

# Design optimisation of railway pantograph- catenary systems

Presenter: Mr. Hanlei Wang (PhD student)

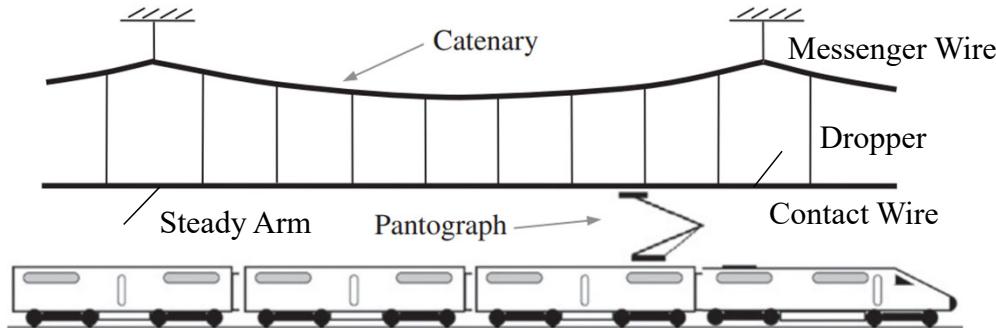
Main Supervisor: Prof. Wenyi Yan

Department of Mechanical & Aerospace Engineering, Monash University

Associate Supervisors: Dr. Dingyang Zheng, Dr. Ryan Huang  
Institute of Railway Technology



# Introduction



**Contact Wire:** Carry electric energy

**Messenger Wire, Droppers and Steady Arms :** Support the contact wire

**Pantograph:** Transport electric energy

• [1] Ning Zhou, Weihua Zhang, Investigation on dynamic performance and parameter optimization design of pantograph and catenary system, Finite Elements in Analysis and Design 47 (2011) 288-295.

# Introduction

*High Contact Force [1]*



*Low Contact Force [2]*



- [1] SD. Dynamic Simulation of the Pantograph/Catenary Interaction. [https://www.sdttools.com/consulting/u\\_sncf\\_oscar.html](https://www.sdttools.com/consulting/u_sncf_oscar.html).
- [2] Luo Y, Yang Q, & Liu S. Novel Vision-Based Abnormal Behavior Localization of Pantograph-Catenary for High-Speed Trains. IEEE Access. 2019;7.

# Literature Review

Title	Author (Year)	Contribution	Limitations
An approach to geometric optimisation of railway catenaries [1]	Gregori S, et al. (2018)	Used genetic algorithm to optimise catenary system.	1. Only optimised the droppers. 2. Only minimised standard deviation.
Optimisation of current collection quality of highspeed pantograph-catenary system using the combination of artificial neural network and genetic algorithm [2]	Su K, et al. (2022)	Combined genetic algorithm and machine learning.	1. Only optimised one parameter at a time. 2. Only minimised standard deviation.
Optimisation of high-speed railway pantographs for improving pantograph-catenary contact [3]	Ambrosio J, et al. (2013)	Optimised the pantograph by genetic algorithm and sequential quadratic programming.	1. Only optimised the pantograph. 2. Only minimised standard deviation.

- [1] Gregori S, Tur M, Nadal E, Fuenmayor F.J. An approach to geometric optimisation of railway catenaries. *Veh Syst Dyn.* 2018;56(8):1162–1186.
- [2] Su K, Zhang J, Zhang J, Yan T, Mei G. Optimisation of current collection quality of highspeed pantograph-catenary system using the combination of artificial neural network and genetic algorithm. *Veh Syst Dyn.* 2022.
- [3] Ambrosio J, Pombo J, Pereira M. Optimization of high-speed railway pantographs for improving pantograph-catenary contact. *Theoretical & Applied Mechanics Letters.* 2013;3(013006)

# Literature Review

## Gaps

- The optimisation parameters of previous optimisation studies were not comprehensive.
- Previous optimisation studies did not control the mean contact force in an accurate way.

## Objective

- Developing an optimisation method to minimise the mean contact force difference and the standard deviation.

# Optimisation Problem

Optimisation multi-objectives



- Minimising the mean contact force difference  
$$F_d = |F_m - F_{ideal}|$$
- Minimising the sample standard deviation of contact force  
$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (F_i - F_m)^2}$$

Where:  $F_m$  is the mean contact force, i.e.,  $\text{mean}(F_i)$

$F_{ideal}$  is the ideal mean contact force

N is the number of sampling points.

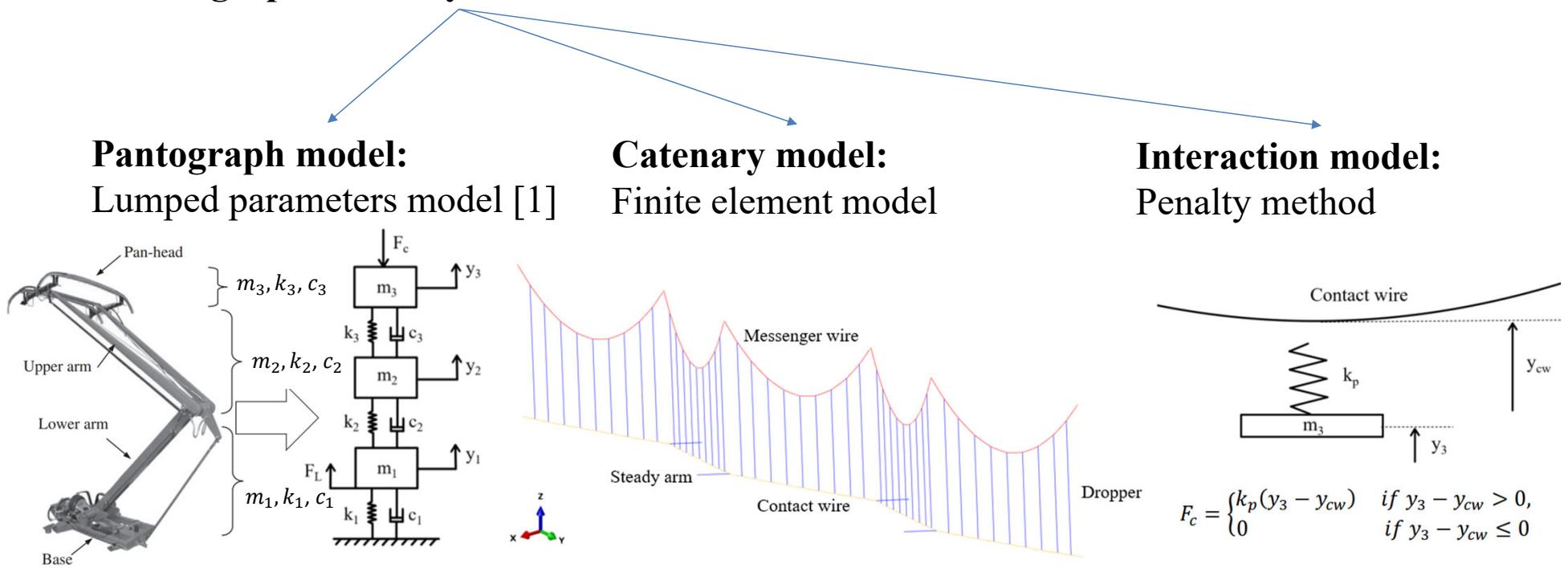
$F_i$  is the contact force of i-th sampling point.

