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Effect of The Staggering of a Contact Wire on Wear Behaviour in Malaysian Railway Traction Power Supply

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Traction power supply, staggering, contact wire

Abstract

With Malaysia's rapid railway development, resolving the issue of train safety assurance during operation is critical. In advanced railway systems, electricity is transmitted to trains via the sliding contact of the pantograph and overhead catenary system, which leads the transmission wire in the pantograph and catenary system to deteriorate continuously. Monitoring of contact wire wear is essential for ensuring the safety and efficient operation of electric trains in terms of precision and service efficiency. This research has been developed to detect and monitor contact and stagger wire wear. The bottom of a contact wire can be captured using image processing technology using a line sensor camera. The measurement is carried out using the binocular ranging principle by evaluating the local wear conditions captured by two cameras in order to ascertain the complete wear data of the contact wire and the stagger value. The method has been used between chainage M403.680 and M390.1476 Upline, and the inspection data shows that 94.12 % of contact wire wear in the SPK-Serdang section of KVDT Line is distributed in the interval (0 mm - 0.3 mm). The highest wear distribution of the whole line is around 0.3 mm.

1. Introduction

Malaysia is a developing nation, and one of the key sectors that supports the nation's economic development is the building industry. Meanwhile, the railway construction projects were the highest contributors among other infrastructure projects. The history of the Malaysian train system began in the 1860s. The first line was attempted between Johor Bahru to Gunung Pulai with a distance of 20 miles where the track was made of timber. The line was said to have been operated in 1869 and disused in 1889. More railway tracks were expanded in the Peninsular, such as the completion of several connections, including Padang Besar and Perlis, to Singapore in 1913. In 1948, the British put into effect the Malayan Railway Ordinance, which streamlined rail administration, as England began to rebuild its rail system following World War 2 [1]. The Federated Malay States Railways became the Malayan Railway Administration (MRA), also known simply as the Malayan Railway (MR), which later in 1962 was known as Keretapi Tanah Melayu Berhad (KTMB). KTMB was corporatized in 1992 but remains wholly owned by the Malaysian Government [2].

In August 1995, the first Malaysian electric passenger train was introduced by KTMB the first commuter to connect Kuala Lumpur to Rawang and Kuala Lumpur to Seremban which increased the effectiveness of commuting [3]. The infrastructure and systems in Klang Valley Double Track (KVDT) were designed to sustain a designed speed of 120km/h, and such characteristics have been adequate in maintaining the requirements of the commuter service and mixed traffic scenario of KTMB's operation at that time. KTMB operates the leading inter-city lines service in Peninsular Malaysia and the Klang Valley Commuter service serving passenger and cargo transportation services. The associated rail assets are owned by the Railway Asset Corporation (RAC) which is a federal statutory body under the Ministry of Transport Malaysia (MOT) [4]. Fig. 1 shows one of the Electric Multiple Units (EMU) used in the Klang Valley Double Track line. In current times, electrification systems for passenger trains are widespread within Malaysia. The number of passengers has increased yearly since 2012 as shown in Table 1.

Fig. 1 *A KTM commuter electric train*

Table 1 *Number of passengers, freight traffic and containers handled by Malaysian Railway Limited*

Year	Rail Services			KTM Commuter	Electric Train Service
	Passenger No ('000)	Freight Tonnes ('000)	Container Teus	Passenger No ('000)	Passenger No ('000)
2012	3,056	6,096	331,871	34,847	1,180
2013	2,703	6,622	343,395	43,942	1,563
2014	2,223	7,136	318,033	46,957	1,692
2015	2,015	6,205	283,063	49,690	2,060
2016	2,791	5,991	331,901	41,469	3,565
2017	3,092	5,617	331,059	37,274	4,148
2018	3,527	5,944	351,222	32,078	3,933
2019	3,746	5,973	243,486	30,404	3,902
2020	1,041	4,551	198,857	11,796	1,647
2021	304	4,793	224,444	5,899	633

According to RAC [6] describe the difficulties in securing funding for new electrification projects. Therefore, most of the work done on electrification systems involves upgrading and maintaining existing overhead lines, rather than installing new ones. New electrification systems are generally only constructed for new railway lines, such as the Gemas – Johor Bahru Double Track Project and East Coast Rail Line Project. Recent focus has been placed on the electrification of the railways. Just over a quarter of the world's railways (344,000 km out of 1.3 million km) are electrified, but this number is expected to grow by about 50 % by 2050 [7]. It is crucial to have a railway system that can handle the future increase of both passenger and freight traffic in order to construct the strong national infrastructure necessary for a successful, competitive, and sustainable economy. Due to the fact that electric trains are lighter, cleaner, more affordable, quieter, and faster to accelerate, electrification is recommended for major railway lines. They make it possible to run more trains faster and more effectively. In electrified railway systems, the overhead catenary system, sometimes referred to as the overhead contact line, is constructed along the track and is in charge of supplying electricity to the trains via pantographs placed on the roofs of the carriages. As depicted in Fig. 2, the sliding contact between the catenary and the pantograph continually transfers the electrical current from the overhead system to the locomotive. The interaction performance between the pantograph and catenary directly impacts the quality of the current collection.

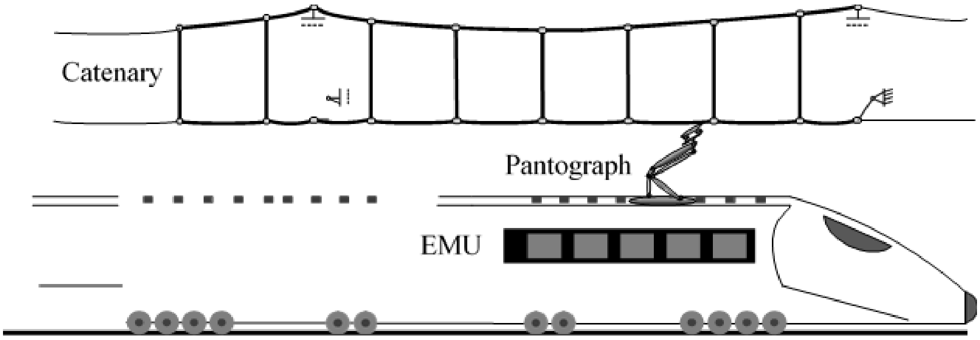


Fig. 2 *An illustration of a pantograph-catenary system*

Zhang and Zhang [8] identified that the overhead catenary system has the lowest reliability of the railway electrification system as compared to other subsystems, such as the Traction Power System (TPS) and the Supervisory Control and Data Acquisition (SCADA) system. Consequently, it is the highest contributor to system faults. Furthermore, Efanov et al. [8] indicate that the failure of the overhead catenary system equipment results in severe disruptions and negatively affects customer service. With the trend in modern railway systems towards low maintenance energy-efficient electric trains, lightweight high-voltage overhead line equipment has become widespread. More recently, the application of computer modelling to the design of the overhead catenary system and the pantograph, considering the vehicle's stability and the aerodynamic effects, has played a crucial role in developing efficient systems [9]. A typical design for an Overhead Catenary System (OCS) is depicted in Fig. 3. On either side of the tracks, individual masts exist in this configuration. This is the preferred design for both mainlines in the Klang Valley Double Track (KVDT) Line.

