas. Identifying the causes of failures, their rate of occurrence, and imposed costs and delays to the transit systems will enable decision-makers to adopt appropriate strategies to reduce the number of insulator failures in their agencies.

#### 5 Case Studies Data Collection

After determining the KEQs, SMEs active in 16 transit agencies in the U.S. were contacted through email and phone calls, and case studies from eight agencies were collected. The case study data was organized into five categories: (1) transit agency information and size, (2) general information about third-rail insulators, (3) cost of insulator failures, (4) causes of insulator failures, and (5) preventive strategies for insulator failures. The data from the eight transit systems collected in this research as case studies are referred to as cases 1–8. They all have third rails of different sizes in their transit networks and are located in different geographical areas in the U.S. An important factor that could be used for the current analysis is the number of insulators per length of the third rail. However, since the number of insulators per rail length was different, the agencies could not provide the exact number of insulators per length of their third-rail systems. Table 2 summarizes the general information of the collected case studies, and a brief description of each case study is presented below.

*CASE 1.* The first case study belongs to one of the oldest public transit systems in the United States and provides subway, bus, commuter rail, ferry, and paratransit service. Even though all five types of the major terrestrial mass transit vehicles are operated by the system, approximately 40% of the 50,000,000 passengers who use it annually are transported by the third-rail system. The voltage of the third rail in this system is 600–750 V, and all of the 140,000 insulators are made of epoxy. An average of 15 insulator failures are reported every year, both inside and outside the tunnels. These failures, which equate to an annual insulator failure rate of 0.00002, cause a loss of less than 1000 passenger hours per year.

*CASE 2.* This transit system is heavy rail that uses a nominal traction power voltage of 600–750 V. Approximately 50,000,000 passengers are transported within this system every year, which requires 134,000 insulators (106,000 made of porcelain and 28,000 made of fiberglass). The annual rate of insulator failure in this system is 0.0001.

*CASE 3.* The third case study is of a transit system that provides bus, heavy rail, and demand-responsive transportation services. The nominal traction power voltage of the third rails of this transit system is 600–750 V, and the number of passengers transported annually is approximately 100,000,000. A total of 176,000 insulators are implemented in and out of tunnels. The 17,000 utilized in the tunnels are made of porcelain, and of the 159,000 used out of the tunnels, 59,000 are porcelain, 60,000 are fiberglass, and 40,000 are wooden. The rate

**Table 2** Comparison of characteristics of case studies

Case study	Voltage (V)	Number of insulators	Insulator material	Annual insulator failure rate	Transit modes
Case 1	600–750	140,000	Epoxy	0.00002	Subway, commuter rail
Case 2	600–750	134,000	Fiberglass and porcelain	0.0001	Heavy rail
Case 3	750–1000	176,000	Porcelain fiberglass, and wood	0.000066	Heavy rail
Case 4	600–750	72,000	Fiberglass and porcelain	0.0002	Commuter rail, light rail
Case 5	750–1000	19,100	Porcelain, fiberglass, and epoxy	0.001	Heavy rail
Case 6	750–1000	100,000	Fiberglass and porcelain	0.00005	Heavy rail, and light rail
Case 7	600–750	75,000	Fiberglass	0.00004	Heavy rail
Case 8	600–750	50,000	Porcelain fiberglass, and wood	0.0001	Heavy rail

of insulator failure per year is 0.000066 at this transit agency.

**CASE 4.** This case study system operates bus, rapid transit, commuter rail, light rail, and electric trolleybus services. The nominal traction power voltage of the third-rail system is 600–750 V, and the passenger load is 100,000,000 per year. Over 72,000 insulators are used in this system, of which 45,000 are out of tunnels and 27,000 are installed inside tunnels. Most of the insulators are made of fiberglass (62,000), and the remaining 10,000 are made of porcelain. The annual failure rate of the insulators is 0.0002.

**CASE 5.** This transit system that implements both heavy and light rail transports 50,000,000 passengers per year. The nominal traction power system voltage of the third-rail system is 750–1000 V. It uses 19,100 insulators: 17,500 fiberglass, 1500 porcelain, and 100 epoxy. While all the porcelain insulators are installed out of tunnels, two-thirds of the epoxy insulators (1000) and 43% of fiberglass insulators (7500) are installed in the tunnels. The annual rate of insulator failure in this transit system is 0.001.

**CASE 6.** The transit system of case 6 is composed of both heavy and light rail and moves 100,000,000 passengers per year. The nominal traction power system voltage of the third-rail system is 750–1000 V, and it uses more than 100,000 porcelain or fiberglass insulators. The rate of insulator failure per year is 0.00005.

