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The Optimal Span Length of the Overhead Catenary System for the Gemas-Johor Bahru Electrified Double Track Project

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ABSTRACT

The span term in the Overhead Catenary System (OCS) refers to the distance between two subsequent supports in the running track direction. Longer spans are preferable for economic reasons because they reduce the number of supporting structures. The maximum span along the track was suggested by OCS designers using a structure spacing table and chart with varying wind speeds and radius of curvature. The structure spacing chart is a logarithmic curve that is plotted based on the specifications of the project and design constraints. According to the current design, the maximum span length for the Gemas-Johor Bahru Electrified Double Track Project is 72 metres (GJBEDTP). The current OCS design can be upgraded to provide a greater maximum span. This study looked at the economic benefits of increasing the maximum span length of the GJBEDTP in terms of reducing the total number of supporting structures. The track is separated into many equal-length track sections, and their individual spans are selected using the wind study assessment report and the structure spacing chart. Divide the total track length by the average span to get the estimated total number of supporting structures. In this study, a graph showing the percentage of cost savings and the maximum allowable span is plotted. In this optimization issue, the Elbow approach is used to select a point where diminishing returns are no longer worth the extra expense of going for a longer span. According to the results, the maximum span of 72 m is the ideal span for the GJBEDTP.

1. Introduction

The Gemas-Johor Bahru Electrified Double Track Project (GJBEDTP) completes the upgrade of the existing Keretapi Tanah Melayu Bhd (KTMB) network. Once completed, it will provide a continuous link from the peninsula's southernmost points to Padang Besar on the Thai border. Upon completion,

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KTMB will operate an electric train service (ETS) with a top speed of 140 km/h and an average speed of 100 km/h. As a result, the travel time between Kuala Lumpur and Johor Bahru will be reduced from seven to four hours. The ETS will be a more appealing option than express buses, which take four and a half hours to travel between the two cities even without traffic congestion. The RM9.5bil EDTP entails doubling the current single rail line and installing an Overhead Catenary System (OCS) along a 197-kilometer section of track [1-5]. The OCS system is based on proven components that have previously been used in KTMB electrified lines, and it meets the fundamental requirements of 160 km/h design speed and 600 A current carrying capacity. The interoperability with existing KTMB installations is critical. As a result, wherever applicable, the KTMB design parameters used in previous projects, namely Seremban-Gemas EDTP, Rawang-Ipoh EDTP, and Ipoh-Padang Besar EDTP, shall prevail. Figure 1 depicts a location map for all EDTP projects. The GJBEDTP features 11 stops and halts, one depot, and 194.22 km of overhead 1 x 25kV electrified double track.

Fig. 1. EDTP Location Map [6]

Figure 2 depicts the project's track alignment.

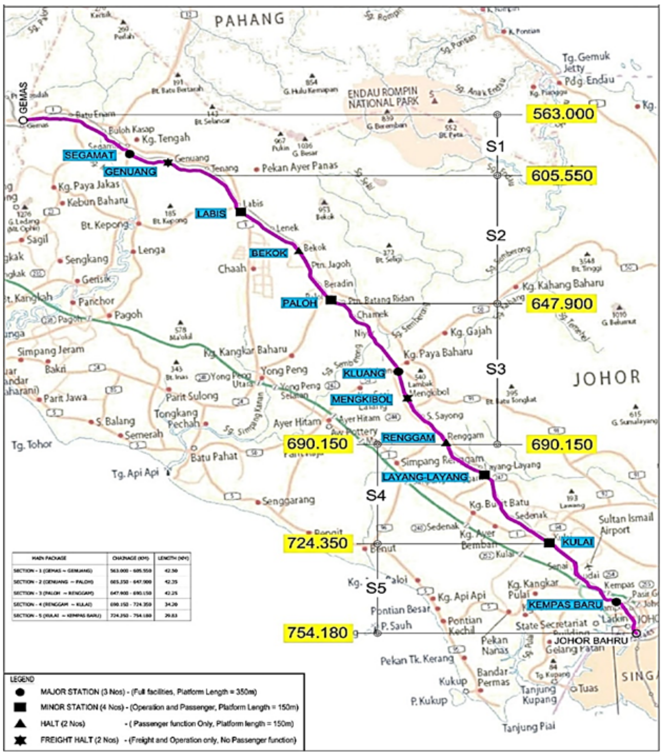


Fig. 2. Project Alignment and Route [7]

The maximum feasible span length employed on tangent and curved track must be specified when determining mast positions in an Overhead Catenary System design. Although longer span lengths are preferable because they reduce the number of supporting structures, there are some economic factors that increase with span length. Vertical and wind loads are proportional to span length. The sag of the catenary increases according to the square of the span length, resulting in a significant increase in the length of the mast and thus in the size of the mast and foundation. Furthermore, the dynamic behaviour of the equipment must be considered. There is no simple rule that states that longer spans provide better or worse current collection than shorter ones. However, span length is an important consideration in dynamic analysis. In a specific case, it may be discovered that the economic benefit of a longer span length is offset by decreased performance [8-11]. As a result, before designing any OCS system, the maximum permissible span length must be studied to ensure a reliable and cost-effective system. Although previous electrified double track projects can provide the maximum permitted span length, the design parameters may differ due to differences in geographical location, track geometry, technology, and contract requirements. The maximum span length is also not always the best span length for that particular project. Furthermore, no equivalent study has been conducted in Malaysia. As a result, the research is carried out. The primary goal of the study was to determine the optimum span length to be employed in the overhead catenary system for GJBEDTP and to assess the relationship between the maximum allowable span and the total number of supporting structures in the overall system. Some sub-objectives can be developed to help achieve the main goal:

i. To study and identify the limiting factors and required data needed to calculate maximum span length.
ii. To estimate the cost savings in terms of the total number of structures based on the previous project's maximum span.
iii. To find the optimum span length for GJBEDTP using the Elbow method.