Constraints in EN50367


$$\begin{cases} F_m < (0.00228v^2 + 90)N \\ F_m > (0.00112v^2 + 70)N \\ \sigma_{max} < 0.3F_m \\ F_{max} < 350N \\ F_{min} > 0N \\ d_{up} \leq 120mm \end{cases}$$

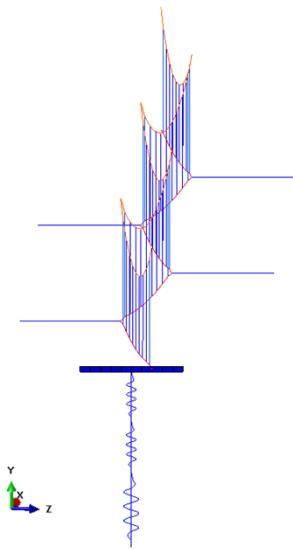
# Numerical Model

## 1. Pantograph-catenary interaction model

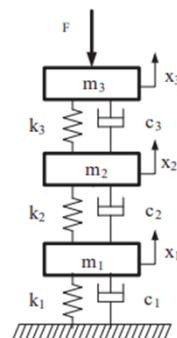
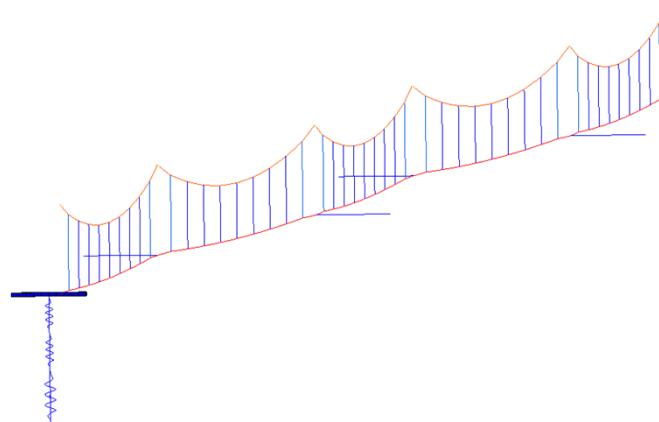


• [1] Ning Zhou, Weihua Zhang, Investigation on dynamic performance and parameter optimization design of pantograph and catenary system, Finite Elements in Analysis and Design 47 (2011) 288-295.

# Numerical Model



Span length: 55 m  
 Encumbrance: 1.2 m  
 Pre-sag at mid-span,  $h_c$ : 55 mm  
 Stagger:  $\pm 200$  mm



$m_1$	6.0 kg
$m_2$	9.0 kg
$m_3$	7.5 kg
$c_1$	100 Ns/m
$c_2$	0.1 Ns/m
$c_3$	45.0 Ns/m
$k_1$	160.0 N/m
$k_2$	15500.0 N/m
$k_3$	7000.0 N/m

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$c_3$	45.0 Ns/m
$k_1$	160.0 N/m
$k_2$	15500.0 N/m
$k_3$	7000.0 N/m

C270 catenary

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Section, $A_c$ :	150 mm <sup>2</sup>
Mass/unit length, $m_c$ :	1.35 kg/m
Tension, $S_c$ :	22 kN
Young's module, $E_c$ :	1.0 E11 N/m <sup>2</sup>
Bending stiffness, $E_c J_c$ :	195.0 N m <sup>2</sup>

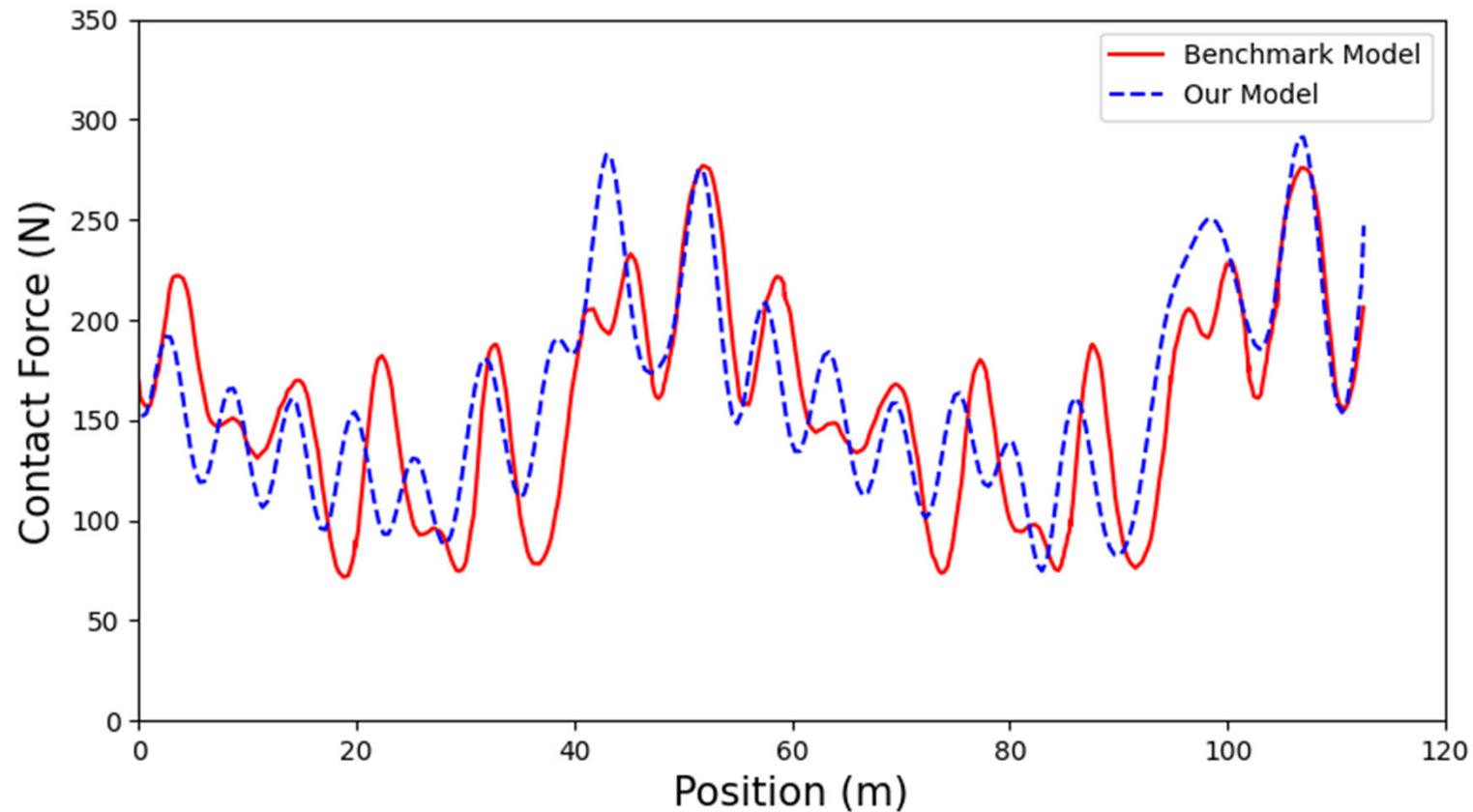
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Section, $A_m$ :	120 mm <sup>2</sup>
Mass/unit length, $m_m$ :	1.08 kg/m
Tension, $S_m$ :	16 kN
Young's module, $E_m$ :	0.97 E11 N/m <sup>2</sup>
Bending stiffness, $E_m J_m$ :	131.7 N m <sup>2</sup>