**CASE 7.** The case 7 system operates heavy rail and moves 100,000,000 passengers per year. The nominal traction power system voltage is 600–750 V, and it uses 75,000 fiberglass insulators. The rate of insulator failure is 0.00004 annually.

**CASE 8.** The transit system of this case study includes heavy rail and buses and moves 75,000,000 passengers annually. The nominal traction power system voltage of the third-rail system is 600–750 V, and it uses 50,000 insulators made of fiberglass, wood, and porcelain. The annual rate of insulator failure in this system is 0.0001.

## 6 Results and Discussion

The results of the case study analyses are presented, discussed, and visualized below.

### 6.1 Size of the Transit System

The SMEs were asked to provide the number of passengers who use their third-rail transit system annually. For this study, the size of the transit system was measured by the number of people who use it annually. It is important to know the size of the transit system because it is indicative of the number of passengers that will be affected by consequent delays if an insulator fails and leads to a system shut-down.

The transit systems of cases 3, 4, 6, and 7 serve the most passengers annually (100,000,000 each); thus, these transit systems are more vulnerable to loss of revenue and passenger trust. Approximately 50% of the transit systems moved 100,000,000 passengers per year; the least number of passengers transported annually among all of the cases is 50,000,000. In general, all of the case studies can be considered as large transit systems that transport 135,000–400,000 passengers per day. Thus, any issue that

stops the system from functioning, including third-rail insulator failures, is a major concern for managers.

## 6.2 Rate of Insulator Failures

When the failure rate of insulators is high, new materials and/or installment methods can be implemented to reduce them. The average annual number of insulator failures of each transit system was investigated during this study, and Fig. 2 shows the distribution of the average rate of insulator failures occurring across all of the case studies. As shown, 37.5% of the transit systems have less than five insulator failures per year, and an average of ten insulator failures occur annually in all of the transit system case studies.

The failure rate measures the reliability of the insulators used in each transit system and can be calculated according to the number of installed insulators and the average annual number of insulator failures. The annual rate of insulator failure for each transit system is shown in Table 2 and was discussed earlier. The case 5 system experiences the highest insulator failure rate (0.001), which shows that the decision-makers for this transit system need to investigate the reasons why this is occurring and adopt appropriate mitigating practices. On the other hand, case 1 has the lowest rate of insulator failure per year (0.00002).

## 6.3 Insulators with Fire Incidents

Fire incidents that occur in insulators are one of the important issues of third rails. The SMEs were asked to determine the type(s) of insulators that have experienced a number of fire incidents in their transit systems, and six insulator types were identified as ones that have caused

major fires: pin, post, suspension, strain, shackle, and bushing. According to the responses, summarized in Fig. 3, fire incidents were less likely to occur in post and strain insulators, both of which had a 9.1% rate of occurrence. The rest of the insulators each had a fire incident rate of 18.2%. Being aware of the insulators more prone to fires helps practitioners prevent or at least lessen the number of fire incidents in their transit systems.

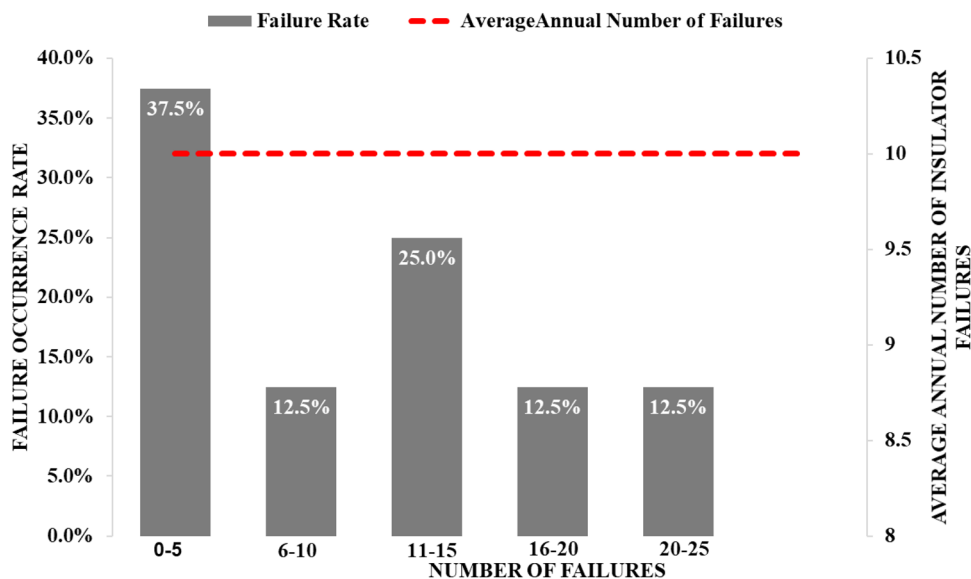
## 6.4 Clearance Distances around Insulators