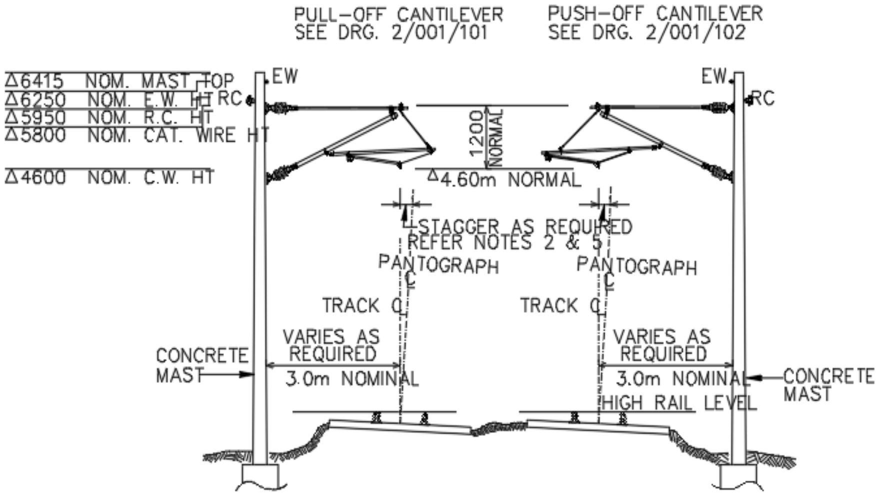


Fig. 3 *OCS arrangement at the tangent track*

The height and stagger of the contact wire are important indicators to measure whether the catenary is working properly [10]. The support structure gives the wires a staggered alignment to avoid centralized contact abrasion of the current collector strip on the pantograph [11]. The transportation capability suffers significantly if a contact wire fails or is not properly operated. Furthermore, ensuring the overhead catenary system's reliability and structural safety is critical as traffic and load demands increase. As shown in Fig. 4, the contact wire is arranged in a z-shape in the horizontal plane, referred to as the staggering of the contact wire in the electrified railway industry.

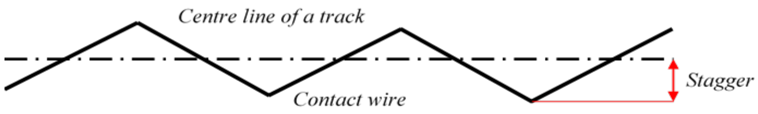


Fig. 4 *The vertical view of staggering*

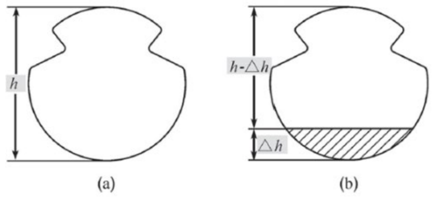


Fig. 5 *Cross section of the contact wire that slides over the pantograph*

The pantograph on the train's roof collects current from the catenary as the train passes through using a sliding contact strip and contact wire [12]. During the process, the pantograph strikes the overhead catenary system, causing the contact wire to vibrate and the pantograph-catenary contact force to change. This work surface is used to measure the surface profile before and after the installation, as shown in Fig. 5 [13]. This brings problems in maintaining the current collection's quality and the train operation's stability. Among all causes of disruption, the defected overhead catenary system usually requires the maximum average duration to recover, because of the difficulty of maintenance operation at meters above the ground. Aiming to reduce disruptions caused by defective OCS and cost saving, there should be more attention on the health condition monitoring of overhead lines [14]. As a result, contact wire failures must be recognized and avoided. For risk management and cost reduction reasons, a new equipment management approach is needed where the factors causing local wear are analyzed based on measurement data of the contact wires to prevent local wear.

This research aims to determine if stagger (the horizontal displacement of the contact wire) affects wear behaviour and to identify the mechanism of fatigue that causes damage. It also seeks to find effective ways to minimize this wear. To achieve this, existing Overhead Catenary System (OCS) contact wires were analyzed to understand the impact of stagger on reducing wear. This study focuses on the impact of staggering the contact wire on wear in the KVDT section, specifically between chainage M403.680 to M390.1476 on the upline. The design of the contact wire is based on literature, including the pantograph design by KTMB. The Department of Electrification System owns the electrification but does not maintain the vehicles, so the measured data mainly reflects wear on the OCS infrastructure, not the pantograph's contact strip. Therefore, the OCS Eye Catenary Inspection Machine data will only show wear on a specific track section, limiting the study's scope.

The selected track segment has minimal curvature, voltage fluctuations, or inconsistent traffic, which might affect the results. The study will not account for wear caused by vehicle speed, acceleration, deceleration, or current and contact force fluctuations. These elements, particularly the contribution of electricity to wear, mainly affect the pantograph contact strips. Understanding the impact of stagger on contact wire wear is crucial for the safety and reliability of electrified trains. The contact wire is essential; if it fails, it can stop the train, leading to major incidents [12]. To develop a predictive maintenance regime, estimating the contact wire’s lifespan is important by considering the OCS wear rate [15].

2. Materials and Methods

The KVDT is 300 km long and first went into operation in 1995. The Klang-Seremban and Tanjung Malim-Seremban stations are the event's starting and finishing points. The line's 300 km were electrified with a single phase 25 kV 50 Hz and had a top speed limit of 160 km/h.

2.1 A 25 kV 50 Hz Traction Power Supply of the KVDT Line

Electric traction delivers people and goods safely by using electrified traction lines. To guarantee the continuous, dependable, and secure functioning of electric traction vehicles, the Traction Power Supply (TPS) was created. The TPS includes all fixed installations for electric traction vehicles from a technical aspect. As part of the TPS system in KTMB, 25 kV 50 Hz transmission lines generate traction power, and the feeder station and OCS distribute traction power. Power delivery to consumers via contact lines separates electric traction systems from the public grid. Contact line systems include OCS installations. To meet the standards for dependable operation of electric traction, the following criteria are applicable, particularly for contact lines:

a) The constant flow of traction power to traction vehicle pantographs.
b) The ability of the train network to continuously gather regenerated braking energy.
c) The voltages accessible at the pantographs of electric traction vehicles adhere to the established quality criteria. Along with these specifications, it is also necessary to consider that the electrical loads on traction systems differ from those on the public electricity supply grid. This is because the electrical loads on traction systems fluctuate over time and are employed in different places.

2.2 Overhead Catenary System Designs and TPS Arrangements

The transportation method requires the consumption of electricity to operate. Research typically uses the term "electrical energy" when discussing electricity-related topics. Using resilient overhead wires [20] and somewhat rigid conductor rails to eliminate electrical concerns is common practice. The catenary systems' designs are modified to be compatible with the running speeds of the vehicles they supply. Different terms have developed over time because of the extensive period of time during which contact line designs have developed in response to an extensive range of requirements. Because of this, it is necessary to use the most significant phrases defined in EN 50119 [16] and EN 50122-1. The TPS system comprises the Feeder Station (FS), the OCS and the Power Supervisory Control and Data Acquisition System (PSCADA). The incoming power supply will be taken at convenient points along the track route from the Tenaga Nasional Berhad (TNB) grid network at 132 kV. The demarcation interface with TNB will be the incoming side insulators on the mast at the FS. Fig. 6 shows one of the Feeder stations used on the KVDT line.

The FS will step down from 132 kV to 27.5 kV for distribution to the OCS. The 27.5 kV is the nominal voltage at the low voltage side of the transformer, considering the voltage drop of the transformer and the power supply line, to ensure that the catenary voltage reaches 25 kV, the voltage at the transformer's low voltage side needs to be increased by 10 %. The FS will provide sufficient flexibility and redundancy for the continuity of TPS and the necessary relay protection for fault clearance in case of OCS malfunction. According to what was said, contact lines are a network of electrical wires used to power automobiles in conjunction with a sliding current collector. Insulators are included in the contact line system and are thought of as a part of the electrical system that comes into touch with high voltages. When they are part of an OCS, insulators are an electrical component that comes into contact with high voltages. Fig. 7 shows the wiring and conductors of the catenary systems, which include catenary wire, contact wire, and return conductor. Electrical power has a greater impact when it is delivered to electric traction vehicles via the contact line. The OCS is based on proven components already used within the electrified lines of KTMB following the basic requirements of 160 km/h maximum design speed and 600 A current carrying capacity. OCS consists of a contact wire, messenger wire, dropper and tensioning device [17]. Other components can vary depending upon the OCS design. However, fundamental parts of the system can be listed as seen in Fig. 7.

The simple catenary suspension consists of a contact wire, messenger wire and dropper. It has the advantages of slight sag, uniform elasticity, good stability, simple structure and easiness of construction [18]. According to experiences from practical operation, simple catenary suspension could perform well on railways with 120 km/h speed and above. The OCS for the main line, which will be a simple catenary system shall be capable of a maximum operation speed of 160 km/h [17].