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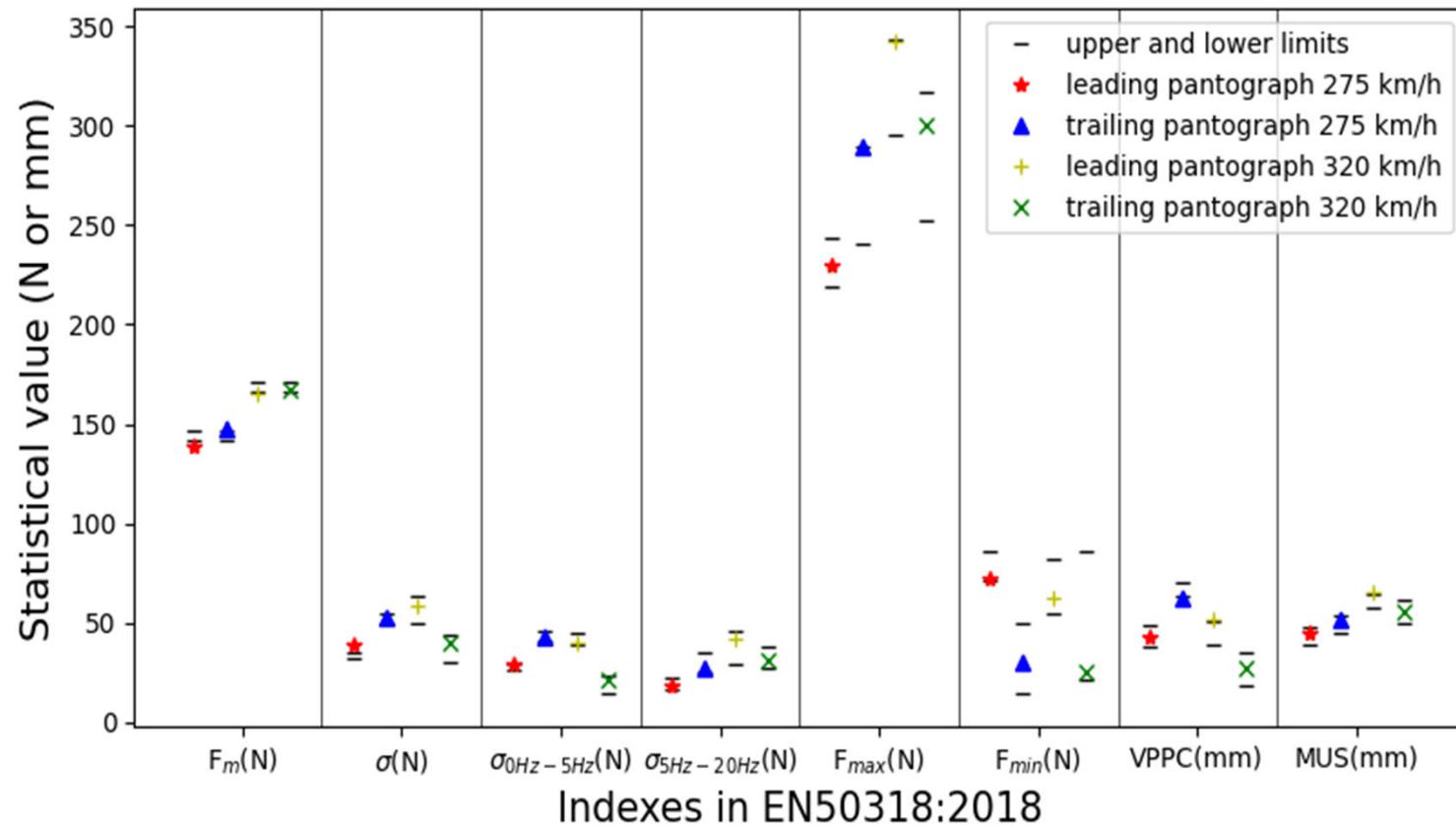
Mass per unit length,  $m_d$ : 0.117 kg/m  
 Axial stiffness parameter, EA: 200 kN

# Verification – Benchmark [1]



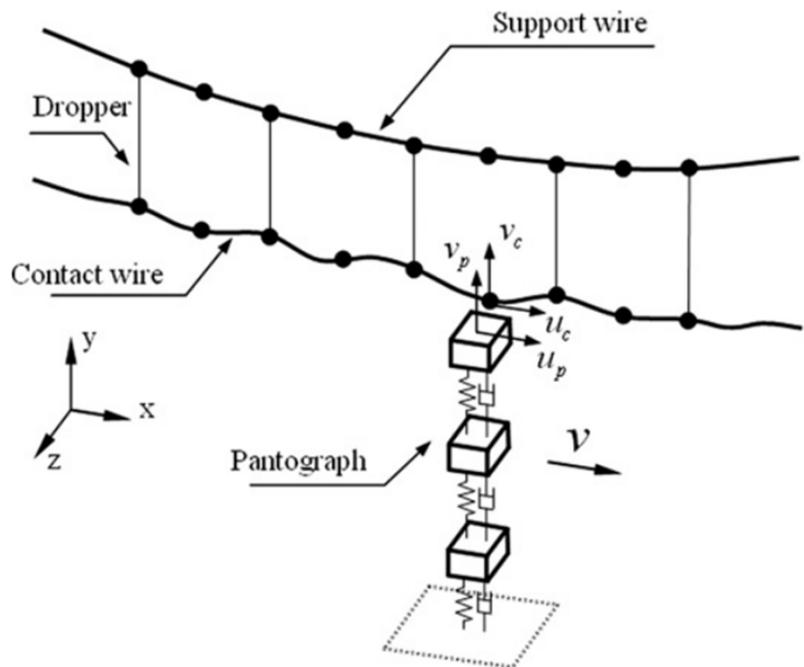
- [1]Bruni S, Ambrosio J, Carnicer A, et al. The results of the pantograph–catenary interaction benchmark. *Veh Syst Dyn*. 2015;53(3):412–435.