1.1 Design Impose for OCS in Determining the Span Length

The Overhead Catenary System (OCS) of the railway is made up of a contact wire, a messenger wire, droppers, registration arms, and brackets. The messenger wire transports the contact wire via the droppers, allowing for the desired geometry, stiffness, and elasticity. The messenger wire is carried by the brackets, which are attached to the poles. The registration arms, which are attached to the contact wire, primary function is to obtain the correct horizontal geometry of the contact wire. The contact wire is the conductive component that conducts electricity to the train via the pantograph [12,13]. Overhead Catenary is supported by a variety of methods, including simple cantilevers on steel masts for single and double track areas, and portal or head span construction for multi or complex track areas. In its most basic form, the mast supports a cantilever, which in turn supports the contact and catenary wires. The return conductor is also attached to the mast. Ceramic [14] or fibreglass insulators separate the cantilever and return conductor supports from the mast. Figure 3 depicts an example of an overhead contact line design with individual masts on both sides of the tracks.

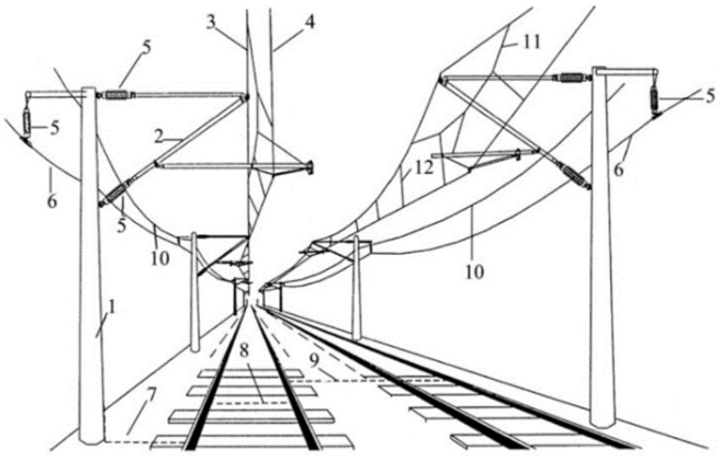


Fig. 3. Overhead contact lines on individual supports [12,13]

The overhead contact system is supported by structures placed at regular intervals along the track. The span length, or simply span, is the distance between successive structures. One of the factors listed in Table 1 may limit the span length [8-11].

Table 1
Span length limitation factors

No.	Span length limitation factors:
1	The sag of the catenary wire, given a maximum system height (i.e., catenary - contact separation at the support) and a minimum dropper length at mid-span.
2	The dynamic behaviour of the equipment when disturbed by passing pantographs.
3	The lateral displacement of the contact wire by wind (blow-off). This is usually the critical parameter.

Figure 4 depicts the OCS span length from the side. It should not be assumed that the longest possible span must always be used. Spans of up to 75 m have been used frequently and successfully. Longer spans are uncommon. As a result, the designer who proposes to use a span greater than 75 m bears the burden of demonstrating that it will work [8-11]. According to Bond R.W. (1987), the goal of all types of contact systems is to provide as much uninterrupted current collection as possible without sparking or contact loss. In an ideal contact system, the contact wire would be absolutely rigid and level. Because this is not possible, its dynamic properties must be compatible with the pantograph's pantograph, which is minimal contact loss at all speeds. There are two major considerations:

i. The wire in its static position (that is, when not disturbed by a passing pantograph) should be as nearly as possible at a constant height above the track.
ii. As nearly as possible, the wire should present constant resistance to the upward thrust of the pantograph at all points in each span.

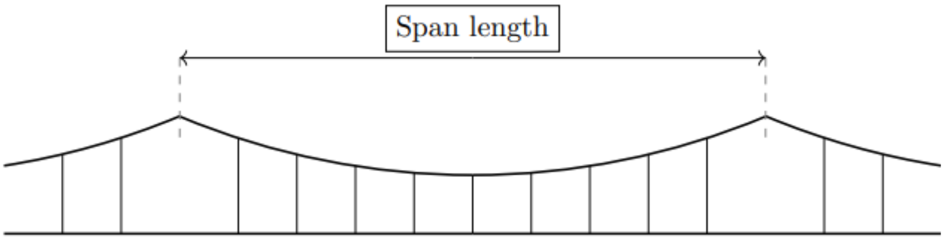


Fig. 4. OCS span seen from the side [15-17]

Table 2 shows station wind speeds for all directions based on 3-second gust wind data according to MS 1553:2002.

Table 2
Wind speed (m/s) for various return period

Station	V_{20}	$V_s = V_{50}$	V_{100}
Senai	26.9	29.1	30.7
Kluang	29.6	32.6	34.9

Wind speed (m/s) for different return periods for the regions depicted in Figure 5. V100 is the wind speed for a 100-year return period, V50 is for 50 years, and V20 is for 20 years. MS1553:2002 places the importance factor, I, for OCS under Category of Structures II, with an I value of 1.0. The basic wind speeds in MS 1553:2002 are obtained from the Gringorten Method Analysis for a 50-year return period, with two main zones taken into account. Zone I is Peninsular Malaysia's inland area, with a basic wind speed of Vs = 33.5 m/s. Zone II is Peninsular Malaysia's on-shore outer perimeter, where the basic wind speed is assumed to be Vs = 32.5 m/s, as shown in Figure 5. The design wind speed is the assumed wind speed acting on the overhead catenary system for design purposes. The calculation of the design wind speed acting on the contact wire is difficult because it will pass through topographically diverse areas. As a result, the wind speed will vary along the track as it moves through various topography and ground roughness. As a result, obtaining the wind speed based on location is critical to ensuring an accurate design wind speed value, which corresponds to a better OCS design. The greater the wind speed acting on the overhead catenary system, the greater the blowoff of the contact wire, limiting the OCS span length. As a result, wind speed surveys must be conducted every few metres to determine the maximum OCS span length in each location [18,19]. Various codes provide guidance on determining the design wind speed, such as:

i. BS6399: Part 2: 1997 – Loadings for buildings. Wind loads;
ii. MS 1553:2002 - Code of Practice on Wind Loading for Building Structure;
iii. ANSI/ASCE 7-95:1996 - Minimum Design Loads for Buildings and Other Structures.