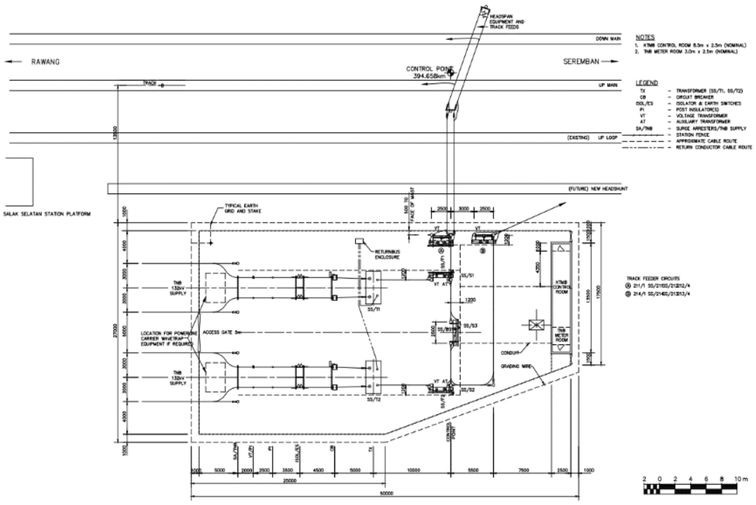


Fig. 6 *Typical layout of feeder station (Salak South)*

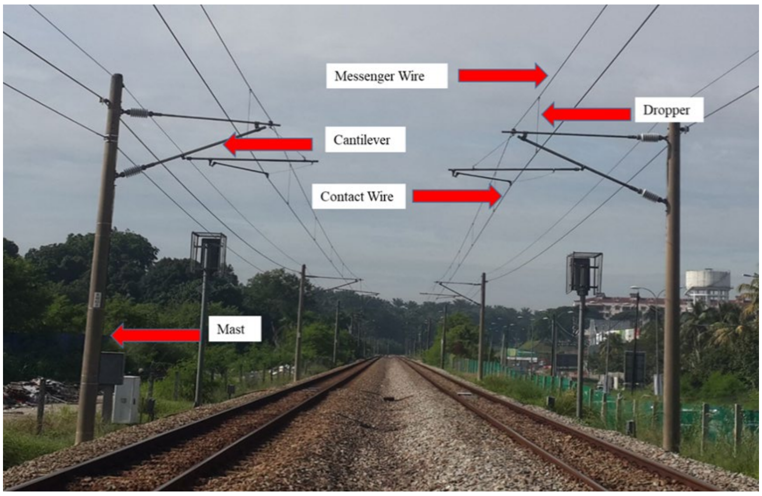


Fig. 7 *Overview of OCS in KVDT line*

2.2.1 OCS Characteristics

High speeds, especially those beyond 100 km/h, make it more difficult to transmit energy, which is a difficult task. This has led to the continued development of overhead contact lines via a wide range of designs, starting with basic overhead lines and moving up to the high-speed OCS that is currently in use. The requirements of the sort of traffic that needed to be served, the resources available to the various railway authorities, and the experience and capabilities of the firms involved determined elements in this development process. The evolved overhead line systems can be classified according to their applications or to the essential structural design characteristics such as the voltage, the use and arrangement of components, the method of the tensile force compensation, and the type of suspension. Both categories are possible to use.

2.2.2 Wires and Stranded Conductor

Contact wires are the pre-tensioned wires along which the pantograph runs. Together with the related catenary wires and droppers, they constitute the equipment for the longitudinal contact line. The primary function of the contact wires is to operate as a contact slide to make sure that electrical energy is continuously transferred to the pantograph collection strips. To ensure more equal wear of the collector strips, the contact wire is separated apart along the track axis. The contact wire must keep reliable electrical and mechanical contact with the pantograph across the whole range of train speeds to transmit current to the traction units [19]. Contact wires that can be clipped together have grooves on either side of the top section. Due to the number of different types of applications, contact wires come in a variety of cross sections and types to accommodate them. The circular cross-section shown in Fig. 8 is the most used for overhead contact wire.

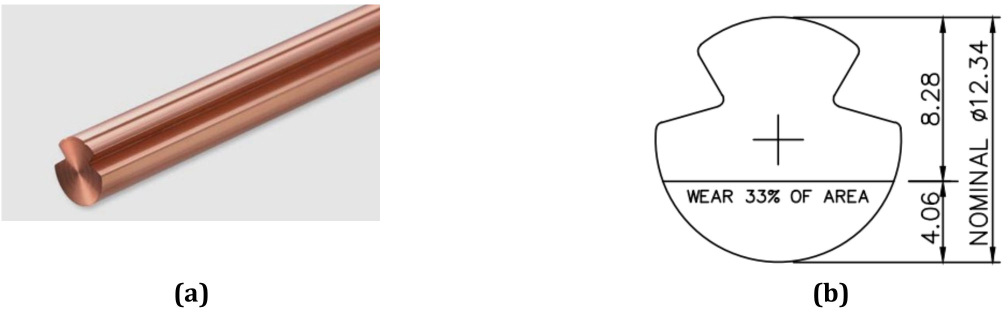


Fig. 8 *Wires and stranded conductor (a) Solid hard-drawn copper conductor; (b) Cross section of contact wire*

The required current, the voltage stability, and the anticipated tensile stresses should all be taken into account when choosing the cross-sectional area of the contact wire [16]. With the technology that is currently available for systems, the cross-sectional area of overhead contact lines has to be restricted [20]. Standards for electrical traction contact cables are outlined in EN50149, which specifies the necessary features and dimensions. Hard-drawn electrolytic copper and copper alloys have evolved into the industry standard for conductor wire due to their high conductivity, tensile strength, and hardness as well as their resistance to corrosion and temperature variations. Copper, when exposed to air, generates a coating of oxide that is both brittle and conductive; this layer does not impede the flow of electrical current. Copper, on the other hand, does not produce an oxide layer with low conductivity like aluminium, making it a suitable material for sliding contacts. The pantograph motion along the contact wires causes the wires to degrade with time. The rate of wear experienced by pantographs and contact wires can be affected by several factors, one of which is the combination of contact materials employed for these components. When trying to obtain the lowest wear rate conceivable, employing a mix of copper contact wire and carbon collector strips is the most effective strategy.

Steel and copper collector strips cause significantly higher wear rates than other collector strips. The permissible wear is limited to 33 % of the cross-sectional area of the wire when it was first manufactured because the resulting decrease in the cross-sectional area of the contact wire lowers its current carrying capacity and increases the tensile stress if the force applied is not reduced proportionally [21]. The cross-sectional measurement taken at the points exposed to the most severe wear is the criterion used to determine when this wear limit has been obtained. In order for the contact wire to wear practically uniformly and, as a result, have a long service life, accurate installation, frequent maintenance, and the best possible interaction between the overhead contact line and pantograph are required.

Change in contact wire height will be achieved with a maximum gradient of 1:500 at the mainline and 1:200 at siding tracks where train speed is reduced to 100 km/h. For smooth guidance of the pantograph, transition gradients of 1:800 and 1:400 for main lines and siding tracks respectively will be considered at the start and finish of the change in height of the contact wire [21]. The contact wire height in the main line is normally 4,600 mm [22]. In special areas under the cross structure with lower clearance, contact wire height shall be decreased properly, and the minimum height above the rail level should not be less than 4,150 mm [23].

2.2.3 Stagger

The contact wire does not run parallel to the track center line when viewed from the contact plane. This ensures continuous contact in curves and when exposed to wind force, preventing uneven wear of the carbon collection strips on the pantographs. As an alternative, it is staggered along the railway with alternating lateral displacement. On the curve track, a contact wire stagger at the support of 350 mm is applied, while 230 mm is used on a straight and tangent track. At KTMB, with overhead contact line system types 107 mm2 solid hard-drawn copper conductor, the catenary wires are placed vertically above the track's center line on straight tracks and above the contact wire on curves. However, on both straight and curved tracks, the catenary wires on 19/2.10 mm2 tin-bearing copper conductor OCS are positioned vertically above the contact wire.

