A Review on High Speed Railway Maintenance Studies

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Outline

- About Chinese HSR and the Availability
- Research Questions
- Research Team
- Review on the HSR maintenance studies

About Chinese HSR and the Availability

Development of Chinese HSR

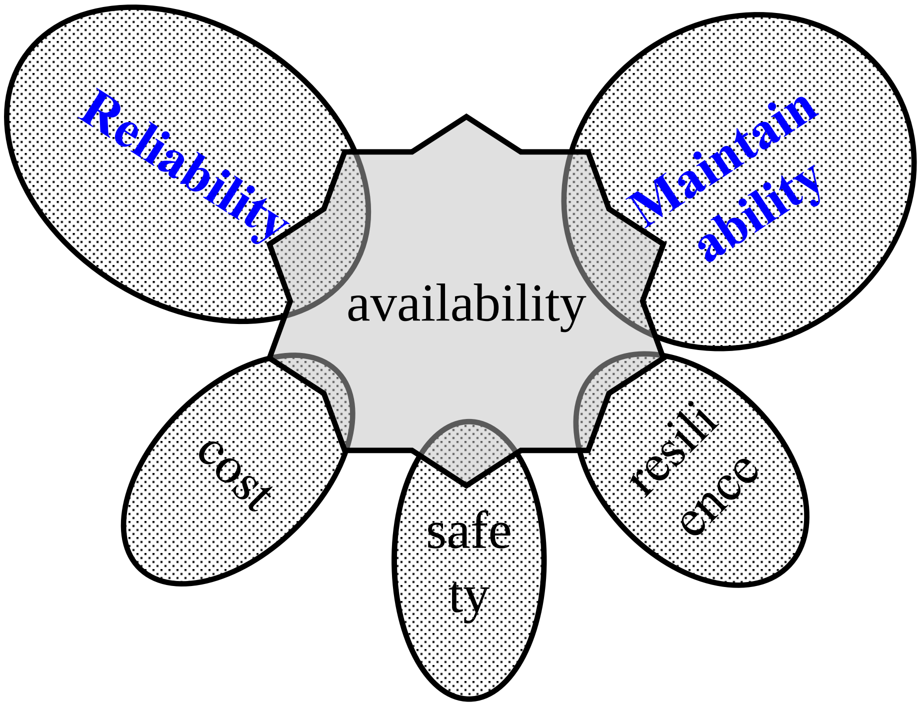
- Over 20,000 kms operation length by 2016
- ‘8 vertical and 8 horizontal’ backbone network
- 3 generations of trains: import → independent R&D → standardization
  - The 3rd generation ‘Fuxing Hao (Rejuvenation)’ can achieve the operation speed at 400 kms/hr

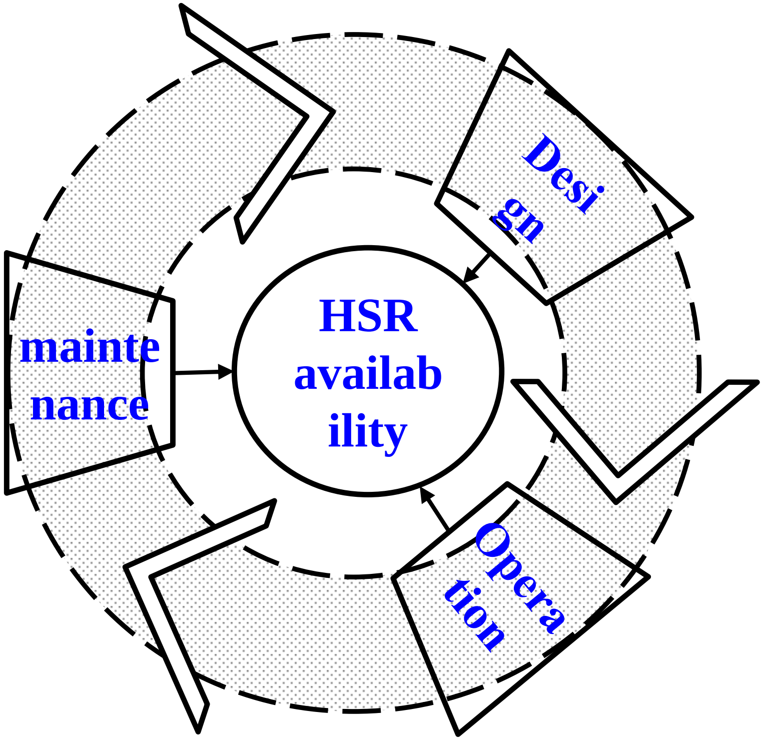
World-wide HSR Accidents

Country	Time	# Casualties	# Injuries	Reason
France	2014. 7.17	0	44	Collision
	2015.11.14	11	42	Derail
Japan	2005.12.25	4	33	Derail, by strong wind
	2011.7.12	0	0	Signaling defect
	2011.7.13	1	0	Hit human
Turkey	2004.7.22	41	80	Derail
Germany	1998.6.3	39	100	Wheel break down
China	2011.7.23	40	192	Signaling defect by lightening