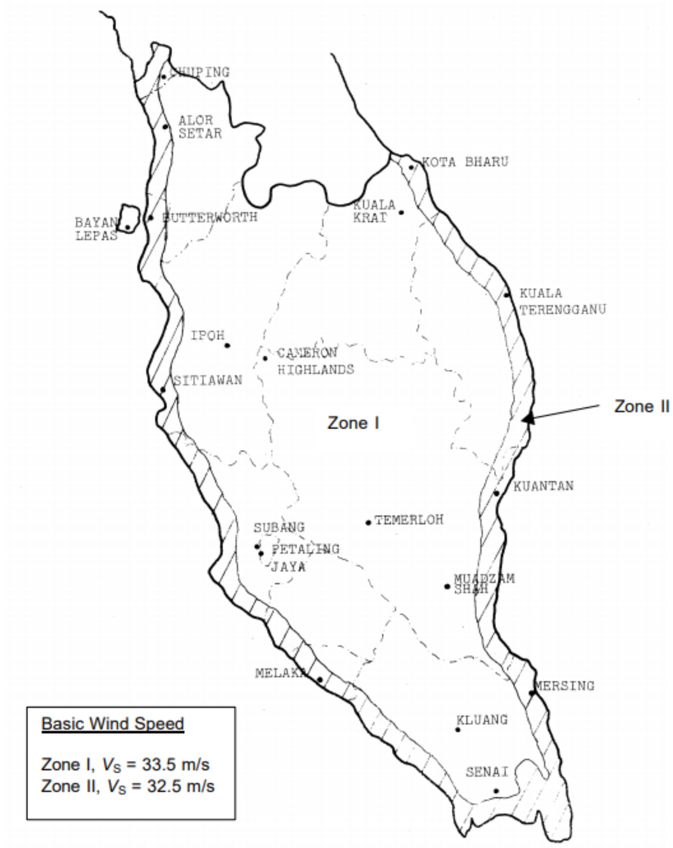


Fig. 5. Basic wind speed for Zone I and Zone II [20,21]

These codes, however, are more concerned with buildings and structures, where complex equations and parameters are required to determine the design wind speed. The design wind speed is computed for this project using the relevant guidelines provided in these standards. The wind assessment survey along the proposed GJBEDTP is being carried out by UPUM Sdn. Bhd. PVNRS Sarma, the past OCS designer of the Seremban-Gemas Double Track Project (personal communication, May 17, 2021), stated that the maximum span length used in the Seremban-Gemas project is 60m, whereas the maximum span length used in the Ipoh-Padang Besar Electrified Double Track Project is only 58m. According to the Skypark Project Design Brief, the maximum span length used is 58m, which is the same as the Subang Jaya KTM line. 2017 The Siemens Product Catalog - Contact line equipment for mass transit and main-line railways describes the products available from Siemens for the construction of modern contact line systems. Siemens' Sicat contact line systems are intended to meet the full range of requirements associated with various traction power supply systems, all speed ranges, various power levels, and open line sections, tunnels, stations, and depots. Table 3 shows the maximum span length of the various Sicat systems. According to the Siemens Catalogue, the OCS can be designed with a maximum span length of 110m. However, Siemens Sicat product may have a different criterion as specified in the Gemas - Johor Bahru Double Track contract specification. For example, the system height in Sicat SX is 1.6 m, as opposed to the 1.2 m specified by the client. As a result, a study must be conducted to determine the maximum span length for this particular project.

Table 3
Various Sicat system with their maximum span length

Running speed	AC (alternating current)	Maximum Span Length
≤ 160 km/h	Sicat LA (main-line railways)	80m
≤ 230 km/h	Sicat SA (main-line railways)	80m
≤ 250 km/h	Sicat SX / Sicat SR (main-line railways)	110m
> 250 km/h	Sicat HA (main-line railways)	70m

2. Methodology

This study will begin by collecting and reviewing various parameters of the GJBEDTP Overhead Catenary System as specified in the contract requirement, standard practise, and international standards. Three maximum span length limitation factors identified in the previous section will be analysed and determined for the current project. Mathematical calculations will be performed using MS Excel Spreadsheet with the help of tables, charts, and Visual Basic for Applications based on the defined parameters and limitation factors. The mathematical calculation will then be validated in the second stage of this study using the Sicat Master programme and Sicat Dynamic simulation software. Once the maximum span values from the three limiting factors have been determined and compared, the lowest values will be used as the project's span limits. The span for each 25m track length will then be calculated and tabulated. The mean values are used to calculate the total number of supporting structures. The results would then be compared to the previous project's span limit and the maximum potential span length. The cost savings are presented in terms of the total number of supporting structures in the comparison. A graph is plotted to show the relationship between percentage cost savings and maximum permissible span length. Finally, the Elbow method is used to determine the best span length for the project.

2.1 Factors Limiting Span Length and Data Synthesis

At this stage, the parameters needed to design the OCS span length are identified and collected. The information is gathered from a variety of sources, including:

i. Basic design parameter from Pestech Technology Sdn. Bhd.
ii. Track Data from SIPP-YTL JV.
iii. Wind speed assessment study from UPUM Sdn. Bhd.

The assessment is carried out to determine the operational wind speed that will be used to compute catenary support and catenary wire displacement, which will then be used to calculate pantograph security and maximum span length. Following data collection, data analysis and design are carried out. During this stage, raw data is analysed, classified, and tabulated in accordance with design parameters.

2.2 Determination of Maximum Span Based on the Three Criteria

As shown in Table 4, the maximum span obtained from the three limiting factors mentioned in the literature review will be compared for the smallest value. The smallest value will be the overall project's final maximum allowable span. The maximum value will then be used to estimate the total number of structures. This maximum value will change as we investigate the relationship between maximum span length and total number of structures. The optimum maximum span length will then be determined using the Elbow method, which is covered in the following subsection.

Table 4
Maximum permissible span based on the limitation factors

No.	Span length limitation factors:	Maximum permissible span length
1	The sag of the catenary wire, given a maximum system height and a minimum dropper length at mid-span.	Results from the mathematical calculation of dropper length.
2	The lateral displacement of the contact wire by wind (blow-off).	Results from the mathematical calculation of maximum total offset and validation from Sicat Master.
3	The dynamic behaviour of the equipment when disturbed by passing pantographs.	Results from the Sicat Dynamic simulation study.
The maximum permissible span length allowed for GJBEDTP:		Smallest of the three numbers

2.3 Determination of the Total Number of Supports Along the Track

The maximum permissible span value will be the upper limit for each span and stagger table. The previous value in the span and stagger table is adjusted based on the maximum span length permitted. In the span and stagger chart, the maximum span should be less than or equal to the maximum permissible span obtained. The total number of supports is calculated by dividing the track into smaller sections (25m intervals) and determining their maximum allowable span based on their wind speed and radius of curvature, as shown in Table 5. Subtracting the first chainage value from the last chainage yields the total track length. The average span is the mean value of the sum of the span lengths in each design. As shown in Eq. (1), the number of supports is calculated by dividing the total track length by the average span length.