As per KTMB requirements, the normal stagger would be 230 mm for tangent track and could increase to 350 mm in curves [24]. The OCS layout plan will specify the stagger at the individual cantilevers. The pantograph and catenary system are protected from harm by the contact strip travelling across the contact wire while having a deep worn groove, which is one advantage of constructing a staggered contact wire installation. Staggers are chosen to ensure that the contact wire will not be displayed beyond the carbon strip of the pantograph head at any point in the span [9]. In calculating the displacement of the wire, the following shall be considered:

a) Blow-off
b) Stagger effect
c) Mast deflection due to wind
d) Temperature effect
e) Net pantograph sway
f) Track tolerances
g) Erection tolerances
h) Effect of increasing span length by 2 m

EN 15273 standard specifies methods for calculating the effect of pantograph sway due to track tolerances [25]. The other effects were derived from quantities resulting from the calculations within the OCS engineering system used. Mast deflection due to wind shall be considered for H- Beam only. The temperature effect can also be reduced at high wind speeds since the catenary's temperature was also reduced. The tension length was determined in combination with the tension difference between the contact wire and messenger wire, the type of tensioned device, and the wire heights [26]. The tension difference value between contact and messenger wires should be less than 10 % of its rated tension.

2.2.4 Pantograph

The pantograph is the train's current collector. The main frame portion is designed to follow the contact wire over a range of contact wire heights extending from the lowest bridge to level crossing and to apply a near-constant contact force throughout the range of vertical travel. This frame also allows the collector to follow the vertical height changes made in passing from span to span. The pantograph comprises a main frame, an arm, a pantograph head, and a drive as shown in Fig. 9.

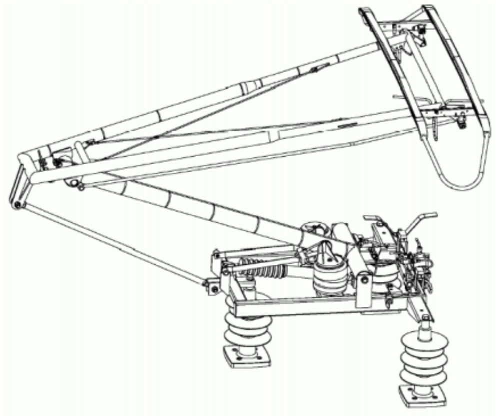


Fig. 9 *Pantograph design*

The frame is fitted with dampers to reduce the tendency of the system to oscillate between spans. The constant rate springs that provide the upward contact force (nominally 90 N) are held down by a pneumatic device when the pantograph is in a stowed position [27]. A pair of carbon strips or even three carbons form the contact surface with the contact wire and is mounted on the pantograph head. The width of the carbon track allows the contact wire to make excursions across the carbons as the wire varies position laterally due to wind, track curvature and stagger. The carbon strips are joined at the ends by curved portions known as pantograph horns. These ensure incoming wires from the side do not hook under the carbon portion. The whole assembly is known as the pantograph head, and it is attached to the main frame via a secondary spring arrangement. This provides cushioning for minor variations in the pantograph trajectory when passing droppers or small deviations in the contact wire profile. Some pantographs allow the contact force to increase significantly with airflow due to forward train speed to compensate for the dynamic variations in contact force that occur as speed increases and loss of contact becomes more likely. The OCS design needs to allow for any increased uplift due to increased pantograph force. The system is not reliable when regular contact loss occurs [28]. As such, 1 % contact loss once considered acceptable is now considered too high by some on account of electromagnetic interference to the modern trains.

The pantograph shall be aerodynamically designed with adequate current collection capacity that will ensure loss of contact is less than 1 % at all speeds up to 140 km/h. However, the reliability and optimization of the pantograph are dependent on the condition and maintenance of the contact wire. The pantograph shall be a single-arm type and mechanically strong enough to ensure air resistance at the maximum speed and have good follow-through characteristics to the rigid bar and catenary wire system. The pantograph is added with a secondary head suspension. Head suspension improves current collection were higher speed multiple operation of pantographs. The pantograph shall be capable of drawing continuous current not less than 600 A [27]. The pantograph shall operate effectively in either direction of travel, with the combined friction, clamping and dynamic forces of the pantograph, not damaging or infringing on any part of overhead equipment. The pantograph shall be raised pneumatically using a battery-operated auxiliary compressor and maintained by air using the main air compressor. The pantograph has been installed with an auto-drop device if the carbon strip is damaged or dislodged. Fig. 10 shows the profile of the pantograph, and the size of the carbon strip shall be compatible with KTMB's OCS. The pantograph head shall be positioned directly over one of the bogie's center pivots.

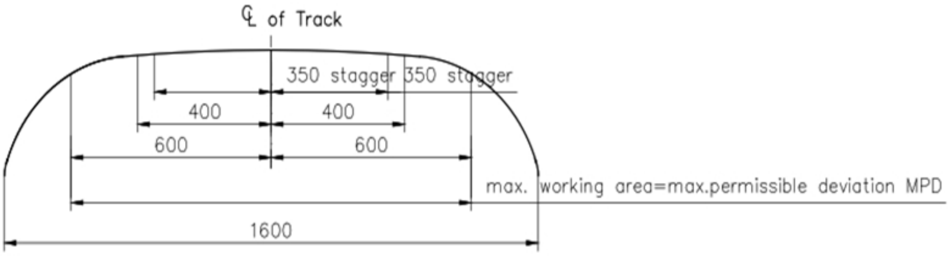


Fig. 10 *Pantograph design philosophy*

2.3 Technical Data Governing the Position of the Contact Wire

The overall length between anchor extremes is limited to 200 m. The rules that limit tension length have been established mainly because of limiting balance weight and registration movement due to temperature and maintaining drag on curves. Fig. 11 illustrates the tension length and typical half-tension length arrangement for the KVDT line. Convenience for length for construction and drum capacity are also considerations, such as switching, feeding, and booster spacing. The rules for head spans are similar to cantilever construction except that head span allowance has to be made for the extra span required taking the wires to anchor off track and that constraint rather than anchoring can be applied at the midpoint.

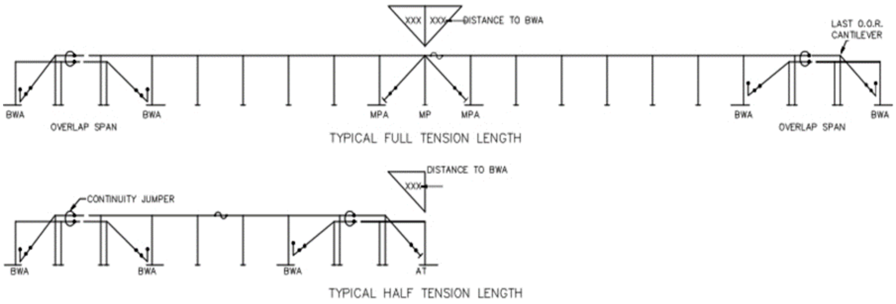


Fig. 11 *Typical tension length and typical half tension length arrangement*

2.3.1 Structure Spacing

The relationship of maximum span to track curvature is fundamental to preparing layout plans. It is based on the contact wire's maximum displacements from the pantograph's center, accounting for blow-off, locomotive sway, etc. [30]. Fig. 12 shows a typical span arrangement of the contact wire [30].

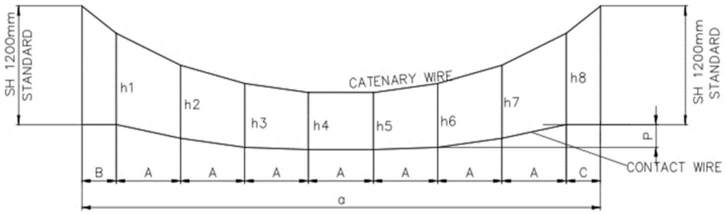


Fig. 12 *Typical span arrangement*

2.3.2 Contact Wire Displacement

Permissible displacement in span (*Y*) is 400 mm as shown in Fig. 14, which includes an allowance of 50 mm maximum for stagger change due to along-track movement. The figure should be reduced by 40 mm per meter rise in contact wire height above 4,600 mm.