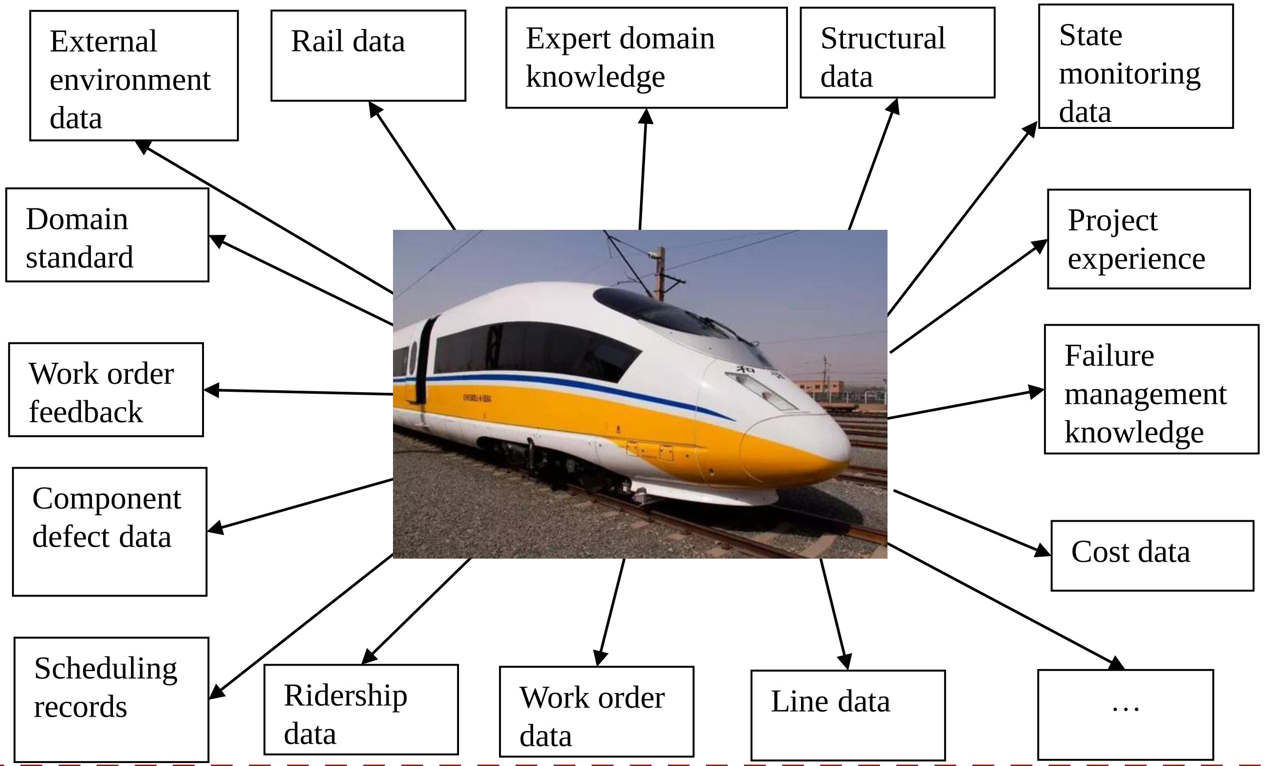
Availability

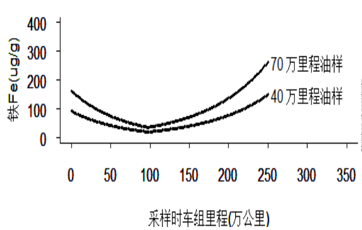
Availability $$A = \frac{MTTF}{MTTF + MTTR}$$

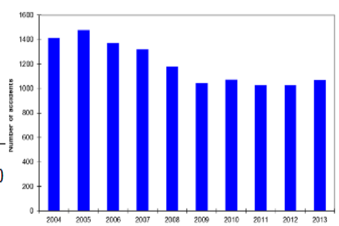


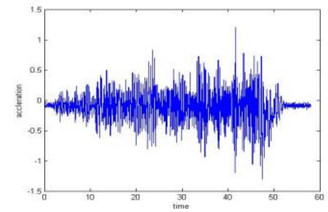


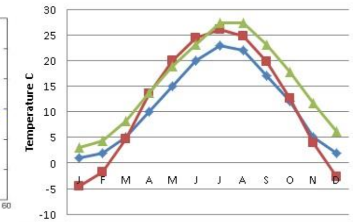
HSR big-data











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Research Questions

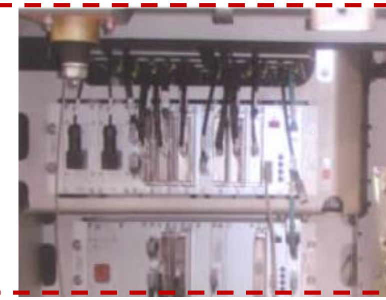
Design

- Redundancy allocation considering multi failure modes and their dependencies
- How to utilize more advanced technology to update the existing system