Table 5
Determination of span for every 25m track length

Track Chainage (every 25m)	Radius of Curvature, m	Design Wind Speed, m/s	Span, m	Adjusted Span, Max at 72m	Adjusted Span, Max at 60m
			(Potential design)	(Current design)	(Previous project design)
562775 562800 562825 … … 754200 754225	… …	… …	Applying line equation in span and stagger chart without considering minimum dropper length at mid-span and pantograph dynamic study	Applying line equation in span and stagger chart with 72m span limit.	Applying line equation in span and stagger chart with 60m span limit.
Total track length	-	-	Average span	Average span	Average span
-	-	-	Total no. of supports	Total no. of supports	Total no. of supports

$$Total\ no.\ of\ supports = \frac{Total\ track\ length\ (m)}{Average\ span\ length\ for\ a\ total\ track\ length\ (m)} \quad (1)$$

2.4 Determination of Optimum Span Length for GJBEDTP

The maximum span length for GJBEDTP is determined by the previous subsection. However, the maximum span length is not always the best span length. The Elbow method is used in this subsection to determine the optimum span length for the GJBEDTP project. Using a curve's elbow or knee as a cutoff point is a common heuristic in mathematical optimization to determine where diminishing returns are no longer worth the extra cost [22]. In this study, a graph of the percentage of cost savings and the maximum allowable span length is plotted, and the point with the greatest distance to the straight line is designated as the elbow. The maximum permissible span length for GJBEDTP is considered to be the maximum span length at that point. The percentage of cost savings above the optimum span will be insignificant and will not justify the cost of upgrading the OCS design. Figure 6 depicts the Elbow method in action over a curve.

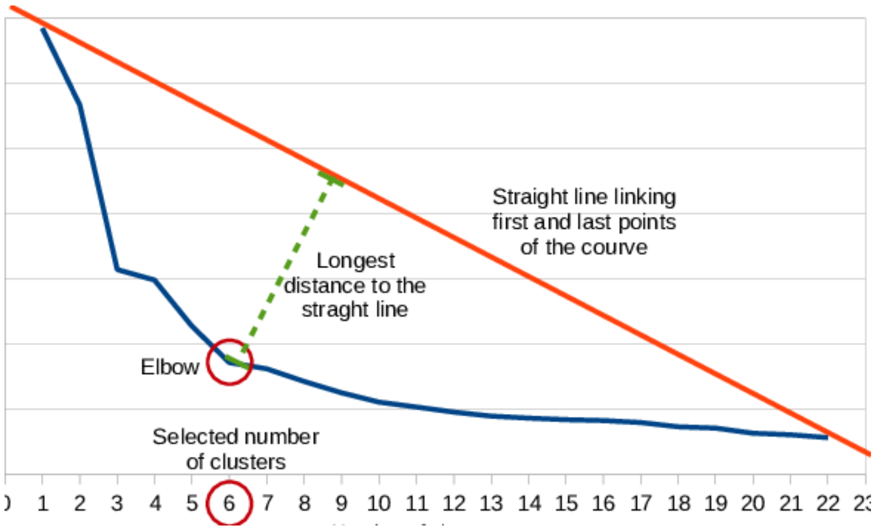


Fig. 6. Example of the elbow criterion applied over a curve [23,24]

3. Result and Analysis

3.1 Span Length Limiting Factors and Data Synthesis

Table 6 shows the limiting factors for the maximum span length defined in Section 2. Before calculating the maximum span length for each limiting factor, their input parameters must first be determined. The sub-chapter that followed discussed the required data and input parameters for each limiting factor. To determine the catenary sag and the minimum dropper length at mid-span, basic OCS design parameters must be used.

Table 6
Limiting factors for maximum span length

No.	Span length limitation factors:
1	The sag of the catenary wire, given a maximum system height (i.e., catenary - contact separation at the support) and a minimum dropper length at mid-span.
2	The lateral displacement of the contact wire by wind (blow-off).
3	The dynamic behaviour of the equipment when disturbed by passing pantographs.

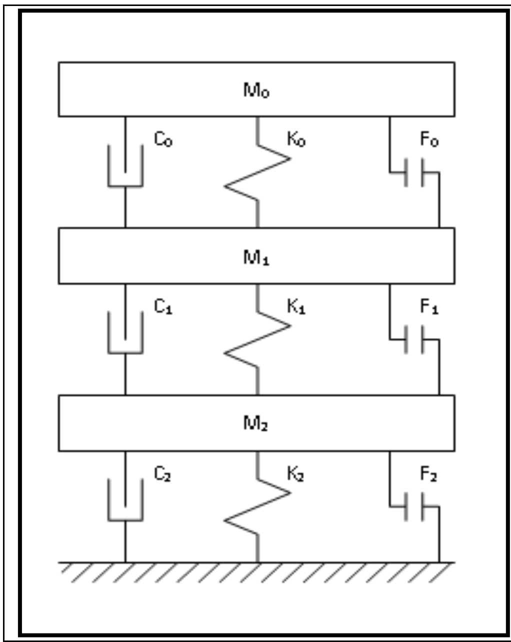
Table 7 contains parameters derived from client specifications and KTMB standard practise using the dropper length method.

Table 7
Basic OCS design parameters

Basic facts of project	**Data**
Nominal contact wire height for open line (m)	5.0
Nominal system height (m)	1.2 (max. 1.4m, min 1.0m), 1.6 and 0.95 for overlaps
Max. dropper spacing (m)	10
Weight set positioned	In front of poles
Weights made of	Concrete
Type of tensioning system	Wheel type
Ratio of tensioning device	1:3
Number of Contact wires	1
CW auto-tensioned with (kN)	12
Number of messenger wires	1
MW auto-tensioned with (kN)	12
Max. radial load on registration arm (kN)	2
Contact wire	Ri 107 (main line) & RiS107 (depot) auto tensioned
Messenger wire	BzII70 (to be replaced by solid wire, if electrical clearance is below 600 mm)

3.2 Pantograph Model

The dynamic modelling was carried out using a pantograph model of the type "KTMB Intercity" (Brecknell Willis BW 12842). Figure 7 depicts the parameters of this pantograph's 3-mass-model. The model is made up of vertically positioned masses linked together by springs. The spring elements' stiffness K, damping C, and friction coefficients F are constant. The design does not include a mechanical stop. The static force acts on mass M2, while the aerodynamic forces act on mass M0. Because these forces can change between simulation runs, they are assigned to simulation parameters rather than pantograph parameters. The pantograph parameters are valid for the pantograph's working range, which is between 4.15 m and 6 m height of the contact wire.