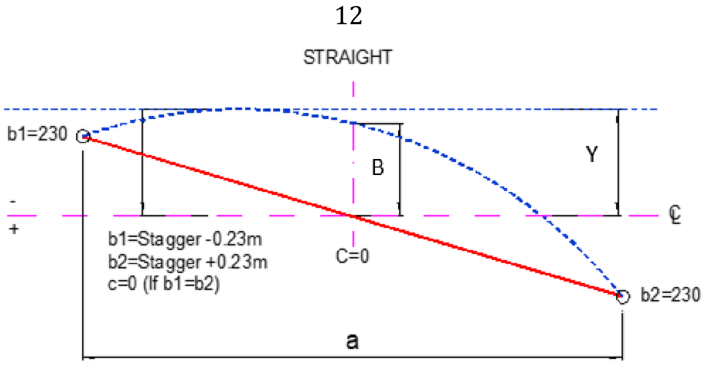


Fig. 13 *Contact wire displacement*

Permissible mid-span offset on each side of the pantograph can be calculated by the equation:

$$M = Y - B - E \tag{1}$$

where M is the permissible mid-span offset, Y is the permissible deviation in-span, B is the blow-off, and E is the stagger effect.

The equation gives the stagger effect:

$$E = \frac{s^2}{16(B - V)} \tag{2}$$

with the condition of

$$S < B - V \tag{3}$$

where S is the stagger sweep, B is the blow-off, and V is the versine or string line.

2.3.3 Catenary Wire Stagger

The catenary stagger shall be as nearly as possible the same as that of the contact wire. The tolerance for acceptance to either side of the optimum position shall be ± 75 mm for encumbrances of 600 mm or more. For encumbrances less than 600 mm, the above tolerance shall be reduced proportionately to the actual encumbrance [24]. There should be no difference in stagger between the catenary and contact wire at the neutral section and overlaps. Stagger values on the straight line section should distribute contact wires like "Z" type. The Stagger value under a typical span length is ± 300 mm and it shall be decreased appropriately under a small span length. Staggers on the curve line shall be determined under the requirement of contact wire lateral deviation to the center of the pantograph, which shall not exceed 450 mm under the worst operation conditions [24]. The maximum stagger shall not exceed 350 mm except for the turnout area. The specific value for installation depends on the calculation result for wire deviation.

2.4 Research Methodology Flow Chart

This research uses image processing technology [31] and laser reflection measurement [32]. In general, the research methodology procedures can be summarized into three phases, which consist of data identification, system implementation and the processing data.

2.4.1 Phase 1 – Data Identification

The device is inspected mainly in the Simpang Pelabuhan Klang (SPK) -Serdang section of the KVDT Line. Data collection from two sources and references as below:

a) Input data and control value from the device - OCS Eye Catenary Inspection Machine.
b) Height and stagger data from operation and project database provided by KTMB Electrification Department.

This system aims to improve the operation and efficiency of overhead line maintenance. Devices such as cameras and lights are installed on the roof of an inspection vehicle, and a system installed in the vehicle obtains and records dynamic status (image data) and location information (such as chainage values) of overhead lines during vehicle travel. The obtained image data and location information are stored in portable disks to transport from the inspection vehicle to an office. Then, image analyses are conducted using a system (station PC system) installed in the office. The analysis result data is maintenance information of overhead lines such as the height, stagger, and wear of contact wires, which are stored in the PC system. Also, the analysis result data is compiled into digital format (table) and analogue format (chart) and viewed on the screen of the PC system [33]. Fig. 14 shows the configuration of the Eye Catenary OCS Inspection System which consists of (1) an Inspection vehicle, (2) a Rooftop system including cameras and lights, (3) a Route monitoring camera, (4) an On-board system, (5) Axle sensor, (6) Portable disks, and (7) Station PC system.

F. T. Xu et al. [13] state that laser reflection measurement and still picture processing technologies are the two most widely used detection methods. The contact wire's wear can be determined by measuring how long a laser reflection lasts [32]. The growth of wear, which is influenced by contact wire condition, determines the duration a contact wire would last [34]. Consequently, the measurement outcomes of the wear trend contact wire analysis might be used to estimate the contact wire's lifetime. The contact wire wear measurements retrofitted to the device have the vital capabilities listed below [33].

a) Measure wire height, stagger and residual height of the contact wires.
b) Measure up to four wires to handle the overlap of two tension-length sections.
c) Provide real-time online visual monitoring during measurement run.
d) Produce an online printout of the data obtained during the measurement run in graphic format.
e) Provide post-measurement analysis, such as irregularities summary, and trend plot for each wire section.
f) Provide database storage of the measured data exportable for analytical use.

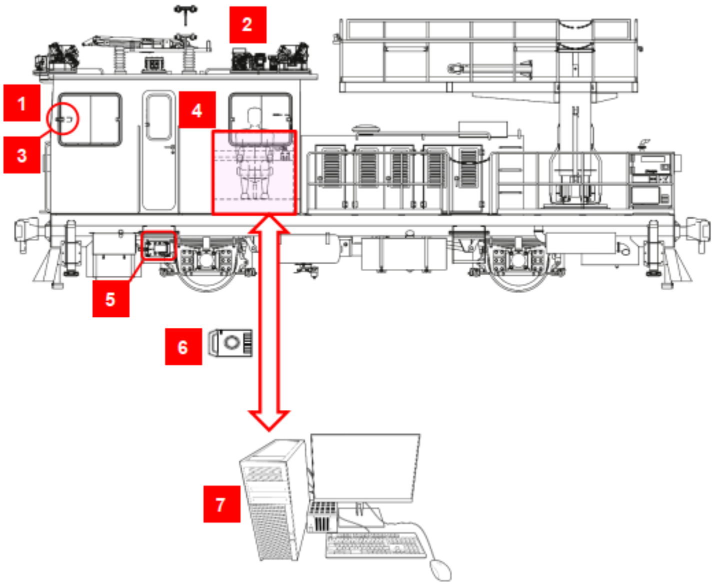


Fig. 14 *Eye catenary OCS inspection system configuration*

2.4.2 Phase 2 – System Implementation

The OCS Eye Catenary Inspection Machine has been chiefly used for image processing using artificial neural networks for monitoring and diagnosing the stagger [11]. They monitor pantograph-contact wire wear and dynamic wire stagger at specific speeds [28]. The measurement specification is in Table 2 below.

Table 2 *Catenary eye specification (Stagger measurement)*

Specification	Description
Measuring method	Non-Contact Type (Line Sensor Camera)
Measurement range	± 400 mm
Accuracy	± 5 mm (Static Accuracy)
Measuring speed	0~80 km/h
Sampling rate between two measuring points	< 30 mm

To measure the stagger, the line sensor pantographs the sliding face of the contact wire from the width of the sliding face, and the center position of the contact wire is extracted [35]. Stagger is figured out by measuring the displacement from the track center (green line) as in Fig. 15.