Train command transmission redundancy design

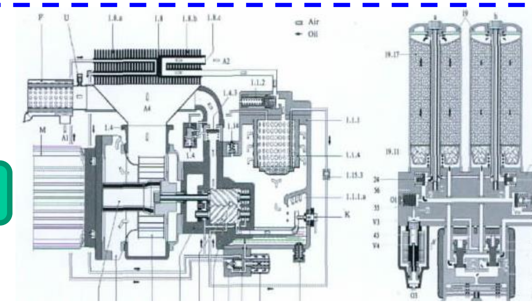
Network

Hard line

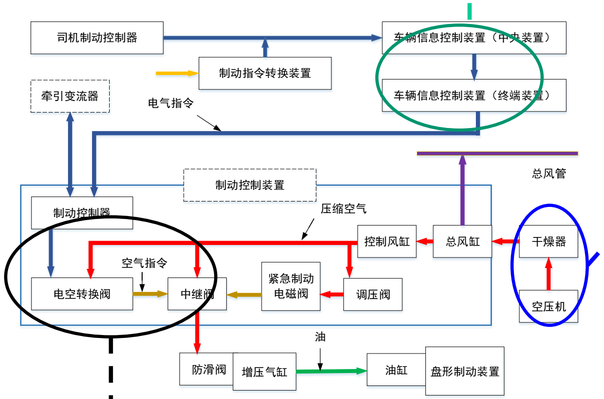


Wind system redundancy design

Dryer → Compressor



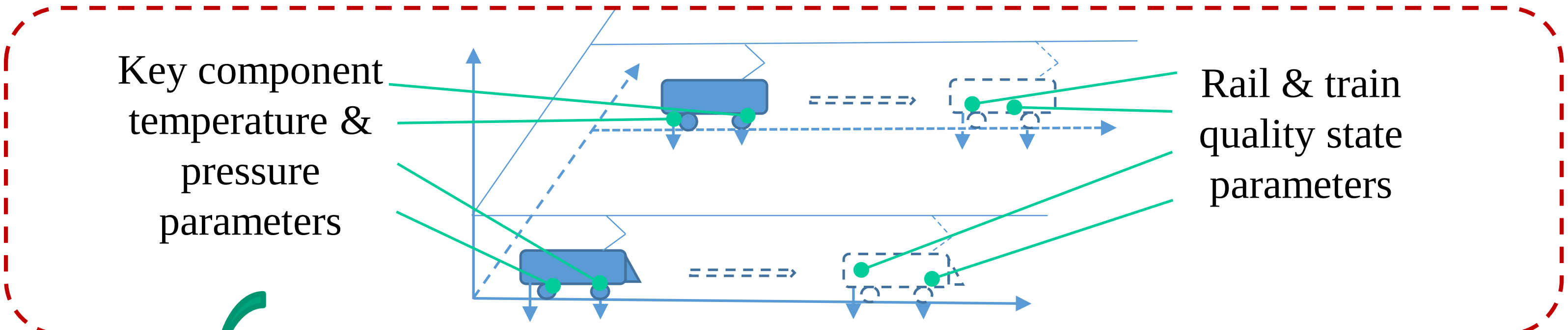
E.g. Braking system

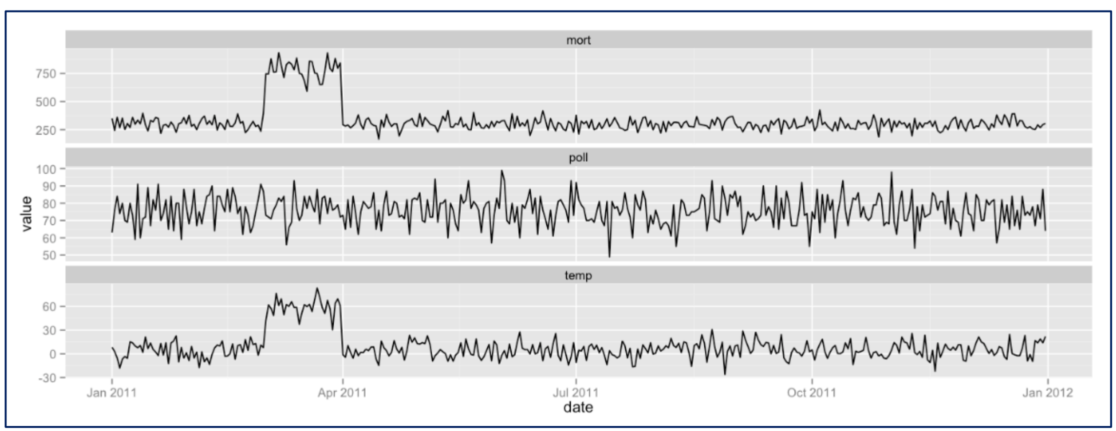


Air braking and electric braking are redundant to each other

Operations

- Operation parameters are the most direct and real-time presentation of availability; based on high-dimensional data, it is necessary to mining the dynamic relation between variables
- Based on high speed flow data, online monitoring of anomalies and pre-warning





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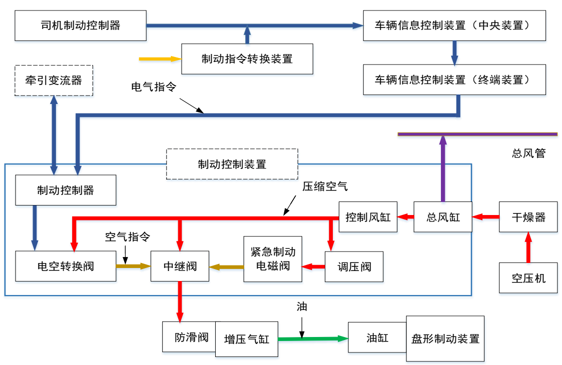
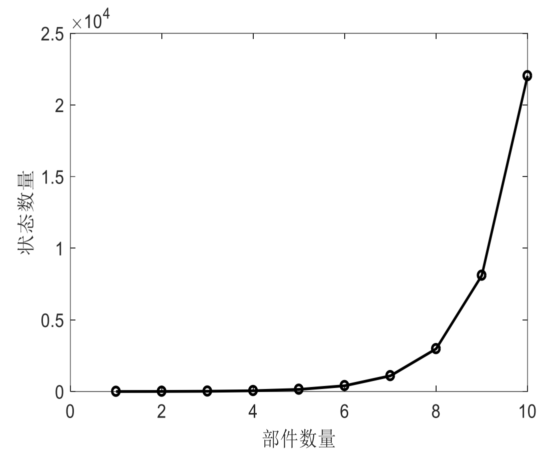
Operations