Masses [kg]	M0	10.0
	M1	7.5
	M2	3.5
Springs [N/m]	K0	12000
	K1	10000
	K2	25
Damping [Ns/m]	C0	0
	C1	0
	C2	50
Friction [N]	F0	0
	F1	0
	F2	8

Fig. 7. Model and parameters of pantograph type BW 12842

3.3 Maximum Span Length Based on Catenary Sag

The first limiting factor in determining the maximum span length is catenary sag. As the span length increases, so does the sag, reducing the dropper length at the mid-span. Dropper length analysis was performed to determine the maximum span length that can be achieved before the dropper length at mid-span falls below 500 mm. Table 8 shows the dropper length for spans ranging from 65m to 76m. According to the table above, the 4th and 5th droppers for 74m span and beyond did not meet the 500 mm minimum dropper length requirement at mid-span. The values are highlighted in red. While the 73m span (shown in yellow) barely met the minimum requirement of 509 mm dropper length. As a precaution, the maximum span length for the given project's parameter is set to 72 m. This value is denoted in green.

Table 8
Dropper length calculation at 1200 mm system height

Span [m]	**System Height [mm]**		**Dropper Length [mm]** Dropper length is measured from the inside of upper thimble to the inside of lower thimble							
	Support 1	**Support 2**	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**
76.0	1200	1200	1015	729	539	444	444	539	729	1015
75.0	1200	1200	1017	741	558	466	466	558	741	1017
74.0	1200	1200	1020	753	576	487	487	576	753	1020
73.0	1200	1200	1022	765	594	508	508	594	765	1022
72.0	1200	1200	1025	777	611	529	529	611	777	1025
71.0	1200	1200	1027	788	629	549	549	629	788	1027
70.0	1200	1200	1030	799	646	569	569	646	799	1030
69.0	1200	1200	1032	810	662	588	588	662	810	1032
68.0	1200	1200	1035	821	679	608	608	679	821	1035
67.0	1200	1200	1037	832	695	627	627	695	832	1037
66.0	1200	1200	1039	816	682	637	682	816	1039	
65.0	1200	1200	1042	827	699	656	699	827	1042	

Figure 8 depicts a dropper arrangement for a 72m span, whereas Figure 9 depicts a cantilever arrangement for a 1200 mm system height. If the system height is increased to 1.4 m or higher, a longer span length is possible. A higher contact and messenger wire tension would increase the dropper length at mid-span, thereby increasing the span limit. The researchers went on to investigate the effect of a minimum dropper length at mid-span when the system height was increased to 1.4m.

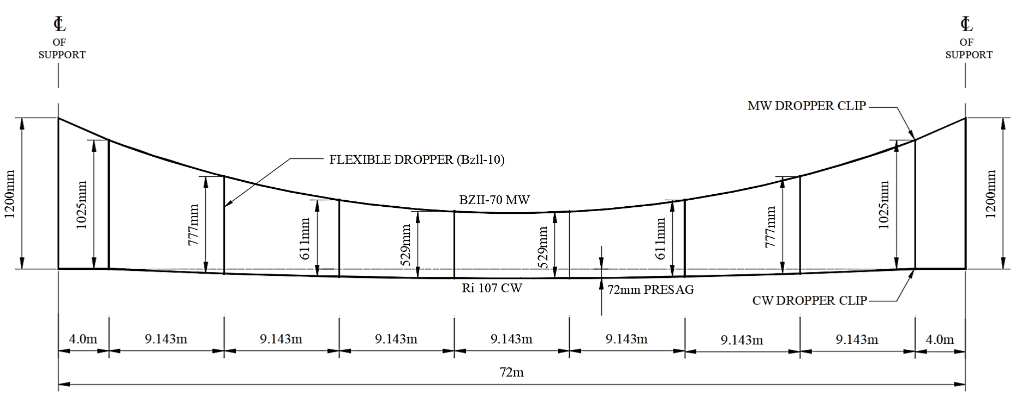


Fig. 8. Dropper arrangement for 72m span

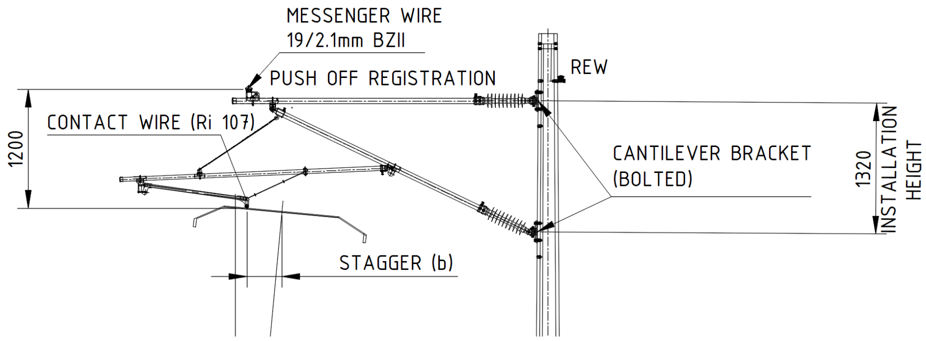


Fig. 9. 1200 mm system height using bolted bracket

Table 9 shows the dropper length for spans ranging from 76 m to 83 m at 1400 mm system height. The maximum span has been increased to 81m based on the minimum dropper length at mid-span. A 9m span increase over the standard 1200 mm system height. However, 1400 mm system height necessitates a change in cantilever bracket design due to the increased installation height.