# Verification – EN 50318: 2018 [1]



[1] EN 50318. Railway applications. Current collection systems. Validation of simulation of the dynamic interaction between pantograph and overhead contact line. European Committee for Electrotechnical Standardization; 2018.

# Optimisation Parameters



## Optimisation parameters (22)

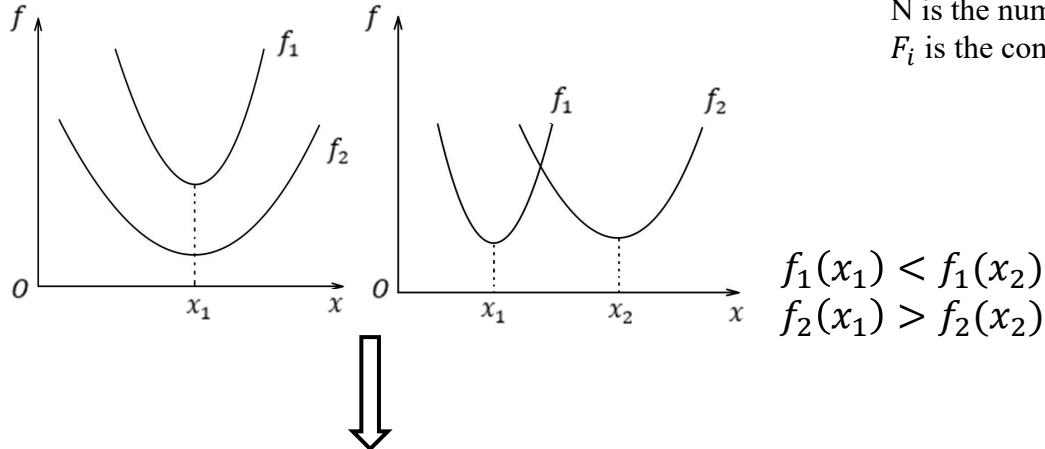
- 1: The droppers' lengths (5)
- 2: The spacing between each two droppers (5)
- 3: The tension force of contact wire
- 4: The tension force of messenger wire
- 5: The lifting force of the pantograph
- 6: The structure of pantograph (9)

# Optimisation Problem

Optimisation multi-objectives



Solve Pareto optimal solutions



- Minimising the mean contact force difference

$$F_d = |F_m - F_{standard}|$$

- Minimising the sample standard deviation of contact force

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (F_i - F_m)^2}$$

Where:  $F_m$  is the mean contact force, i.e.,  $\text{mean}(F_i)$

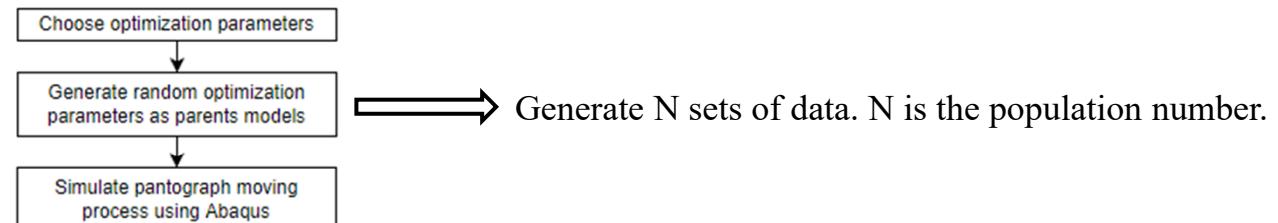
$F_{standard}$  is the ideal mean contact force

N is the number of sampling points.

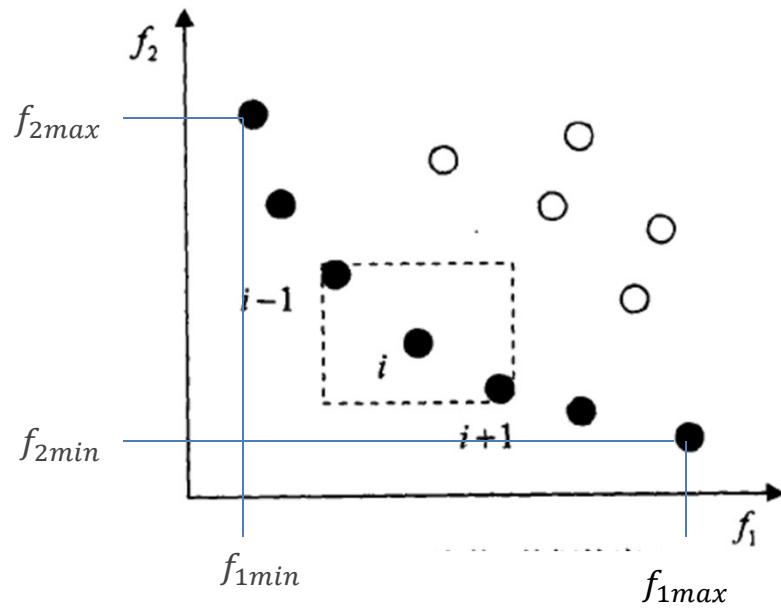
$F_i$  is the contact force of i-th sampling point.