A clearance space is required in the space above and around each installed insulator off third-rail systems to provide good access. Each transit agency determines its own clearance space requirement due to several different criteria and limitations, such as safety considerations. If sufficient clearance space is not provided, access is limited, and cleaning the insulators is either prevented or marginalized. Figure 4 shows a comparison of the clearance space provided around insulators by the studied transit agencies. The highest implemented clearance space is 20 inches, while an average of 11.25 inches of clearance space is implemented by the third-rail systems.

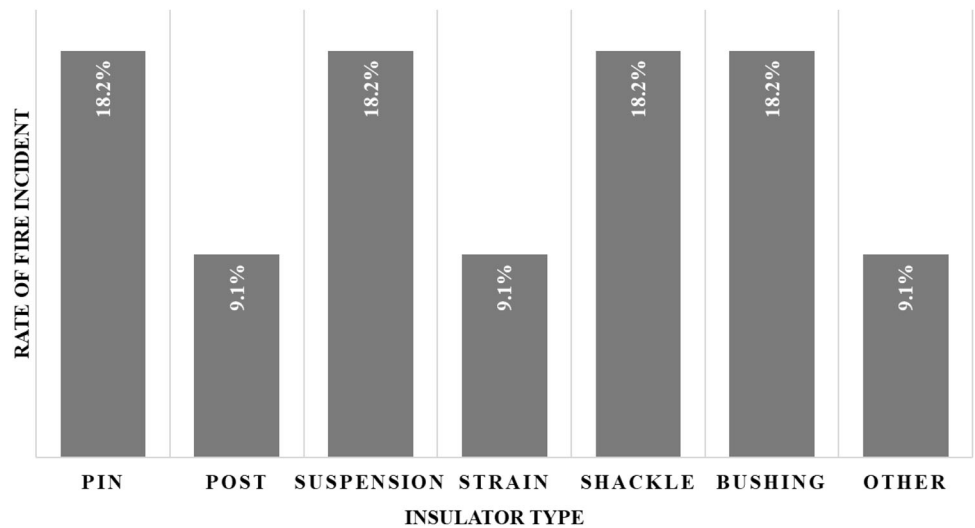
## 6.5 Delays Due to Insulator Failures

Insulator failures cause transit systems to shut down for a while for repair and replacement. These types of delays cause passengers to lose confidence in the transit system and might result in their exploring other means of transportation. The SMEs were asked to provide information about the number and duration of delays that their transit system experiences annually due to insulator failures. Five of the case study agencies reported less than 10 h of delays

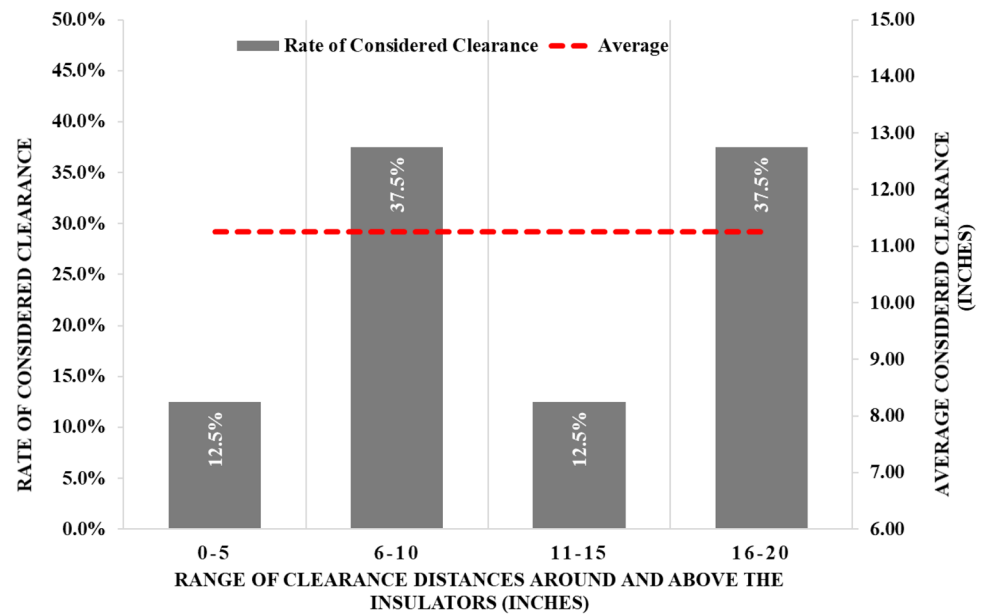
**Fig. 2** Rate of insulator failures per year in case studies



**Fig. 3** Rate of fire incident occurrences in various insulators



**Fig. 4** Range of clearance spaces around insulators



annually, while the maximum estimated accumulative annual delay was approximately 40 h. Each of the other three transit systems reported an average accumulation of 15, 25, and 35 h of delays per year.