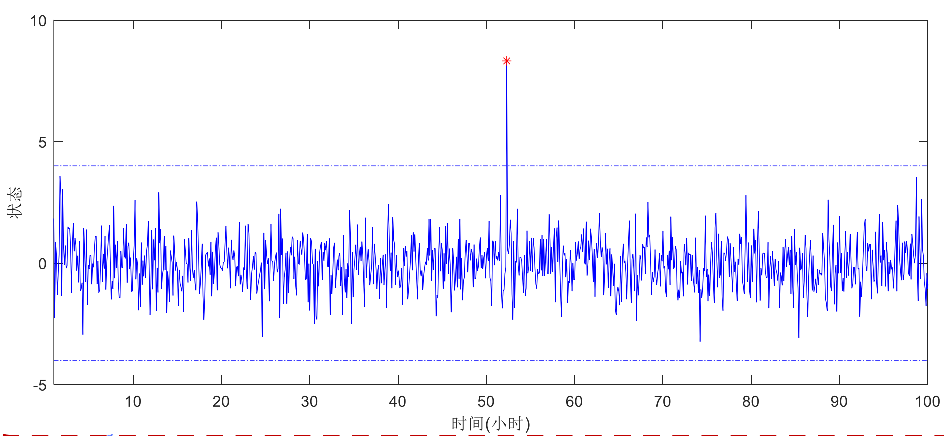
- Large number of components, dynamic and complex structural composition are the big challenges of the HSR system reliability assessment
- Rare event prediction under real-time monitoring data

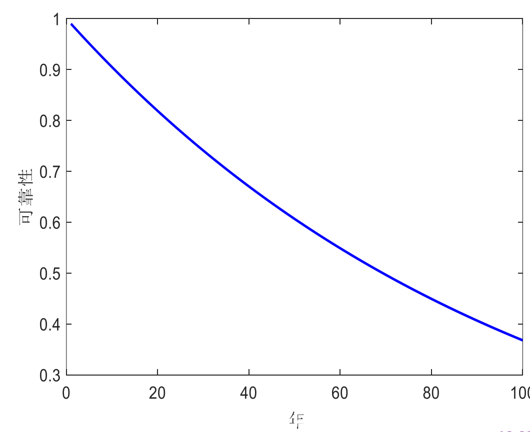


System reliability assessment challenge



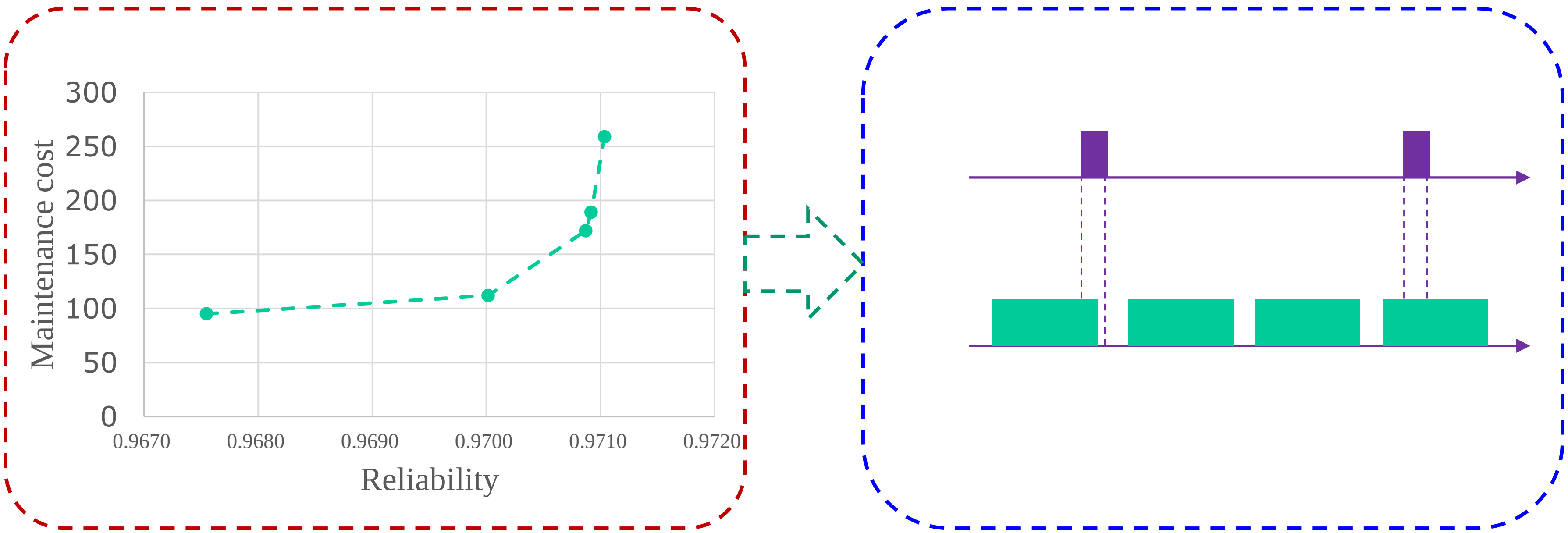
Rare event failure prediction





Maintenance

- Maintenance largely increase operation costs, meanwhile insufficient maintenance will result to risk of failure
- Economic, random and structural dependences exist between components, however, research is lacked
- Time, location and level of maintenance have direct impacts on scheduling, jointly optimize maintenance and operation needs research



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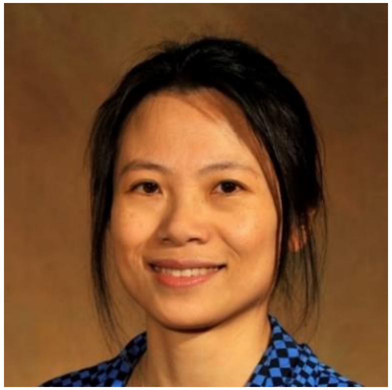
Research Team