Non-dominated sorting genetic algorithm-II (NSGA-II)

# Optimisation Method

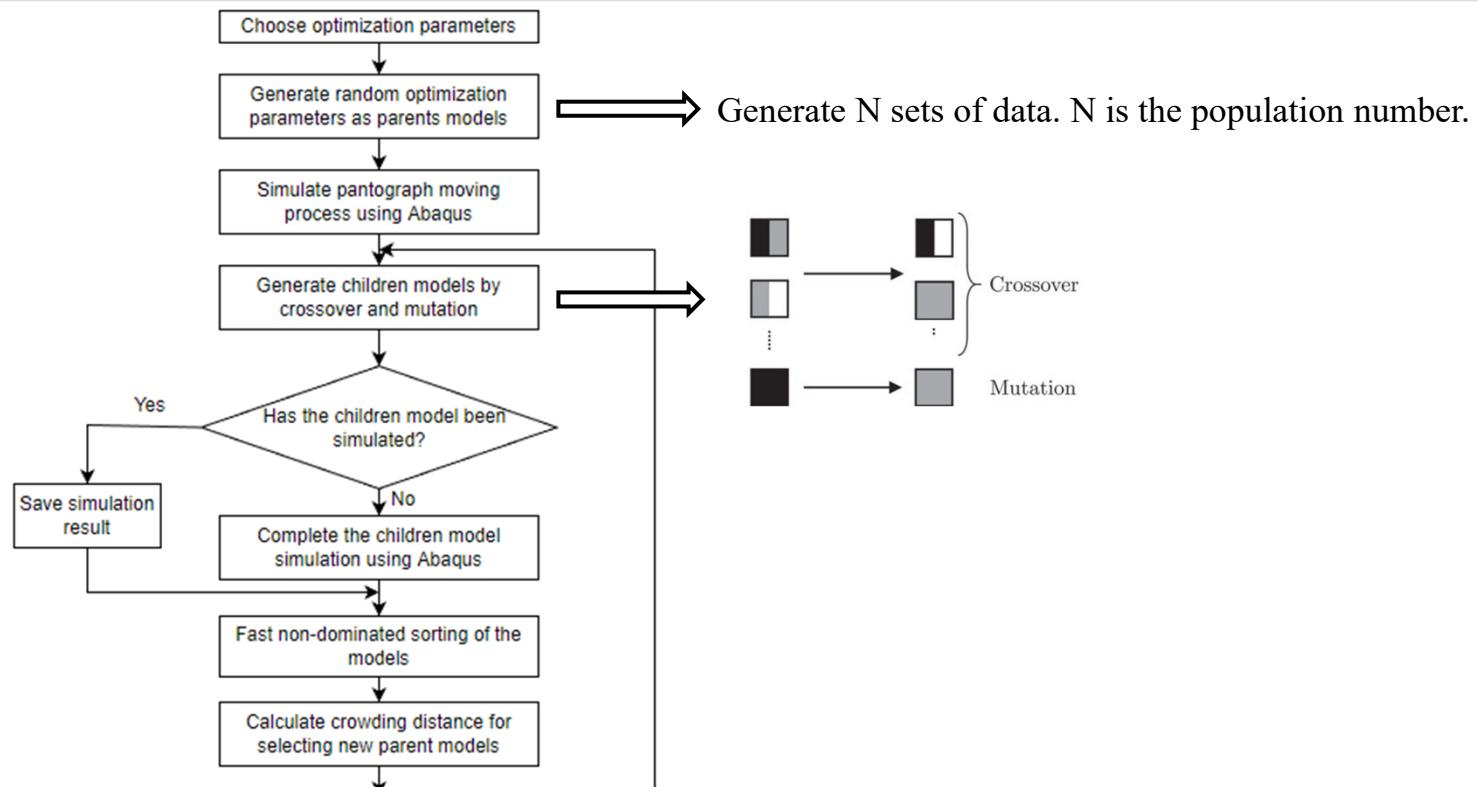


## Fast Non-dominated Sorting and Crowding Distance

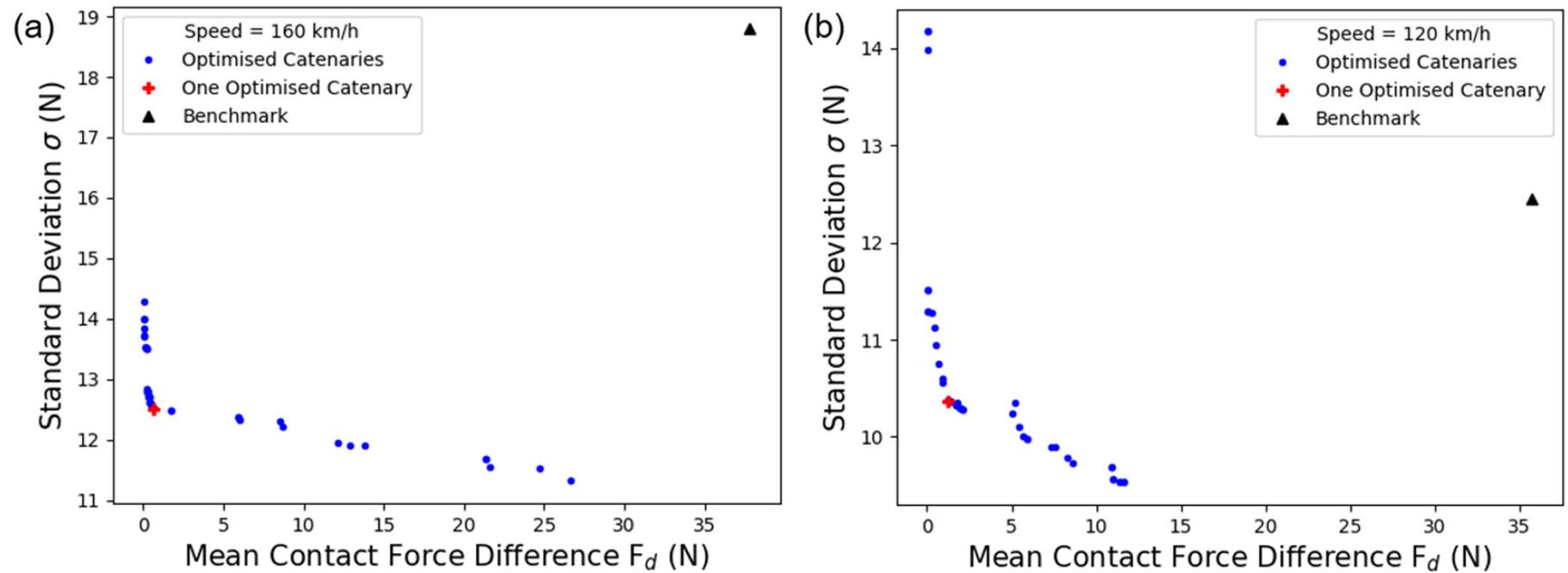


$$\text{Crowding distance} = \frac{f_1(i+1) - f_1(i-1)}{f_{1max} - f_{1min}} + \frac{f_2(i+1) - f_2(i-1)}{f_{2max} - f_{2min}}$$