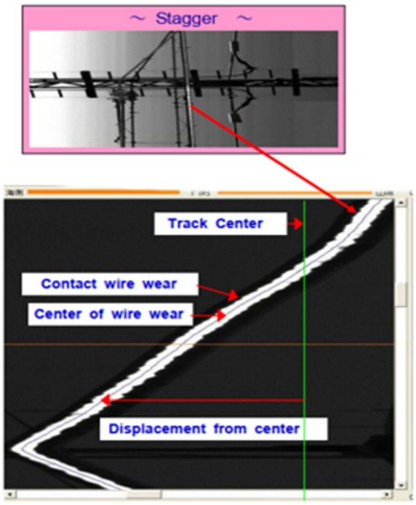
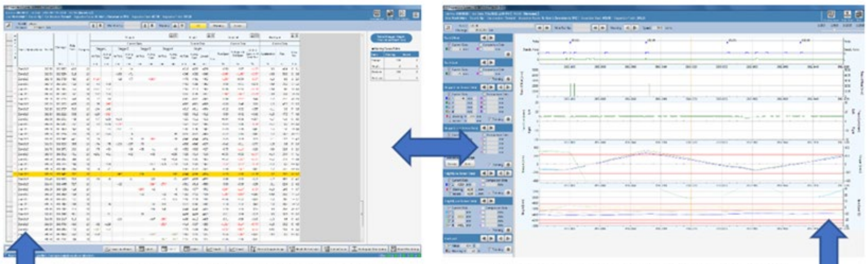


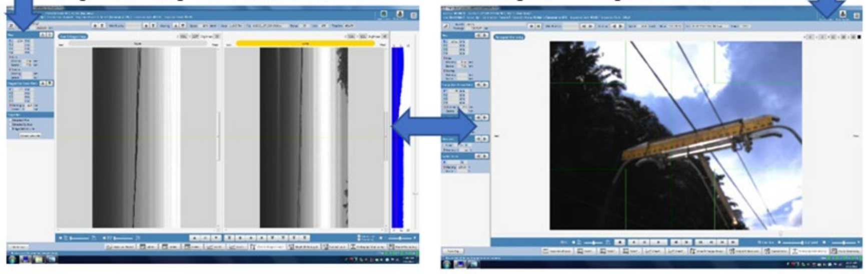
Fig. 15 *Stagger measurement*

2.4.3 Phase 3 – Processing Data

Fig. 16 shows the processing data structure diagram in stagger measurement. The contact wire wear measuring system comprises three components: a chainage positioning system, a data processing system, and a contact wire wear acquisition system [36]. The length of the laser reflection was used to determine how much the contact wire had worn.



Inspection Report in Tabular Form   Inspection Report in Chart Form



Contact Wire Wear Image   Pantograph Monitoring

Fig. 16 *Dynamic linking between image data and numeric data*

Fig. 17 illustrates the measurement of contact wire wear where h represents the height of the contact wire and Δh represents its worn height. The contact wire wear acquisition system consists of a line sensor camera and a set of linear array cameras. The contact wire and the line laser interact to form a laser stripe that holds information about the contact wire's profile. Two high-speed cameras must be positioned parallel to one another in order to capture the stripe image and provide it to the data processing system for processing. The parallax, internal, and exterior parameters of the two cameras as well as the triangular disturbance measuring concept can be used to calculate the height of the contact wire. Since the curve of the contact wire wear surface is smaller than that of the non-wear area, it has a brighter appearance in the image than the worn region does. As a result, the wear width can be estimated using image processing technology, and the real wear surface width can be determined using information from the camera's internal and external sensors. The relevant wear depth can be determined based on the contact wire's inherent form characteristics.

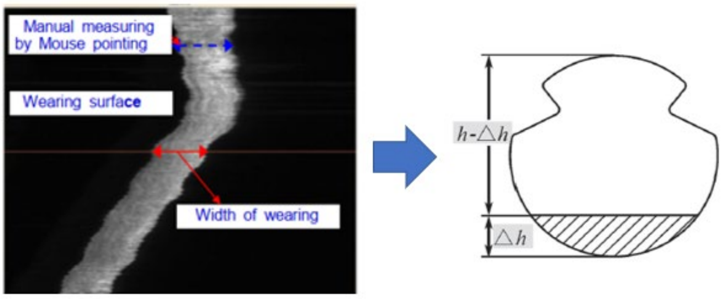
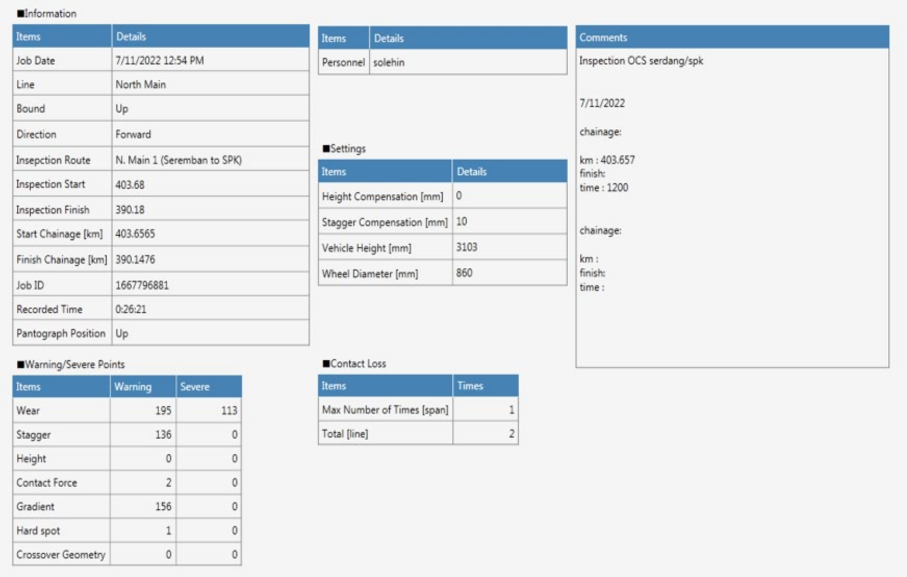


Fig. 17 *Measurement of contact wire wear*

3. Results and Discussion

Wear occurs in contact wire mainly due to the contact between the wire and the conductor. The contact wire constantly moves against the conductor, pulling along the track and creating friction. This friction causes the wire to wear away. The wire comprises metals such as copper and aluminum, which are soft and easily worn away. The size of the contact wire, the train's speed, and the force being applied to it all affect how much wear occurs. As the train's speed and force rise, the wear increases as the wire's diameter decreases. Additionally, the wear worsens the longer the contact wire is in contact with the conductor.

To investigate the behavior of wear further, the inspection was carried out in the SPK-Serdang Upline section, and measuring data of the entire line was sampled for this analysis. Fig. 18 shows the information from the Eye Catenary OCS Inspection System between chainage M 403.680 Upline and M 390.1476 Upline as per the November 7, 2022 field inspection. When inspection data is registered, image data collected during the inspection is associated with the result of the analysis. However, the image data is not duplicated in the software system. Registration of inspection data enables the station PC system to play back image data collected during the inspection.



■Information

Items	Details
Job Date	7/11/2022 12:54 PM
Line	North Main
Bound	Up
Direction	Forward
Insepction Route	N. Main 1 (Seremban to SPK)
Inspection Start	403.68
Inspection Finish	390.18
Start Chainage [km]	403.6565
Finish Chainage [km]	390.1476
Job ID	1667796881
Recorded Time	0:26:21
Pantograph Position	Up

Items	Details
Personnel	solehin

■Settings

Items	Details
Height Compensation [mm]	0
Stagger Compensation [mm]	10
Vehicle Height [mm]	3103
Wheel Diameter [mm]	860

Comments

Inspection OCS serdang/spk

7/11/2022

chainage:

km : 403.657
finish:
time : 1200

chainage:

km :
finish:
time :

■Warning/Severe Points

Items	Warning	Severe
Wear	195	113
Stagger	136	0
Height	0	0
Contact Force	2	0
Gradient	156	0
Hard spot	1	0
Crossover Geometry	0	0