Major team members



Prof. XY Zhu
UCAS

Dr. H Peng
CAS

Prof. U. Kumar
LTU, IVA Member

Dr. J Lin
LTU

Prof. KB Wang
Tsinghua

Prof. YF Li
Tsinghua

Dr. C Zhang
Tsinghua

And we look for more…

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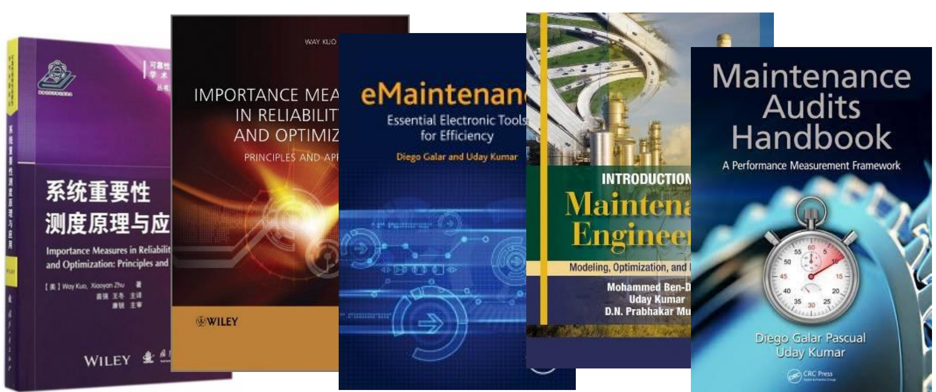
Competences

- Over 100 SCI publications

Domain	Journals	#
Reliability	**IEEE,RESS**	**27**
	JRR,QREI	8
OR	EJOR,AOR	4
	COR,MMOR	4
Transportation	JRRT,TR,JTE	13
Big data	CSDA,CSSC,IEEE	4
IE	**IISE, CIE**	**13**

- 5 books



- Expertise

Reliability | Maintainability

Modeling | OR, optimization

Industrial statistics | Data mining, machine learning

Industrial partners and sources of data

Chinese

中国中车
CRRC

…

International

JVTC LULEÅ RAILWAY RESEARCH CENTER
at Luleå University of Technology

ALSTOM

…

We are actively looking for more collaborators in China and world-wide

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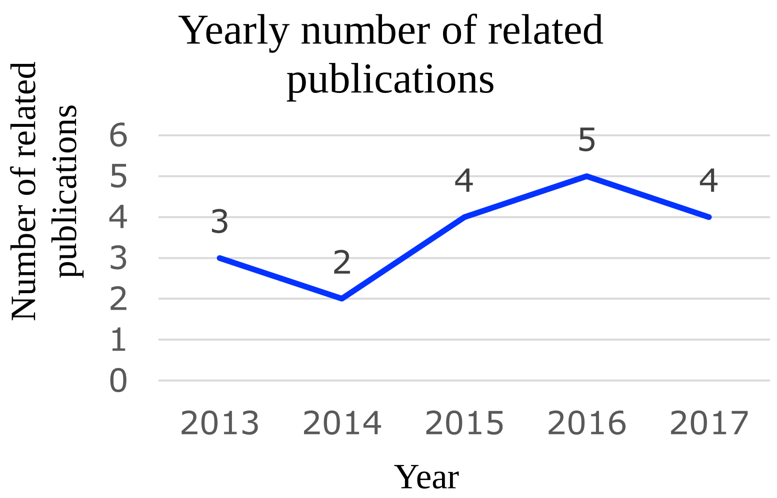
Review on the HSR Maintenance Studies

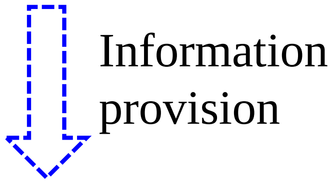
Literature Search

- Database: web of science
- Keywords: ‘high speed railway’ & ‘maintenance’
- Time span: 2013~2017
- Publications found: 82
- Related publications: 18



Related literature

- Detection & Prediction: 11



- Maintenance planning: 7

Detection & Prediction

Recent boom in high speed railway development

Increasing need for detection & prediction

- Basis of maintenance planning (e.g. CBM)
- Enhance system safety and reliability

Train oriented detection

- train presence, speed, etc.
  (Zhang et al. 2013）
- components wear condition
  (Barmada et al. 2016)
- split pin missing
  (Lu et al. 2016)

Track oriented prediction

- track irregularities long-term evolution
  (Lestoille et al. 2016)
- track geometric condition prediction
  (Xu et al. 2015)

Track oriented detection

- track vertical stiffness
  (Cano et al. 2015)
- track fastener inspection
  (Zhang et al. 2013)
  (Wei et al. 2017)
- fatigue defects
  (Muñoz et al. 2013)
- track irregularity
  (Chen et al. 2015)
  (Tsai et al. 2015)