**6.6 Passenger Loss Due to Insulator Failures**

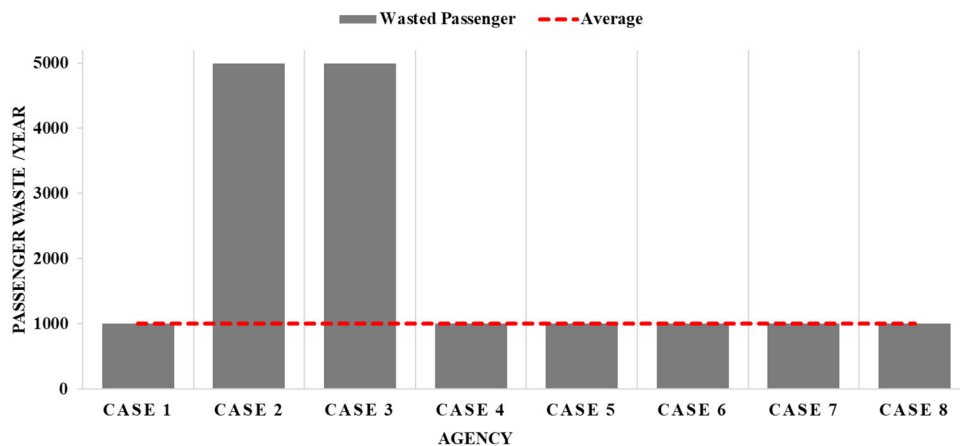
Due to insulator failures and the corresponding shut-down of the system for a while, some of the passengers switch to another transit system, which means a loss of passengers. The SMEs were asked to determine the range of annual passenger loss due to insulator failures, and their estimated ranges are summarized for each agency in Fig. 5. As demonstrated, cases 2 and 3 experience the biggest losses, with 1000–5000 passengers who switch to another system.

The rest of the agencies declared a loss of less than 1000 passengers annually. It can be concluded that an average of 1000 passengers are lost by each transit system annually because of delays attributed to insulator failures.

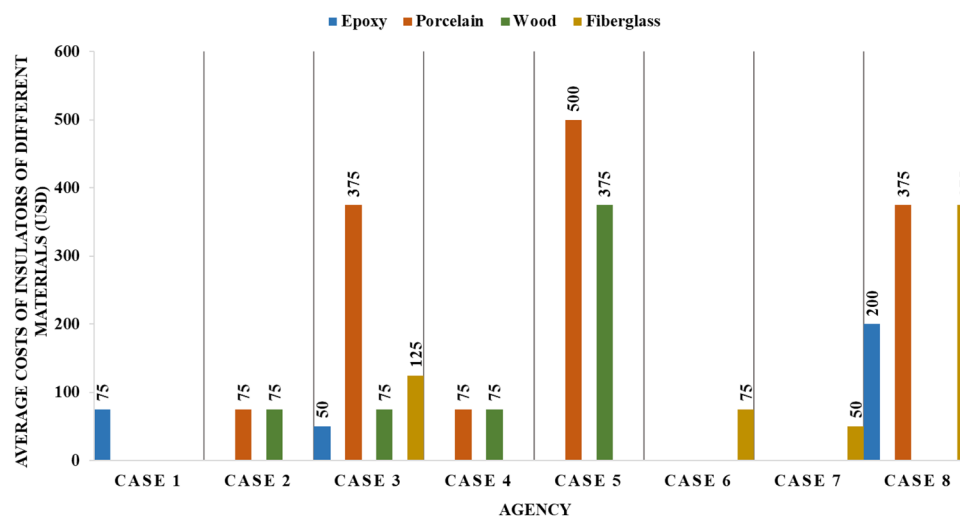
**6.7 Costs of Insulators**

The cost of insulators varies with the type of material and according to the regular inspection intervals in each agency. The insulator materials for which the SMEs provided the corresponding costs included epoxy, porcelain, wood, and fiberglass, as shown in Fig. 6. Porcelain insulators are, on average, the most expensive insulators with an average declared cost of \$256 and maximum cost of \$500. Epoxy insulators, at \$108, seem to be the least

**Fig. 5** Range of annual lost passengers for each case study



**Fig. 6** Average costs of insulators made of different materials



expensive; however, that may be somewhat misleading because their use often results in leakage currents and flashovers. The SMEs indicated that an average of \$15,000–\$20,000 is imposed annually on the case study transit agencies due to leakage currents. It must be added that the costs include the average cost of an insulator and the cost of regular inspection of the entire transit system due to the failure of the insulators.