Table 1
Dropper length calculation at 1400 mm system height

Span [m]	System Height [mm]		Dropper Length [mm] Dropper length is measured from the inside of upper thimble to the inside of lower thimble								
	Support 1	Support 2	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
83.0	1400	1400	1197	879	652	516	470	516	652	879	1197
82.0	1400	1400	1200	891	671	539	495	539	671	891	1200
81.0	1400	1400	1202	903	689	561	518	561	689	903	1202
80.0	1400	1400	1205	915	708	583	542	583	708	915	1205
79.0	1400	1400	1207	926	726	605	565	605	726	926	1207
78.0	1400	1400	1210	938	743	627	588	627	743	938	1210
77.0	1400	1400	1212	949	761	648	611	648	761	949	1212
76.0	1400	1400	1215	929	739	644	644	739	929	1215	

In contrast to the bolted design utilised in the standard installation height, a wraparound bracket is required to attach the cantilever to the OCS mast (see Figure 10 for wrap-around bracket arrangement). Another option is to redesign the standard OCS mast to include the extra ferrules for higher installation height. Both designs will incur additional costs for the OCS designer; therefore, the benefits of the additional 9m span must be researched to justify the cost. A higher contact and messenger wire tension would increase the dropper length at mid-span, thereby increasing the span limit. The researchers went on to investigate the effect of minimum dropper length at mid-span when catenary tension is increased to 14 kN.

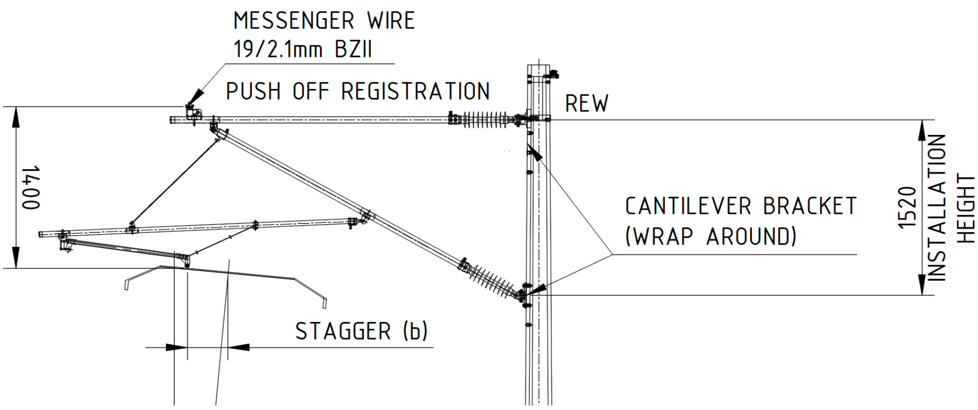


Fig. 10. 1400 mm system height using wrap-around bracket

Table 10 displays the dropper length for spans ranging from 79 to 83 metres at 1400 mm system height and 14 kN catenary tension. The maximum span has now been increased to 88 m. A 7-meter extension over the standard 1.2-kN catenary tension. Static calculations and bending tests, however, must be performed to ensure that the current OCS mast can withstand the increased tension force. In comparison to the next two factors, the OCS designer can easily manipulate the catenary sag limitation. Such limitation compensation would incur additional costs and would require the approval of the Superintendent Officer. As a result, the maximum span of 72 m and the minimum dropper length at midspan were retained in the study.

Table 10
Dropper length calculation at 1400 mm system height and 14 kN tension

Span [m]	System Height [mm]		Dropper Length [mm] Dropper length is measured from the inside of upper thimble to the inside of lower thimble									
	Support 1	Support 2	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
90.0	1400	1400	1211	916	695	547	473	473	547	695	916	1211
89.0	1400	1400	1213	926	711	567	495	495	567	711	926	1213
88.0	1400	1400	1216	936	727	587	517	517	587	727	936	1216
87.0	1400	1400	1218	946	743	607	539	539	607	743	946	1218
86.0	1400	1400	1220	927	719	594	552	594	719	927	1220	
85.0	1400	1400	1222	938	735	614	573	614	735	938	1222	
84.0	1400	1400	1224	948	752	634	594	634	752	948	1224	
83.0	1400	1400	1226	959	768	653	615	653	768	959	1226	

3.4 Maximum Span Length Based on Lateral Displacement of Contact Wire

The lateral displacement of contact wire caused by wind and track curvature is the second limiting factor for maximum span length. This is usually the most important parameter because the OCS designer has no control over it. The span length must be reduced in high wind areas and with high track curvature to ensure that the contact wire does not come off the pantograph head. As a result, the maximum span length can be found only at the tangent track with the lowest design wind speed because it produces the smallest lateral displacement of contact wire. Based on the wind speed assessment study from the previous section, the overall project's minimum design wind speed is determined to be 22 m/s. By plugging the minimum design wind speed into Eq. (2) and Eq. (3), the maximum span length based on lateral displacement can be calculated as shown below.

$$0.0000935156L^2V_{fcw}^2 + \frac{(460)\text{^}2}{16(0.0000935156L^2V_{fcw}^2)} = 400 \quad (2)$$

$$L_{max} = \frac{1971.92}{V_{fcw,min}} \quad (3)$$

$$L_{max} = \frac{1971.92}{22}$$

$$L_{max} = 89.63\ m$$

The maximum span length is rounded to 89 m because the span length is usually provided as an integer. The maximum span length obtained was then validated using Siemens Sicat Master software. Figure 11 and Figure 12 show the software outputs for span lengths of 89 and 90 metres, respectively. The blow-off wire has not passed the pantograph working range of 400 mm at any point, as shown in Figure 11.

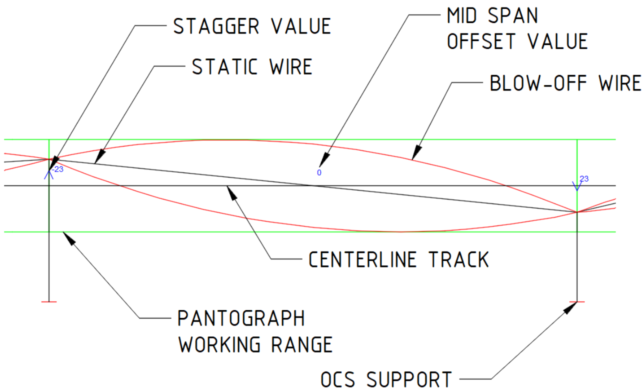


Fig. 11. Blow – off wire at 89 m span length and 22 m/s wind speed

However, when a span length of 90 m is used, as shown in Figure 12, the blow-off wire has at some point exceeded the pantograph's allowable working range.