# Optimisation Method

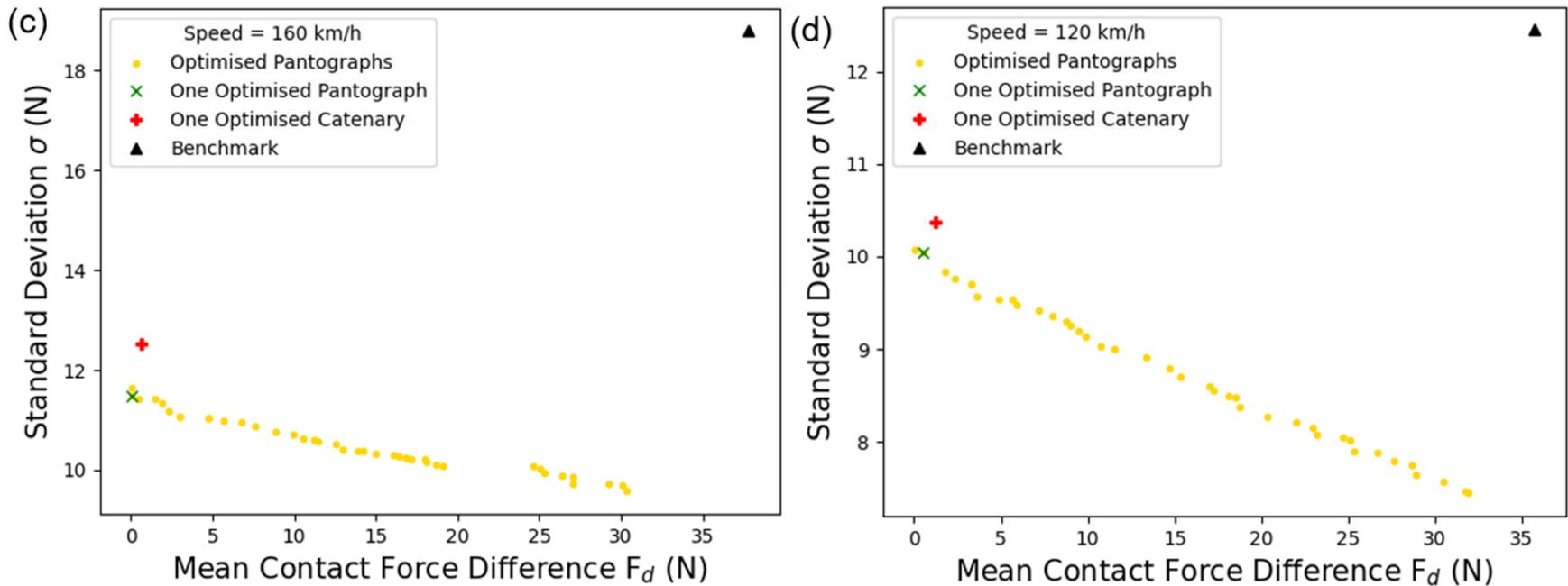


# Optimisation Results - Catenary



Running speed (km/h)	Benchmark structure		Representative of optimization results (red point)		Reduction Compared with Benchmark	
	$F_{dB}$ (N)	$\sigma_B$ (N)	$F_{dO}$ (N)	$\sigma_O$ (N)	$F_{dB_r}$	$\sigma_{Br}$
160	37.84	18.79	0.65	12.52	98.3%	33.4%
120	35.74	12.45	1.23	10.37	96.6%	16.5%

# Optimisation Results - Pantograph



Running speed (km/h)	Benchmark structure		Representative of optimization results (red point)		Reduction Compared with Benchmark		Reduction Compared with optimized catenary results	
	$F_{dB}$ (N)	$\sigma_B$ (N)	$F_{dO}$ (N)	$\sigma_O$ (N)	$F_{dB_r}$	$\sigma_{Br}$	$F_{dOr}$	$\sigma_{Or}$
160	37.84	18.79	0.02	11.47	99.9%	39.0%	96.9%	8.4%
120	35.74	12.45	0.51	10.04	98.6%	19.4%	58.5%	3.2%

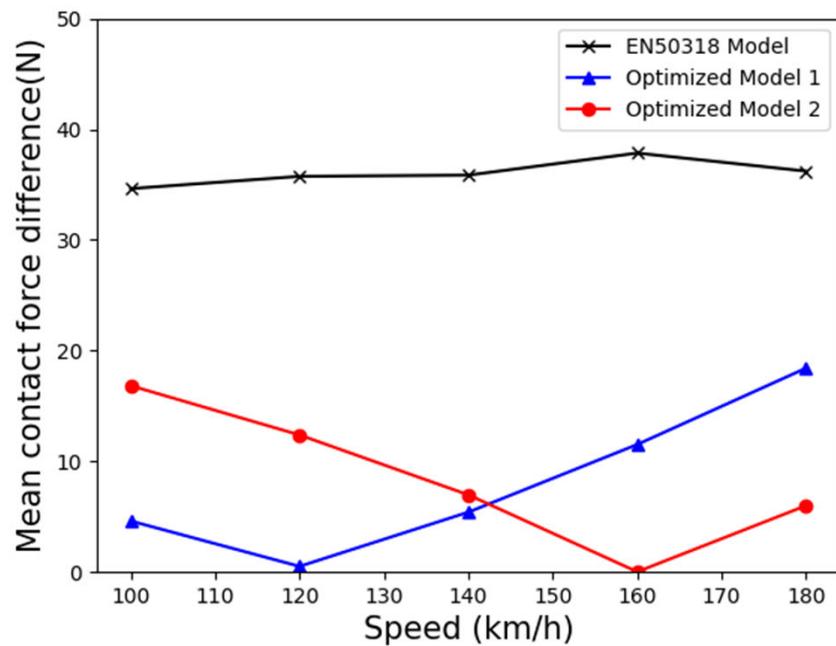
# Comparison of the optimisation parameters

Model	Optimised model at 160 km/h	Optimised model at 120 km/h	Benchmark Model
Dropper lengths d1 d2 d3 d4 d5 (m)	1.006, 0.867, 0.839, 0.824, 0.829	1.007, 0.869, 0.763, 0.697, 0.655	1.017, 0.896, 0.81, 0.758, 0.741
Dropper spacings L1 L2 L3 L4 L5 (m)	7.07, 6.618, 6.271, 5.384, 2.158	6.118, 4.686, 5.596, 4.034, 7.066	4.5, 5.75, 5.75, 5.75, 5.75
Contact wire tension force (N)	33201.4	32106.5	22000
Messenger wire tension force (N)	14010.3	12963.1	16000
Pantograph uplift force (N)	157.3	147.6	131.752/120.048