■Contact Loss

Items	Times
Max Number of Times [span]	1
Total [line]	2

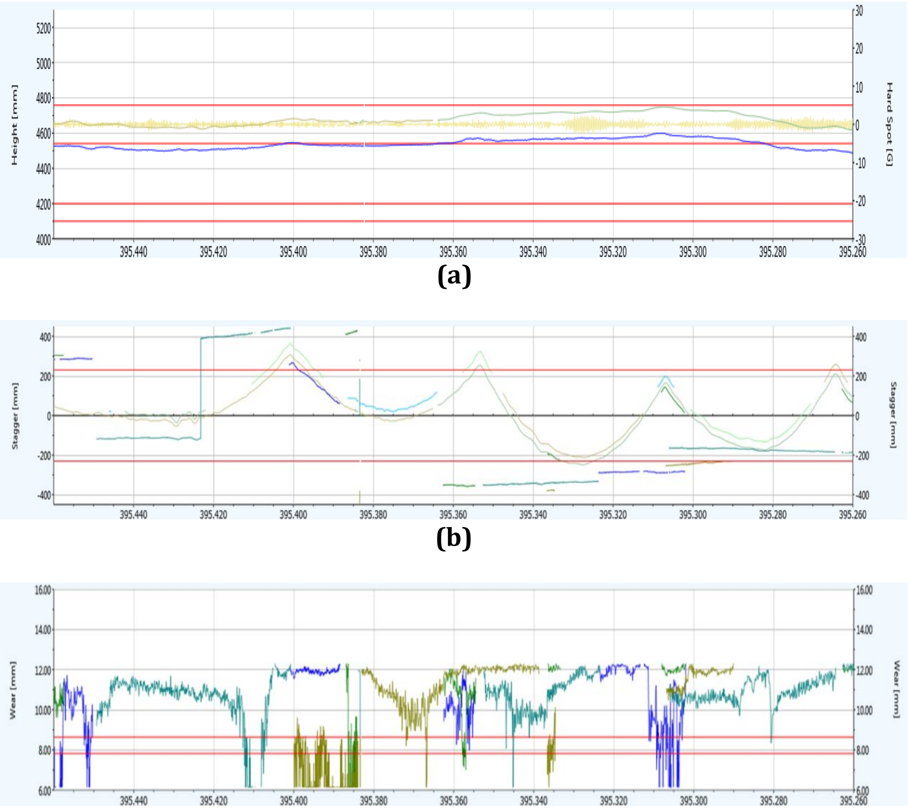
Fig. 18 *Inspection report for SPK-Serdang upline*

The data collected on the warning and severe points shows the number of wears, staggers, heights, contact forces, gradients, and hard spots. If the data exceeds the control value data, the warning and severe points will be shown in the table. There were 195 warnings, and 113 severe abnormal alarms were recorded. The table also indicates 136 of stagger exceed the control value of 230 mm and 350 mm. This data suggests an issue with contact wire wear, as evidenced by the large number of warnings and severe abnormal alarms. Therefore, the number of stagger measurements exceeding the control value of 230 mm and 350 mm is concerning and indicates that further investigation is needed to identify and address the underlying cause of the excessive wear.

Railway system control values are used to monitor and control a variety of critical railway system functions such as speed, direction, scheduling, and safety. The railway system operator typically sets these control values and can be adjusted as required based on the specific conditions of the railway system [37]. Appropriate control values are set for the analysis parameters upon delivery on the system. Most of the raw data is recorded by the device. Specifically, the parameters from the device are the height and stagger, while those obtained by the software system are contact wire wear, train speed, contact force, voltage, and mode. Then, an image of the most appropriate location of the pantograph is captured as a binarized image, resulting in the measurement of the dynamic stagger and contact wire wear. After the detection wire occurs, data association filters out inaccurate measurements obtained in practical conditions. The contact wire has a limited range of movement due to the relation between image samples and the location of the contact wire. This limited range is defined as the validation region and detection results outside of these regions are discarded as noise.

3.1 Staggering Effect of the Contact Wire

Staggering of the contact wire is an important process in railway track maintenance, as it allows for the even distribution of wear on the contact wire. Staggering involves changing the position of the wire on the track, so that the contact points of the train wheels move from one rail to the other, alternating the area of contact on the wire. This helps reduce the wear concentration on one area of the contact wire and even out the wear on the rail over time. By staggering the contact wire, the wear on the contact wire can be reduced to a minimum, and the service life of the contact wire can be extended [38]. Fig. 19 shows a graphical glimpse of the records using the data segment between chainage M395.460 to M395.260 Upline. They show the height, stagger and wear of the contact wire respectively using the data collected from the device. The track segments of 20 m are used irrespective of the same or different tension lengths. Stagger height is the vertical difference between two adjacent rails. It is important to analyze this graph to ensure that the design criteria of the track are met. The graph showed the staggering height for each point on the track and was used as a baseline to ensure that the track was kept within the design criteria.



(a)

(b)

(c)

Fig. 19 *Data recorded by instrumented pantograph (a) height (b) stagger (c) wear*

Fig. 20 shows the trend of staggering at chainage M393.600 to M392.400 Upline. It is clearly seen that in the range of staggering 0-200 mm at the tangent track, the wear of the contact wire is uniform. At this point, it is proven to achieve uniform wear, the contact wire shall follow a zig-zag lateral pattern or stagger that prevents the contact wire from damage. By minimizing the amount of contact between the pantograph and the contact wire, staggering the contact wire in a railway system minimizes wear. This lessens the friction between the two components and guards against contact wire damage. The arched shape of the pantograph's ride on the contact wire evenly distributes the weight of both the pantograph and the train along the wire. The pantograph can move freely, and the contact wire experiences less wear when it is staggered because it changes its form [39]. Furthermore, it visually represents the results of a wear analysis conducted on the OCS Eye Catenary Inspection Machine. This analysis was carried out to evaluate the state of the system's cables and spot any potential problems. The machine found up to four cables with severe wear. The lateral relative sliding between the pantograph and contact wire, as well as other elements like contact force, speed, and acceleration, are probably to blame for this [12]. The serious wear detected in these four cables is a cause for concern, as it can negatively impact the system's functioning and the train's safety. This information can be used to prioritize rectification works, such as replacing or repairing the affected cables, to ensure that the system continues to operate smoothly and safely.

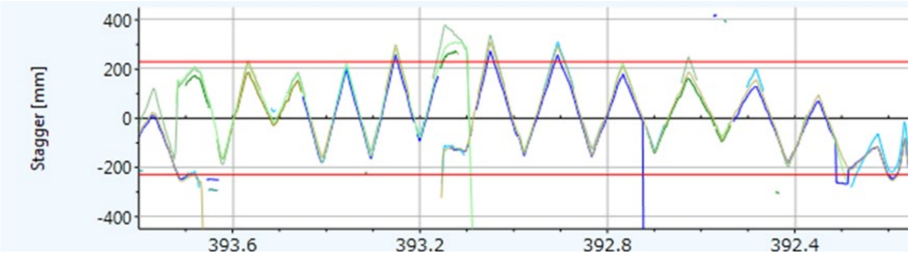
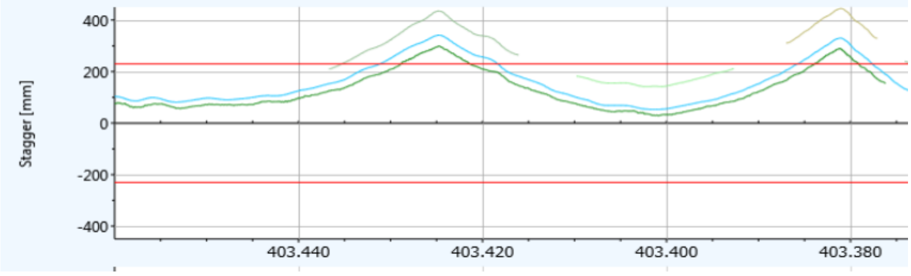


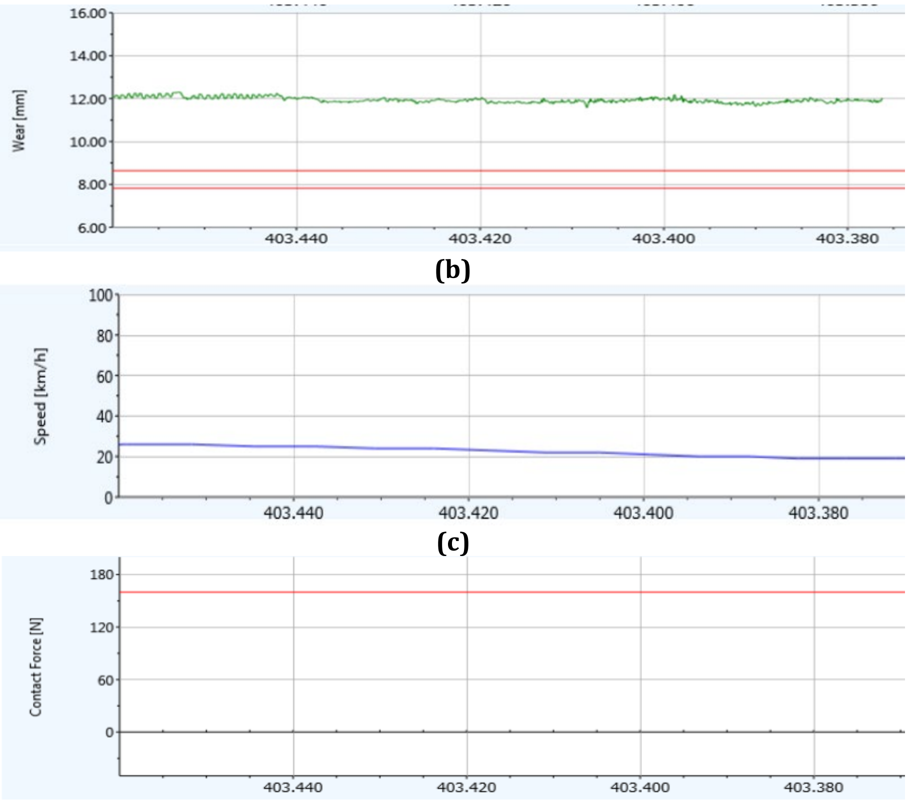
Fig. 20 *Measurement of contact wire wear*