### 6.8 Operational Costs Per Insulator Failure

In addition to the cost of replacing a failed insulator, the transit company also realizes an increase in its operating costs, which vary for different third-rail systems. The SMEs determined the range of costs attributed to operational activities that are depicted in Fig. 7. As is shown, the highest operational cost (\$400–\$500) belongs to case 6, and the lowest belongs to case 5 (\$400–\$500). The average operational cost per insulator (excluding the cost of the insulator itself) among all of the case studies was estimated

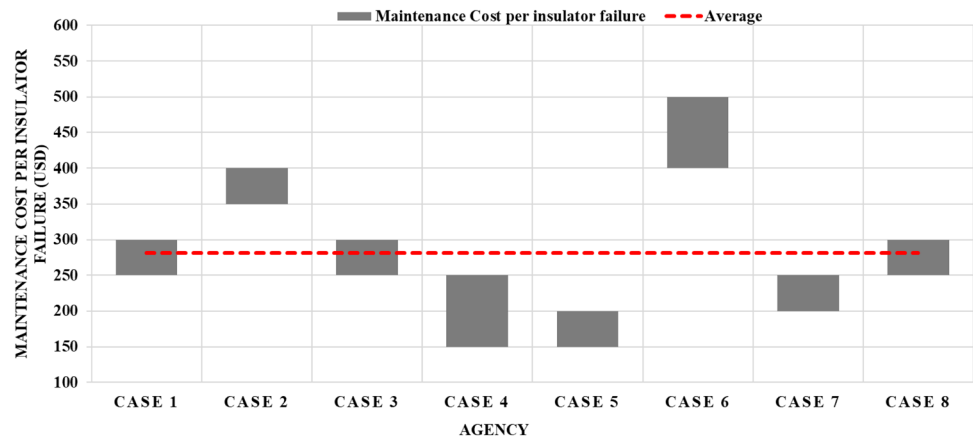
as \$281.25, as shown in Fig. 7. According to the experts, the average cost of replacing an insulator of any type and material is much less than \$281.25; therefore, it can be concluded that it is more economical to replace the insulators that are likely to fail before failure occurs. The development of a failure prediction model and/or conducting regular inspections and maintenance practices can help transit agencies reduce their operating costs that have been impacted by insulator failures.

### 6.9 Insulator Failure Causes

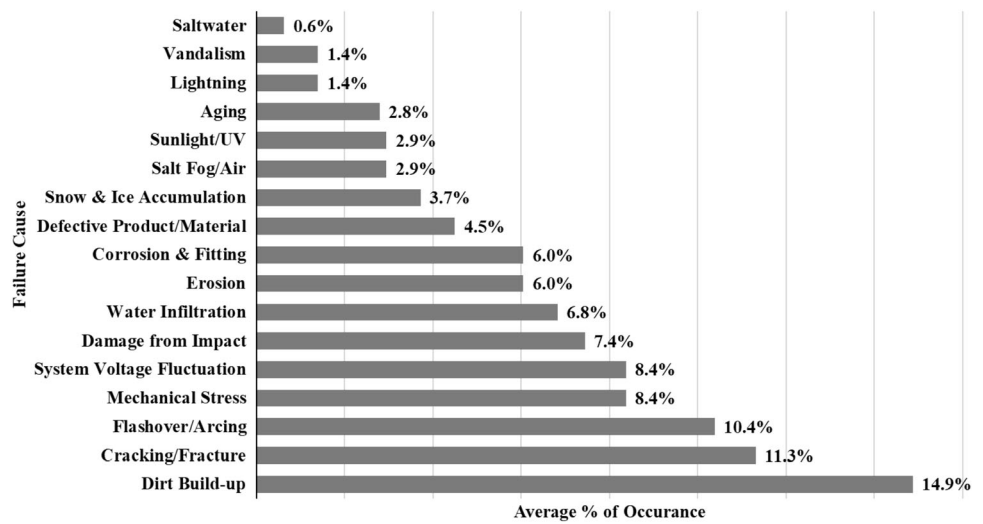
As shown in Table 1 in the literature section, the existing literature identifies 17 causes of insulator failure. Figure 8 shows that dirt build-up, cracks/fractures, and flashovers/ arcing are the top three most frequent causes of failure, with rates of 14.9%, 11.3%, and 10.4%, respectively. The least frequent causes are saltwater penetration, vandalism, and lightning, with rates of occurrence of 0.6%, 1.4%, and 1.4%, respectively.