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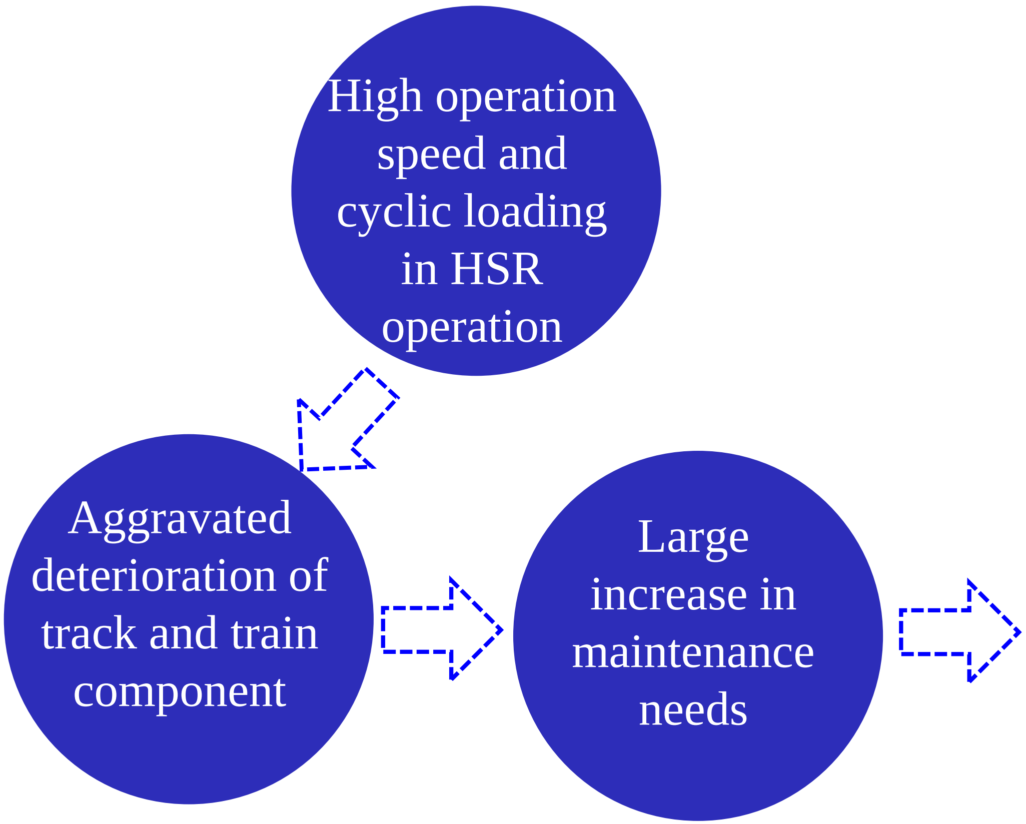
High Speed Railway Maintenance



- Electric Multiple Units (EMUs) Circulation Scheduling
- EMU-to-Track Assignment
- Shunting Schedule of EMUs Depot
- Equipment Maintenance Planning

EMU Circulation Scheduling (Zhou et al. 2014)

- EMUs are regularly maintained to ensure their safety.
- Different types of EMUs have different cycles for maintenance with levels ranging from 1 to 5

Table 1
Maintenance regulation of EMUs in China.[a]

Maintenance levels	EMU types Maintenance cycle			
	CRH1	CRH2	CRH3	CRH5
Level 1	4000 km or 48 h	4000 km or 48 h	4000 km or 48 h	5000 km or 48 h
Level 2	12,500 km	30,000 km	20,000 km	60,000 km
Level 3	1,200,000 km	600,000 km	1,200,000 km	1,200,000 km
Level 4	2,400,000 km	1,200,000 km	2,400,000 km	2,400,000 km
Level 5	4,800,000 km	2,400,000 km	4,800,000 km	4,800,00 km

[a] China Railway. Procedures and Standards of EMUs Maintenance in China[M]. China Railway Publishing House, Beijing, 2013.

First and second level maintenance:
operating maintenance;
carried out in operating depots.

Third to fifth level maintenance:
overhaul maintenance;
carried out in overhaul depots.

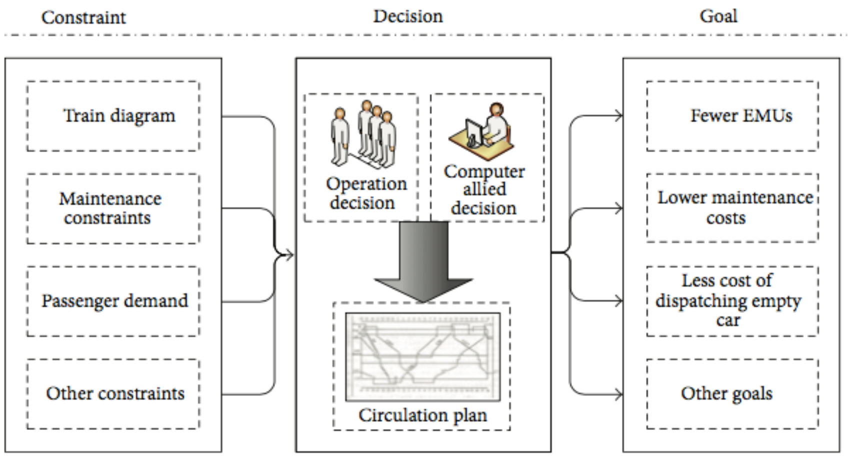


Figure 1. EMU circulation problem in China

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EMU Circulation Scheduling (Zhou et al. 2014)

Maintenance cost is measured by amount of maintenance as follow:

$$\text{Min} \sum_{i=1}^{n} \sum_{j=1}^{n} y_{ij}$$

$$y_{ij} = \begin{cases} 1 & x_{ij} = 1, R_i = 1, \sum s_i \geq S \\ 0 & others \end{cases}$$

x_{ij}: equal to 1 when trip i and j are connected
R_i: equal to 1 when arrival station of i is near the maintenance depot

s_i: distance of completed trip i before maintenance
S: distance standard of specific maintenance level

Maintenance constraints:

$$w_{ij} \geq T$$

v_i: trip i
w_{ij}: dwell time between trip i, j
T: required standard maintenance time

$$w_{ij}(v_i, v_j) = \begin{cases} t_j^d - t_i^a & s_j^d = s_i^a, t_j^d - t_i^a \geq t_{ij} \\ 1440 + t_j^d - t_i^a & s_j^d = s_i^a, t_j^d - t_i^a < t_{ij} \\ +\infty & s_j^d \neq s_i^a \end{cases}$$

t_{ij}: operation time
s_j^d: departure station
s_i^a: arrival station
t_j^d: departure time
t_i^a: arrival time

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EMU Circulation Scheduling (Li et al. 2016)

Assigning well-conditioned EMUs to each route and arrange the maintenance work via considering the EMUs item maintenance effectiveness and number of EMUs.