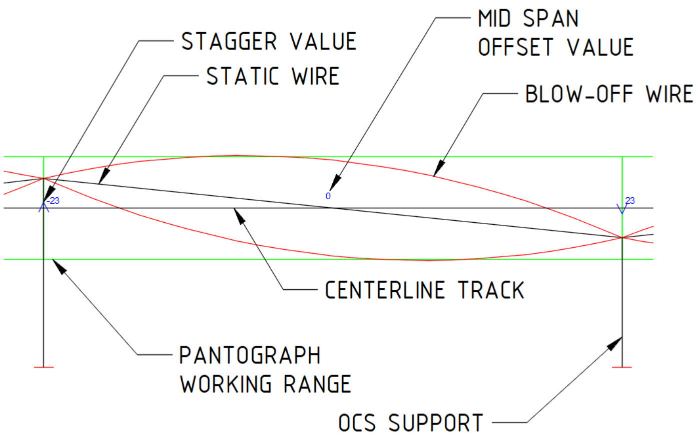


Fig. 12. Blow–off wire at 90 m span length and 22 m/s wind speed

As a result, it has been demonstrated that the previously calculated maximum span length is correct. The obtained value of 89 m is significantly greater than the maximum span length determined by the catenary sag. This means that this limitation factor has no effect on the maximum span length of this project. The limitation in using a longer span length for this project is catenary sag. Because it was discovered in the previous sub-section that the catenary sag can be compensated, the 89 m span length is said to be the potential maximum span length that can be obtained. The study then compared the effect of using this potential maximum span value with the maximum span length obtained for this project in terms of total support number. Table 11 shows a portion of the span and stagger chart for 22 m/s.

Table 11
Span and stagger chart for 22 m/s wind speed

R (m)	V (mm)	L (m)	S_1 (mm)	S_2 (mm)	B (mm)	SE (mm)	MSO (mm)	MSO + SE (mm)	MTO (mm)
Tangent	0	89	-230	230	359	37	0	41	396
20000.00	50	89	-230	130	359	23	0	41	382
10000.00	100	89	-230	30	359	12	0	41	371
7000.00	140	89	-230	-50	359	6	0	41	365
5000.00	200	89	-230	-170	359	1	0	41	360
4000.00	250	89	-350	-150	359	7	0	41	366
3500.00	280	89	-350	-210	359	3	0	41	362
3000.00	330	89	-350	-310	359	0	0	41	359
2700.00	370	89	-350	-350	359	0	20	41	379
2400.00	390	87	-350	-350	343	0	40	57	383
2000.00	430	83	-350	-350	312	0	80	88	392
1800.00	440	80	-350	-350	290	0	90	110	380
1600.00	460	77	-350	-350	268	0	110	132	378

The best fit curve has been plotted as the structure spacing chart in Figure 13 based on the span and stagger chart. The structure spacing chart displays the line equations for each design wind speed band.

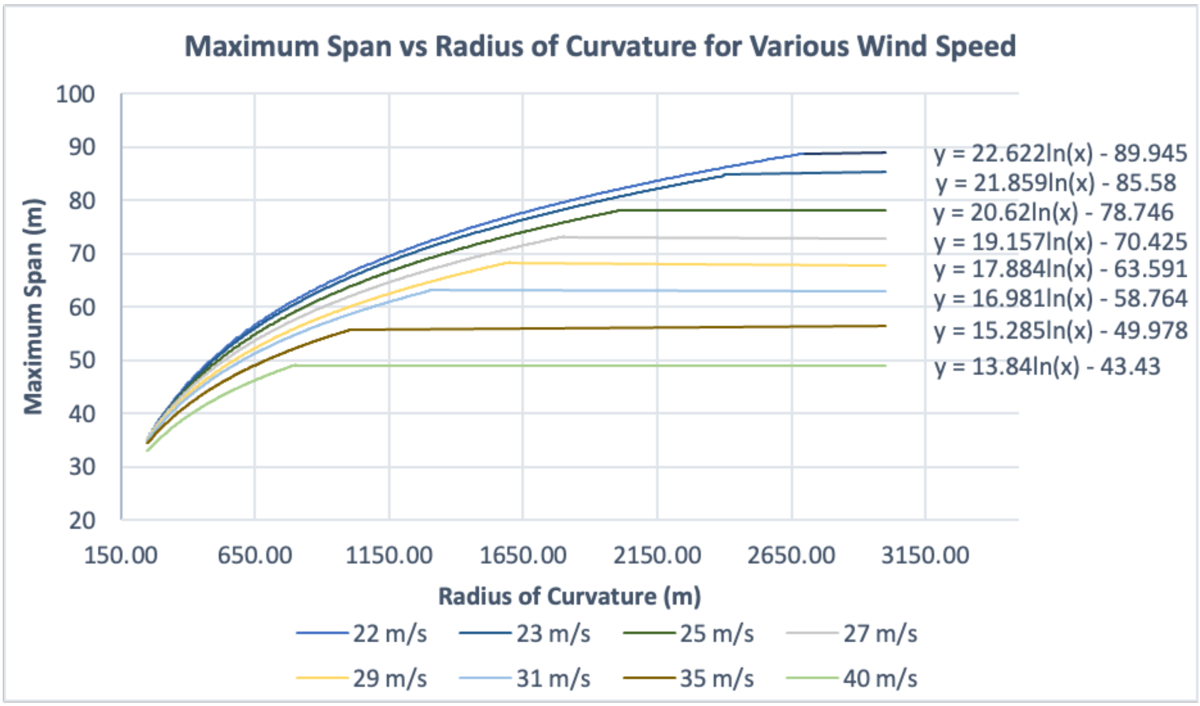


Fig. 13. Structure spacing chart

Finally, Table 12 summarises the line equation in terms of track radius for each design wind speed.

Table 12
Summary of span length based on wind blow-off

Wind speed, m/s	Line equation in span and stagger chart	Max. span length (m)
22	L = 22.622ln(R) - 89.945	89
23	L = 21.859ln(R) - 85.58	85
25	L = 20.62ln(R) - 78.746	78
27	L = 19.157ln(R) - 70.425	73
29	L = 17.884ln(R) - 63.591	68
31	L = 16.981ln(R) - 58.764	63
35	L = 15.285ln(R) - 49.978	56
40	L = 13.444ln(R) - 40.849	49

3.5 Simulation Summary

It can be concluded that the sag of catenary wire and its minimum dropper length at mid-span are the limiting factors of maximum span length for GJBEDTP. Table 13 summarises the results for all three limiting factors in this project's maximum span length.