**Fig. 7** Range of operational costs per insulator per case study



**Fig. 8** Average frequency of insulator failure causes in the transit agencies studied



**6.10 Failure Rates of Renewed Track Systems**

One of the strategies that can be employed to reduce the number of failures in a transit system is to improve the system by replacing the aged track sections with new segments. The rate of failure of newer/replaced track systems was investigated, and the average annual number of failures of renewed segments in every agency was compared with the average annual number of failures of track segments that had not been replaced. Figure 9 shows that the rate of failure in renewed segments decreased, but in case 7, the same number of failures was observed for the renewed and not-renewed segments. In case 6, where the largest failure rate reduction occurred, a 400% reduction in the number of failures was observed. Therefore, it can be concluded that regular replacement of aged track systems helps transit agencies significantly reduce their rates of failures.

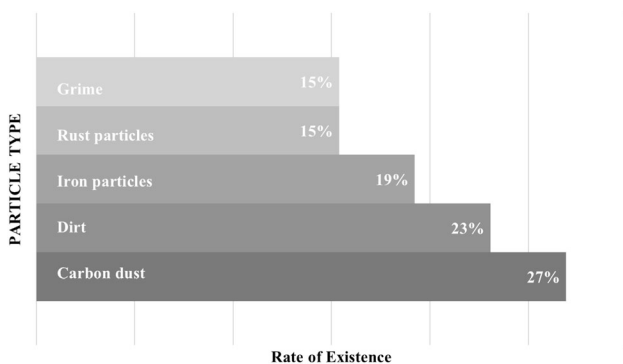
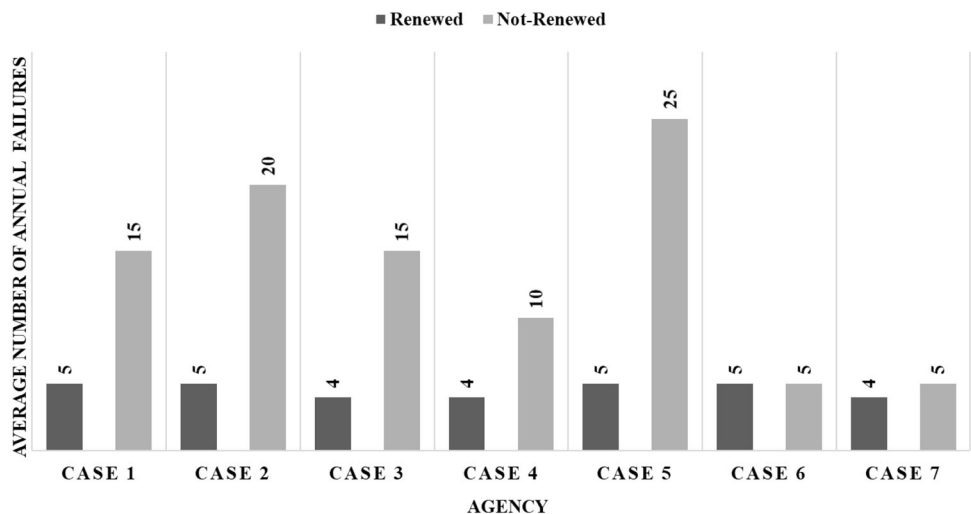
**6.11 Particle Types Leading to Insulator Failures**

Dirt build-up was the most frequently cited cause of insulator failure in the case studies; therefore, identifying the particles that lead to failure can help transit managers prevent the build-up by implementing appropriate strategies. As shown in Fig. 10, five particle types leading to insulator failures were identified, with carbon dust (27%) and dirt (23%) found the most often in third-rail systems. Grime and rust particles were the least observed particles, averaging 15% each.

**6.12 Occurrence of Safety Failure Events**

Some failure events, called safety failure events, cause safety issues. Smoke events caused by arcing, damaged electrical equipment, poor track conditions, fires due to short circuits, and explosions were named by the SMEs as safety failure events that have occurred in their transit

**Fig. 9** Comparison of average number of annual failures of newer/replaced track systems with not-renewed track systems



**Fig. 10** Rate of particle types leading to insulator failures

systems. They reported that smoke events due to arcing are the most frequently occurring (30%), while damaged electrical equipment is the least frequently occurring safety failure event (10%). The rest of the safety failure events occurred equally, with an average of 20% frequency of occurrence for each event.