In the case of the curve track, vehicle velocity runs for a speed below 40 km/h and applied contact force 160 N. Fig. 21 shows the trend of stagger and wear at chainage M403.440 to M403.380 Upline. A fitting curve may be seen in the graph's pattern in the staggering 0-350 mm range. On the other hand, the curved track shows the wear contribution is consistent with the wear formulation used in this study. It can be determined under the requirement of contact wire lateral deviation to the center of the pantograph, which shall not be more than 450 mm under the worst operation conditions. Based on the information given, it can be concluded that the wear contribution of the curved track is in line with the wear formula used in the study. This is crucial to understand because it ensures that the contact wire's deviation from the center of the pantograph does not exceed 450 mm even under the worst operating conditions. As time goes on, it will be essential to keep an eye on the wear caused by the curved track to make sure that the contact wire's lateral deviation stays within the allowed range.

Based on the initial investigation via visual inspection, there were differences between the measured and manual locations. The data for measured location are obtained directly from the measuring device and the data for manual location are based on height and stagger data provided by KTMB. The difference between the two data types is mainly due to the changes in the track alignment from the upgrading works currently ongoing by Project KVDT Upgrade Phase 1. The OCS Eye Catenary Inspection Machine was calibrated based on the location adjustment before the upgrading. This would affect the location accuracy and the condition of the Pull Off Arm. When the location and orientation of the machine are changed, this can affect the accuracy of its readings. This is because the machine's sensors are designed to detect specific physical parameters, such as contact force, speed, and acceleration. If the position and orientation of the machine are altered, the sensors may no longer be able to measure these parameters accurately. The sensors may no longer align with the pantograph and contact wire if the machine is rotated or moved from its initial location. As a result, the sensors may not be able to detect the critical physical properties effectively, which could lead to inaccurate readings.



(a)



(b)

(c)

(d)

Fig. 21 *Visual inspection between M 393.600 and M392.400 upline (a) stagger; (b) contact wire wear; (c) speed; (d) contact wire*

3.2 Wear Behaviour of the Contact Wire

The statistical analysis carried out to examine the contact wire wear is summarized in Table 3. Group statistics on the wear data are run based on location. Results showed that on the SPK-Serdang segment of the KVDT Line, the first interval accounted for 94.12 % of contact wire wear (0 - 0.3 mm). The entire line's highest wear distribution is about 0.3 mm. Railway contact wire wear happens between 0 to 0.3 mm intervals because of the constant contact between the contact wire and the pantograph. The contact wire deteriorates due to friction created as the pantograph runs along it. Mechanical wear often happens in the first interval because the contact point between the contact wire and the pantograph is the most reliable. This constant contact point is where the most wear occurs because the contact wire is pulled and pushed against the pantograph to create an electrical connection. The pressure and friction between the contact wire and the pantograph are increased by the train's weight, speed, and weight, all of which hasten wear [38].

Table 3 *Statistics of contact wire wear, Δh in SPK-Serdang section*

Wear section height of contact wire (mm)	Data volume of monitoring mast	Percentage of data (%)
$0 \le \Delta h < 0.3$	256	94.12
$0.3 \le \Delta h < 0.6$	11	4.04
$0.6 \le \Delta h < 0.9$	3	1.10
$0.9 \le \Delta h < 1.2$	1	0.37
$1.2 \le \Delta h < 1.5$	0	0.00
$1.5 \le \Delta h < 1.8$	0	0.00
$1.8 \le \Delta h < 2.1$	1	0.37

However, 0 % of a contact wire wear value exceeds the safety alert standard. The safety warning value is a fixed level of wear deemed unsafe for operation. The vehicle shouldn't be driven if the safety warning value for contact wire wear is exceeded. This indicates that the wear found on the wire is below the safety warning threshold, allowing a train to be operated safely because the percentage of the contact wire wear value above the safety warning value is 0 % [40]. Total contact wire wear on the SPK-Serdang Line is mostly focused on a lower interval, where there are fewer significant wear phenomena and the contact wire is in good condition. There are engineering limits in the minimum cross-sectional area of the contact wire to ensure the wire can survive the tension due to mechanical limits and sufficient copper to reduce the voltage drop along the contact wire [41]. The research shows that the system device accurately monitors the contact wire wear of the entire line and that it is in good condition, providing a certain benchmark for line maintenance. Railway contact wire wear behaviour is a complicated process driven by numerous factors. The contact wire must have the proper wear characteristics to last as long as possible and avoid premature failure. Therefore, by performing regular maintenance with the usage of the appropriate materials and lubrication, the wear behaviour of the contact wire can be optimized, hence assuring the safe and effective operation of the railway system.

4. Conclusion

This research aims to evaluate the effect of staggering on contact wire wear in the Malaysian railway TPS. The data was collected using the Eye Catenary OCS Inspection System and recorded using the station PC system. The railway system operator set the control values and monitored to ensure that the system was within the desired parameters. The pantograph and contact wire detection were conducted in an image, and data association was conducted to filter out inaccurate measurements. The findings from the inspection carried out on the SPK - Serdang Upline section showed that there was an issue with the contact wire wear. It was found that the machine detected up to 4 cables that were experiencing severe wear. The serious wear detected in these 4 cables is a cause for concern, as it can negatively impact the system's functioning and the train's safety. This information can be used to prioritize rectification works, such as replacing or repairing the affected cables, to ensure that the system continues to operate smoothly and safely.

On the other hand, the staggering of the contact wire was an essential process in railway track maintenance, as it helped reduce the wear on the wire and extend its service life. The data collected using an instrumented pantograph showed the correlation between stagger and contact wire wear. The results showed that the wear can be reduced to a minimum by staggering the contact wire. The graphs of height, stagger, and wear of the contact wire were analyzed to ensure that the track was kept within the design criteria. The correlation between the stagger and contact wire wear was also analyzed using data collected from the device. The findings showed a strong correlation between the stagger and contact wire wear, and further investigation is needed to address the issue.

Overall, the simulation results showed that the OCS Eye Catenary Inspection Machine is a reliable tool for estimating the value of contact wire wear. The maximum value of stagger that causes wear on the contact wire was determined, providing valuable information for optimizing the staggering of the contact wire. The comparison between the measurement data from the machine and the manual data confirmed the reliability and effectiveness of the system in detecting contact wire wear. In conclusion, utilizing the OCS Eye Catenary Inspection Machine is crucial for ensuring the longevity and efficient functioning of the Malaysian railway traction power supply. By providing accurate and reliable data on contact wire wear, the machine able to support efforts to optimize the staggering of the contact wire and improve the performance of the railway system.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Farah Shuhadah Mohd Ramli and Hairulazwan Hashim; data collection: Farah Shuhadah Mohd Ramli;* ***analysis and interpretation of results:*** *Farah Shuhadah Mohd Ramli, Azwan Othman and Halim Mamat;* ***draft manuscript preparation:*** *Farah Shuhadah Mohd Ramli and Hairulazwan Hashim. All authors reviewed the results and approved the final version of the manuscript.*

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