Table 13
Maximum span length summary for three limitation factors

No.	Span length limitation factors:	Maximum span length obtained
1	The sag of the catenary wire, given a maximum system height of 1200 mm and a minimum dropper length of 500 mm at mid-span	72 m
2	The dynamic behaviour of the OCS equipment when disturbed by passing pantographs according to EN50119.	72 m
3	The lateral displacement of the contact wire by wind (blow-off). MTO ≤ 400 mm	89 m
Final maximum permissible span length for GJBEDTP:		**72 m**

Table 14 modifies the maximum span length in Table 11. Finally, the structure spacing chart is adjusted to show the maximum span value of 72 m.

Table 14
Maximum span length after adjustment

Wind speed, m/s	Line equation in span and stagger chart	Max. span length (m)
22	L = 22.622ln(R) - 89.945	**72**
23	L = 21.859ln(R) - 85.58	**72**
25	L = 20.62ln(R) - 78.746	**72**
27	L = 19.157ln(R) - 70.425	**72**
29	L = 17.884ln(R) - 63.591	68
31	L = 16.981ln(R) - 58.764	63
35	L = 15.285ln(R) - 49.978	56
40	L = 13.444ln(R) - 40.849	49

3.6 Estimated Cost Savings

Based on the findings of this study, the maximum span length for the Gemas-Johor Bahru Double Track Project is 72 m. The price is $12 million higher than the previous Skypark, Ipoh-Padang Besar

Electrified Double Track Project, and Seremban-Gemas Electrified Double Track Project. The additional 12 m allowable span length increased the overall project's average span length, reducing the total number of supports used. When compared to the maximum span length used in the previous project, the cost savings percentage is approximately 13.11%. Further investigation reveals that increasing the maximum span length to 89 m increased the overall project's average span length even more. However, the cost savings from the additional 17 m span length are not as significant as the cost savings from going from 60 m to 72 m spans. The cost savings increased by only 5.34% when the span length was increased from 60 to 72 metres. Table 15 contains a summary of the findings. As a result, when choosing a longer span length, care must be taken. To weigh the total benefits and costs, a cost-benefit analysis must be performed. A longer span length will incur additional costs due to a change in OCS design.

Table 15
Comparison table based on different maximum span length values

Design	Maximum span length	Average span length obtained	Total number of supports	Cost savings (material & installation)
Previous Project Design	60 m	59.7 m	3210	Baseline
Current Design	72 m	68.7 m	2789	13.11 %
Potential Design	89 m	73.2 m	2617	18.45 %

Figure 14 depicts a graph of the percentage of cost savings versus the maximum allowable span length. A linear trend line is drawn based on the graph's logarithmic curve. The elbow, which is the point with the greatest distance to the trend line, is determined to have a maximum allowable span of 72 m. As a result, it is possible to conclude that 72 m is the ideal span for GJBEDTP.

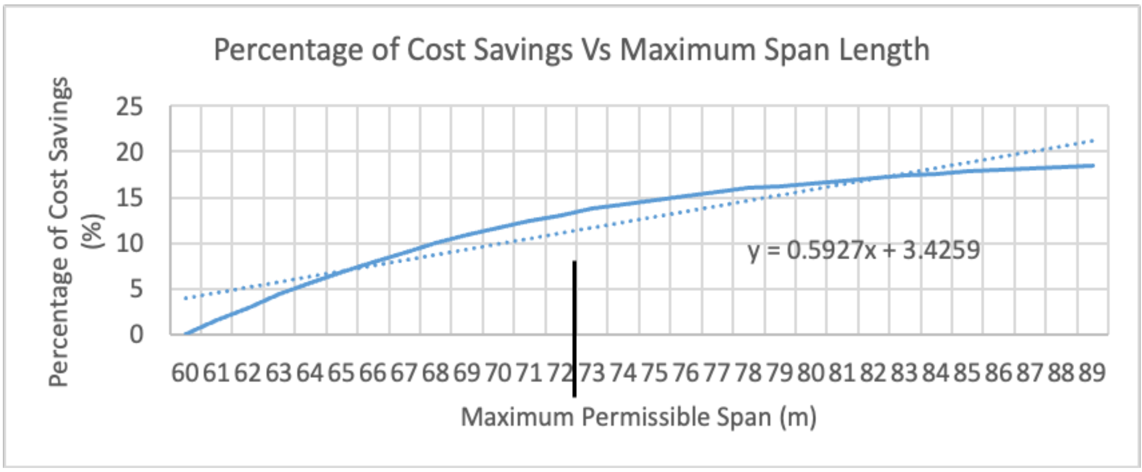


Fig. 14. Graph of percentage of cost savings vs maximum span length

4. Conclusions

The study aims to determine the maximum and optimum span length for the Johor Bahru Electrified Double Track Project's overhead catenary system design. The mathematical formula, as well as the Sicat Master and Sicat Dynamic software, are thought to be accurate in determining maximum span length across the entire track length. Furthermore, the Elbow method is an excellent tool for determining the optimum permissible span length for GJBEDTP, thereby reducing unnecessary upgrade costs. The optimum span length for GJBEDTP is discovered to be the same as the maximum span length determined for GJBEDTP. This is not always the case with other projects because it is entirely dependent on the geographical characteristics and track design. As a result, determining the maximum and optimum span length is critical in every electrification project to ensure a safe and cost-effective design of the OCS.

4.1 Research Achievement

This study identified the span length limitation in overhead catenary system design and used it to calculate the maximum span length for the GJBEDTP, which is 72 m. The cost savings percentage is then calculated based on the maximum span length. The optimum span for GJBEDTP is also 72 m, based on the percentage cost savings vs maximum span length graph. One of the most important aspects of OCS design is determining the maximum span length. The following are the findings' advantages:

i. Ensured safe and efficient current collection between the 25kV OCS wire and the train's pantograph per client specifications and international standards.
ii. Design and construction time is reduced because the placement of supporting structures along the track is easily determined.
iii. In terms of management, the total number of supporting structures is useful for estimating the overall system cost.
iv. The optimal span length will further optimise project costs by avoiding unnecessary expenses and increasing profit.

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