**6.13 Methods Employed to Predict/Diagnose Flaws in Insulators**

Failure predictive/diagnostic methods for insulators were studied for each of the represented transit systems. Seven methods were used by all of the case-study agencies, among which visual inspection was the most frequently adopted (38.4%). As shown in Fig. 11, the second most frequently adopted method was mechanical inspection, with an implementation rate of 23.08%, while the rest of the methods were implemented at the rate of 7.69% each. The main reason that the visual inspection is the most frequently used method is that it is the least costly and the easiest to implement. It is not able to help with the diagnosis of every type of flaw in insulators, however, so

several technologies and tests, such as thermal imaging and heat testing, can be implemented to achieve more reliable results (see Fig. 11). It is highly recommended that new methods be implemented by the transit agency decision-makers.

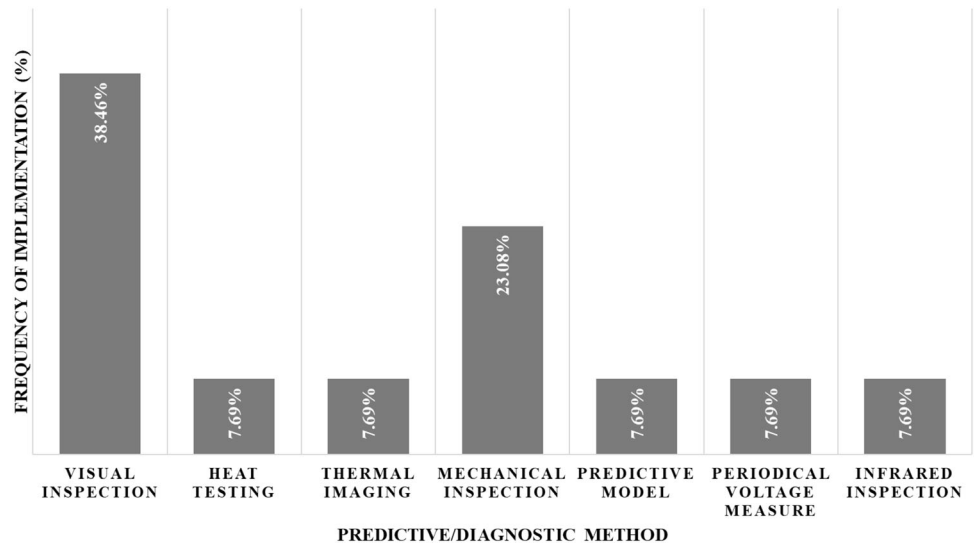
**6.14 Frequency of Cleaning Tunnel Walkways and Insulators**

Cleaning the tunnel walkways and insulators is a preventive practice that prevents dirt from building up on insulators and possibly causing failures. The SMEs were asked to how often the tunnel walkways and insulators of the third rails were cleaned at their transit agencies, and while all except case 1 and case 7 responded that they clean them, the frequency varied from once every month (case 5) to once every 24 months (cases 3 and 6). The average time interval between the cleanings was 13 months (see Fig. 12).

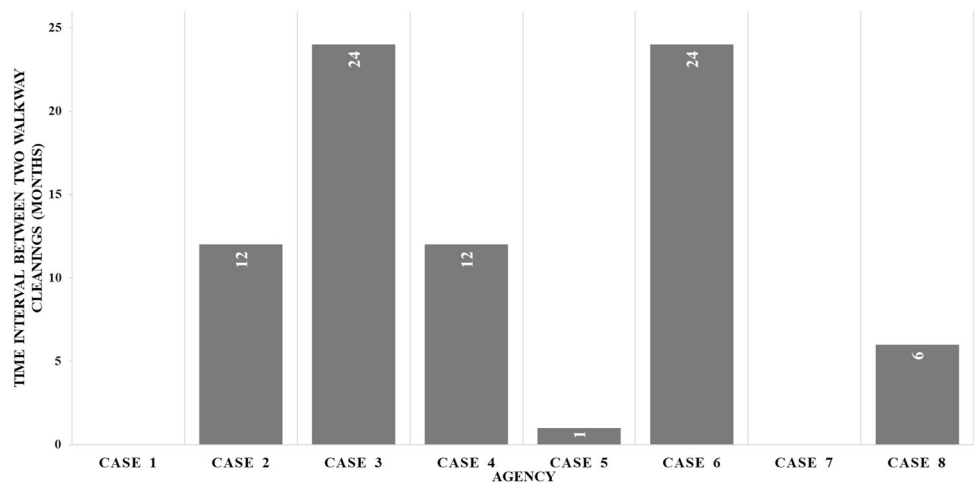
**6.15 Frequency of Conducting Safety Compliance Inspections and Investigations**