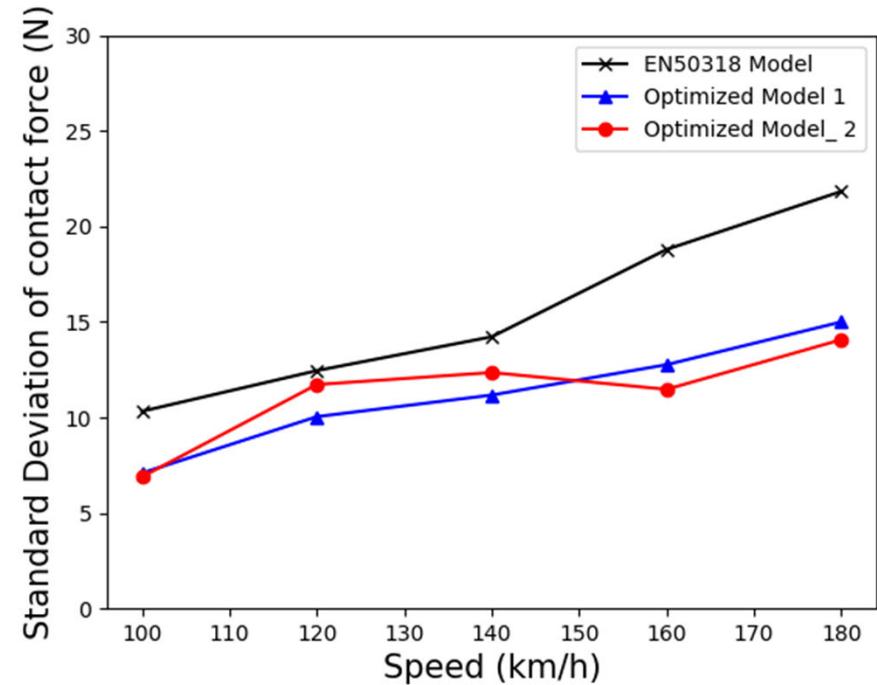
Model	Optimised model at 160 km/h	Optimised model at 120 km/h	Benchmark Model
Mass parameters m1 m2 m3 (kg)	3.0, 4.2, 3.0	6.4, 9.1, 4.5	6.0, 9.0, 7.5
Damping ratio parameters c1 c2 c3 (Ns/m)	89.8, 0.3, 44.8	109.4, 0.6, 63.8	100.0, 0.1, 45.0
Stiffness parameters k1 k2 k3 (N/m)	100.1, 7580.6, 7475.1	133.0, 5674.5, 4204.3	160.0, 15500.0, 7000.0
Pantograph uplift force (N)	148.7	146.7	131.752/120.048

# Performance of optimised structures at different speeds

*The Mean Contact Force at Different Speeds*



*The Standard Deviation of Contact Force at Different Speeds*



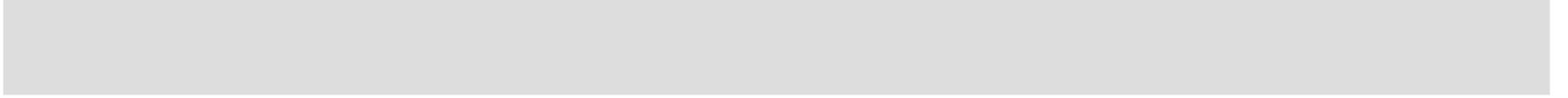
Optimised model 1 represents the structure optimised at 120 km/h

Optimised model 2 represents the structure optimised at 160 km/h

# Conclusions

- Optimisations of catenaries and pantographs were performed via the NSGA-II algorithm.
- The NSGA-II algorithm was improved by avoiding the repetition of FEM simulations and retaining only one of the duplicated results for the next generation selection.
- The mean contact force difference and the standard deviation of the contact force can be significantly minimised.
- The optimised structures performed better under the train speed between 100 km/h and 180 km/h.

Title	Year	Journal
<b>Design optimisation of railway pantograph-catenary systems with multiple objectives</b>	2022	Vehicle System Dynamics



# Part 2

# Literature Review

Class of Locomotive and Permitted Speeds (km/h) [1]

			CLASS OF LOCOMOTIVE			
			G, XR, BL	A, B, GM, N, S, X	H, P, T	Sprinter/ Vlocity
WERRIBEE and NORTH SHORE -66.513km	Freight	80	80	80	..	
	Pass	80	115	100	130	
NORTH SHORE – 66.513km and GEELONG – 72.190km	Freight	80	80	80	..	
	Pass	80	115	100	115	
GEELONG – 72.190km and GEELONG - 72.655km	Freight	70	70	70	..	
	Pass	70	70	70	70	
GEELONG – 72.655km and SOUTH GEELONG – 74.844km Except over Bridge at 74.080km (Between Geelong and South Geelong)	Freight	65	65	65	..	
	Pass	65	65	65	65	
	All Trains	15	65	65	65	
SOUTH GEELONG – 74.844km and WAURN PONDS - 87.238km	Freight	65	70	70	..	
	Pass	65	115	100	115	
WAURN PONDS – 87.238km and WARRNAMBOOL Platform	Freight	80	80	80	..	
	Pass	..	115	100	..	
Except for Up trains approaching Queen St. PCR at Colac (Between 153.300km and 152.895km)	All Trains	70	70	70	..	
Except for all Trains between Cressy Road PCR and Church St PCR at Camperdown (Between 198.129km 198.808km)	All Trains	65	65	65		
Except over Bridge at 263.856km (Between Terang and Warrnambool)	All Trains	65	65	65	..	
WARRNAMBOOL Platform and WESTVIC SIDING	Freight	15	25	25	..	

• [1] NA\_NSP\_02.01 – R06-2015. Train Operating Data. Vline; 2015.

# Literature Review

## Gaps

- The optimisation parameters of previous optimisation studies were not comprehensive.
- Previous optimisation studies did not optimise the catenary structure at different speeds.

## Objective

- Developing an optimisation method to optimise the catenary structure at different speeds

# Optimisation Problem

Optimisation objective:

- Minimising the sample standard deviation of contact force

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (F_i - F_m)^2}$$

Where:  $F_m$  is the mean contact force, i.e.,  $\text{mean}(F_i)$

$F_{standard}$  is the ideal mean contact force

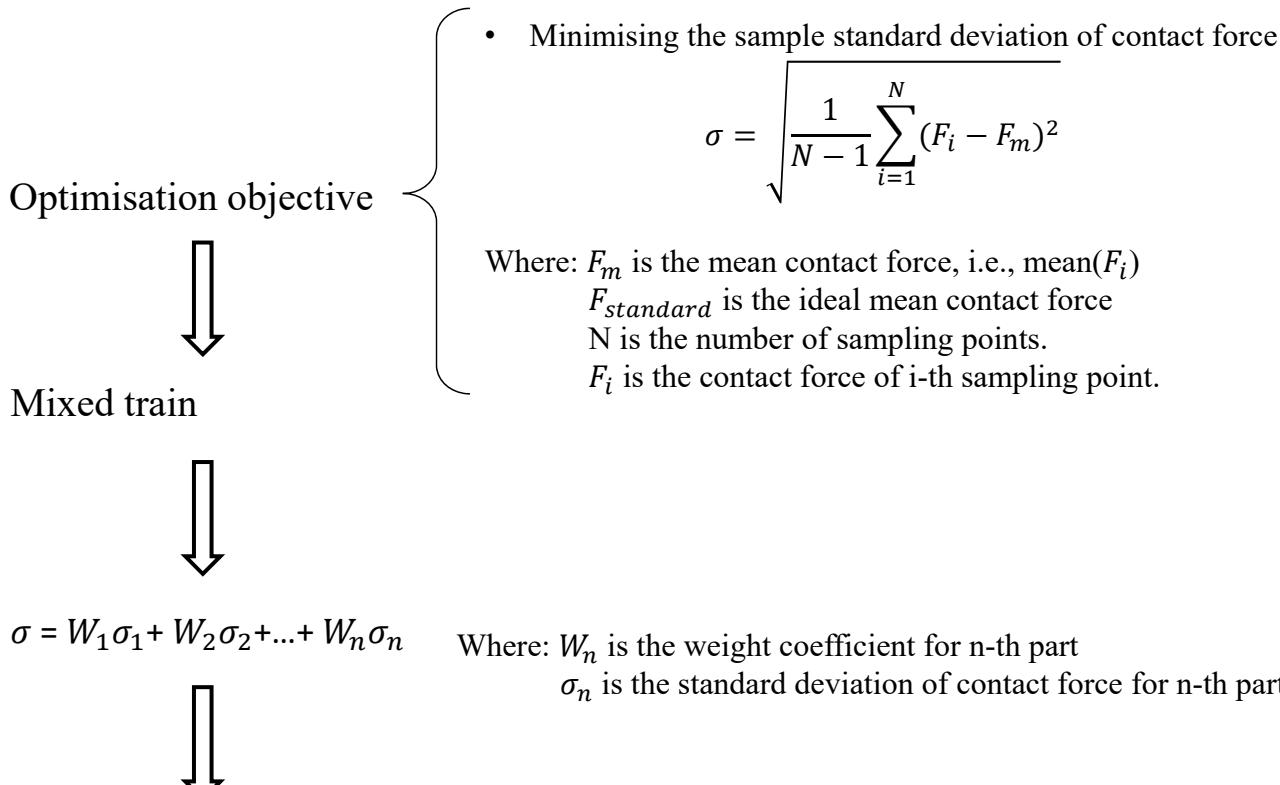
N is the number of sampling points.

$F_i$  is the contact force of i-th sampling point.

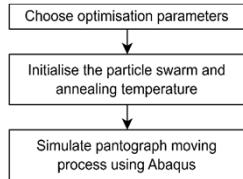
Constraints in EN50367

$$\left\{ \begin{array}{l} F_m < (0.00228v^2 + 90)N \\ F_m > (0.00112v^2 + 70)N \\ \sigma_{max} < 0.3F_m \\ F_{max} < 350N \\ F_{min} > 0N \\ d_{up} \leq 120mm \end{array} \right.$$

# Optimisation Problem



# Optimisation Method



Generate several sets of  $u$ .  $u \in (0,1)$   
 $x = x_{min} + u(x_{max} - x_{min})$

$$\Rightarrow v_i = \underbrace{w \times v_i}_{\text{previous velocity}} + \underbrace{c_1 \times \text{rand}() \times (lbest_i - x_i)}_{\text{local best position}} + \underbrace{c_2 \times \text{rand}() \times (gbest_i - x_i)}_{\text{global best position}}$$

$$u_{i,new} = u_i + v_i$$

$$\Rightarrow \text{Better results: accept} \quad \text{Worse results: } P = \min \left[ 1, \exp \left( \frac{-\Delta C}{K_B T} \right) \right]$$

Constraints in EN50367

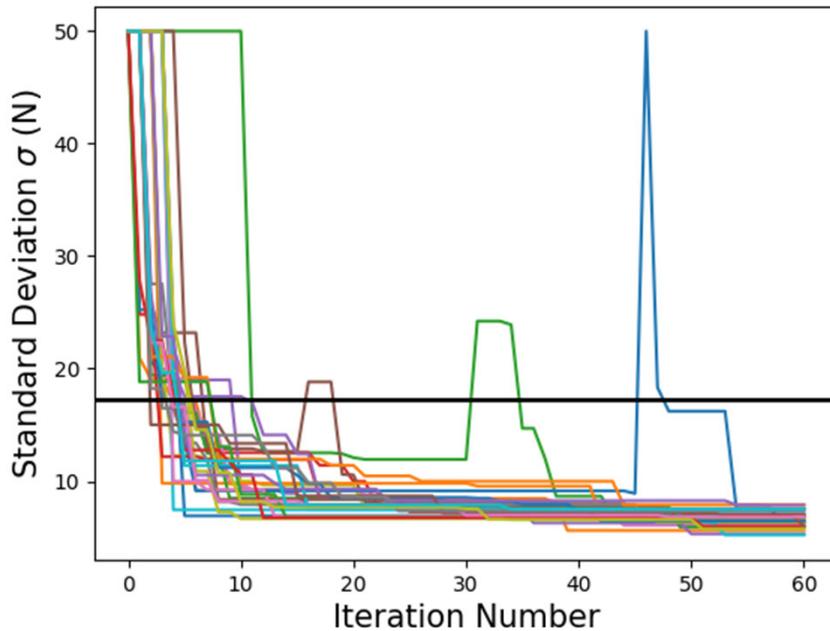
$$\begin{cases} F_m < (0.00228v^2 + 90)N \\ F_m > (0.00112v^2 + 70)N \\ \sigma_{max} < 0.3F_m \\ F_{max} < 350N \\ F_{min} > 0N \\ d_{up} \leq 120mm \end{cases}$$

# Optimisation Results

Speed 1: 160 km/h

Speed 2: 80 km/h

$$\sigma = 0.5\sigma_{160} + 0.5\sigma_{80}$$



Standard Deviation of Current Best Individual (N)	Standard Deviation of Benchmark Model (N)	Reduction compared with optimised model
5.22	17.31	69.8%

# Conclusions

- Optimisation of catenaries was performed via the PSSA algorithm.
- The PSSA algorithm was improved by avoiding the repetition of FEM simulations and deleting the model with the worst performance after each lowering the simulated annealing temperature.
- The standard deviation of the contact force can be significantly minimised, thereby improving the current collection quality, and reducing the contact wear.
- The PSSA method is proved to be applicable to the optimisation of railway catenary systems.

## Q&A

Thank you!