The SMEs were also asked to specify how frequently they conduct safety compliance inspections. Case 2 reported that they never conduct safety compliance inspections, and the SMEs of case 3 and case 6 reported that they perform safety compliance inspections every 6 months, which is the shortest interval reported. Case 1 indicated that it takes them 24 months to conduct a safety compliance inspection which is the longest interval reported. The remaining transit systems reported that they perform the safety compliance inspection every year; however, case 4 does not conduct the compliance on a regular basis. Figure 13 shows the time intervals between safety compliance inspections for the studied transit agencies.

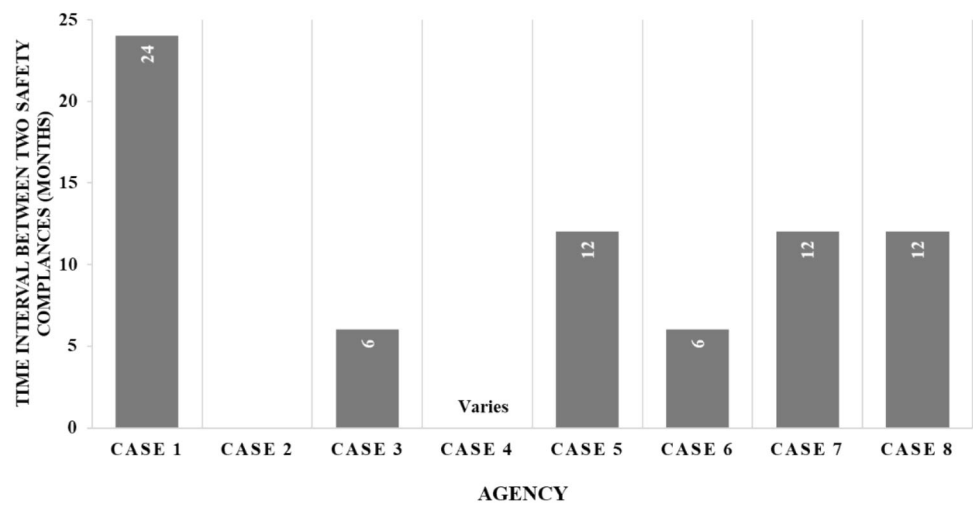
**Fig. 11** Frequency of implementation of predictive/diagnostic methods



**Fig. 12** Time interval between two cleaning practices



**Fig. 13** Time intervals between two safety compliance inspections



## 7 Conclusions

The objective of the study was to collect and analyze data on transit system characteristics, features of insulators, insulator failure causes, insulator failure costs, and insulator failure mitigating practices. Eight third-rail transit systems were investigated, synthesized, and compared in this study, with a focus on the causes of insulator failures. The relative literature was comprehensively studied, and key evaluation questions and the 17 most significant failure causes were identified.

The results showed that the studied transit agencies experience an average of ten insulator failures annually, and approximately 1000 passengers change transit systems because of delays caused by these agencies. The average operational cost of each insulator, excluding the cost of the insulator itself, is approximately \$281.25. Dirt build-up is the biggest cause of insulator failures among all the case studies with an occurrence rate of 14.9%, and saltwater penetration is the smallest, with an occurrence rate of 0.6%. Carbon dust (27%) and dirt (23%) are the most present particles on all of the third-rail systems studied. The average time interval between cleaning practices was reported as 13 months. Fire incidents are less likely to occur in post and strain insulators (9.1% in both post insulators and strain insulators).

Furthermore, the results of this study revealed that some transit agencies (e.g. case 1) have a minimal failure rate, despite having the oldest system, using the cheapest insulator, being more prone to leakage current and flashover, and not performing any cleaning practice for the insulators. This shows that not only implementing appropriate policies before insulator failures contributes to minimizing the rate of insulator failures, but there are other aspects that may help in reducing the rate of insulator failures in third-rail systems. Among such aspects, the geographical condition of the area and the mechanical stress imposed on the insulators due to environmental impacts could be very prominent factors to consider. The findings of this research study will help transit managers examine the current status of the insulators in their third-rail systems and adopt proper mitigation strategies to prevent/reduce failures.

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