- Maximize the accumulated mileage between two maintenance:

$$\text{Max } Z_1 = \sum_{e \in E} \sum_{t \in D} \sum_{p \in P} l_p^e(t-1) y_p^e(t)$$

$l_p^e(t)$: the accumulated mileage of the EMUs e until the t-th day after the latest maintenance of item p

$y_p^e(t)$: binary decision variable, equal to 1 when EMU e starts to conduct the maintenance item p on the t-th day

- Minimize the number of EMUs:

$$\text{Min } Z_2 = \sum_{e \in E} I(\theta^e)$$

$$\theta^e = \sum_{r \in R} \sum_{t \in D} x_r^e(t) \quad e \in E$$

$$I(x) = \begin{cases} 1, & x > 0 \\ 0, & x \le 0 \end{cases}$$

θ^e: the times EMUs e undertook a certain route during the scheduling cycle

$x_r^e(t)$: binary decision variable, equal to 1 when EMUs e starts to undertake the route r on the t-th day

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EMU-to-Track Assignment (Li et al. 2017)

Currently 61 EMU depots in China provide maintenance services to EMUs:

- inspection
- maintenance
- washing
- temporary storage…

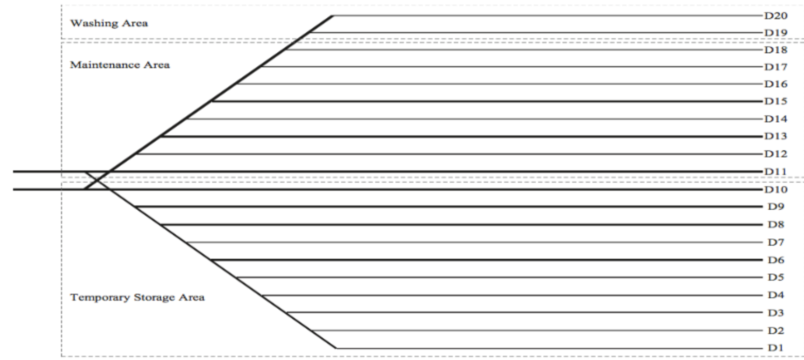

Figure 2. One type of EMUs depot layout

Tracks at EMU depots have two sections:

- each section accommodates one short train
- two sections accommodates one long train or a reconnection train.

Two typical yards at EMU depots:

- through yard
- stub-end yard

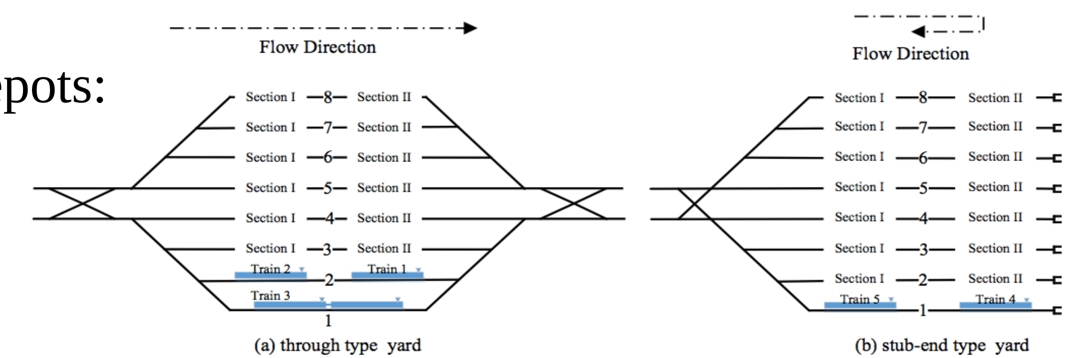

Figure 3. Typical yards at EMU depots

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EMU-to-Track Assignment (Li et al. 2017)

EMU-to-track assignment problem is to assign EMUs to tracks in order to

- implement maintenance tasks
- make sure no routing conflict among EMUs.

Maximizing the total number of EMUs that can be arranged on any track to finish the specific tasks under assignment constraints:

$$\text{Max} \sum_{i \in I} \sum_{w \in W} y_{iw}$$

$$\text{s.t.} \begin{cases} \sum_{w \in W} y_{iw} \leq 1, \forall i \in I \\ y_{iw} + y_{jw} \leq 1 \ \forall i \in I, \forall i \in \delta_i, w \in W \\ y_{iw} \in \{0,1\} \end{cases}$$

I: set of EMUs

W: set of tracks

w: track index

δ_i: set of EMUs that cannot be assigned to the same track with EMU i

y_{iw}: binary variable, equal to 1 if EMU i is assigned to track w

Shunting Schedule of EMUs Depot (Wang et al. 2016)

Throat section is occupied when carrying out:

- Shunting operation
- Receiving operation
- Departure operation

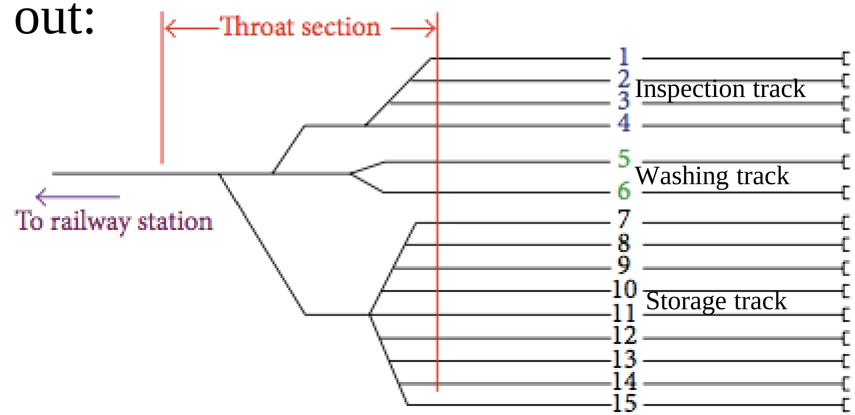

Figure 5. Typical track layout of EMU depot

Example: EMUs arrives at depot

received to track 1
through throat section

inspection process

shunted to track 5

washing process → stay on the track

shunted to track 7 to
wait for the departure

leave depot
through throat section

Shunting schedule of EMUs depot determines:

- Which tracks are occupied by EMUs
- When EMUs occupy tracks
- When EMUs should be shunted between tracks

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Shunting Schedule of EMUs Depot (Wang et al. 2016)

Minimize the total shunting cost, i.e. minimizing the total number of shunting movements:

$$\text{Min} \sum_{e\in E} \sum_{t\in T_e^S} \left(\sum_{i\in I} |x_{ei}^{t+1} - x_{ei}^t| + \sum_{w\in W} |y_{ew}^{t+1} - y_{ew}^t| + \sum_{s\in S} |z_{es}^{t+1} - z_{es}^t|\right)$$

Total staying time period on inspection track of e:

$$IT_e = \sum_{t\in T_e^S} \sum_{i\in I} x_{ei}^t$$

Total staying time period on washing track of e:

$$WT_e = \sum_{t\in T_e^S} \sum_{w\in W} y_{ew}^t$$

Dwell time constraints:

$$IT_e \geq IT$$
$$WT_e \geq WT$$

x_{ei}^t: binary variable, equal to 1 if inspection track i is occupied by e at time t

y_{ew}^t: binary variable, equal to 1 if washing track w is occupied by e at time t

z_{es}^t: binary variable, equal to 1 if storage track s is occupied by e at time t

E: set of EMUs

T_e^S: pure staying time period of EMU e at the depot

I: set of inspection tracks

W: set of washing tracks

S: set of storage tracks

IT: constant time duration for inspection process

WT: constant time duration for washing process

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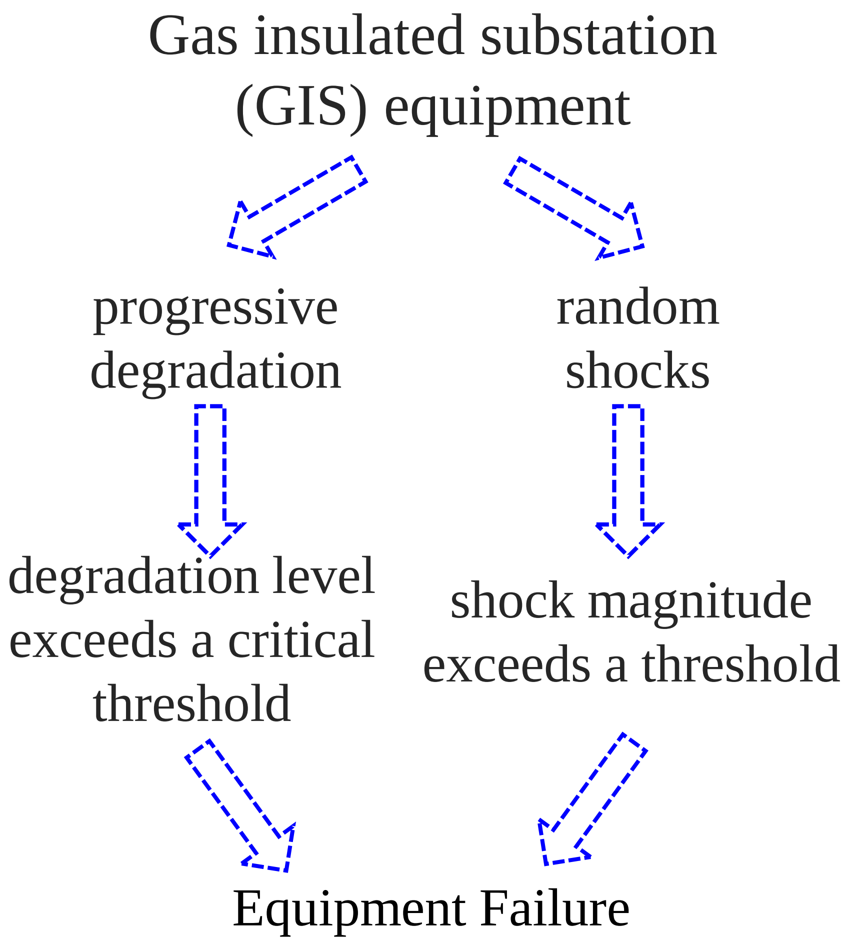
Equipment Maintenance Planning (Wang et al. 2017)



Degradation Process:

- approximately monotonic increasing without maintenance activities
- gamma process $\{X(t), t \geq 0\}$ with continuous state space is satisfactorily fitted to data of degradation phenomena

Shock Process:

- compound Poisson process
- homogeneous Poisson process $\{S(t), t \geq 0\}$ describes stochastic arrival time of shocks
- normal distributed random variables $Y_i, i = 1, \ldots, S$ reflect stochastic magnitudes of shocks, distribution function F

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Equipment Maintenance Planning (Wang et al. 2017)

Reliability is used to

- reflect current equipment performance
- predict equipment future reliability

$$R(t) = \Pr\{X(t) < L, S(t) = 0\} + \sum_{i=1}^{S} \Pr\{X(t) < L, Y_1 < H, \ldots, Y_{S(t)} < H, S(t) = i\}$$

$$= \Pr\{X(t) < L | S(t) = 0\} \cdot \Pr\{S(t) = 0\} + \sum_{i=1}^{S} F_Y^i(H) \cdot \Pr\{X(t) < L | S(t) = i\} \cdot \Pr\{S(t) = i\}$$

Combined maintenance strategy:

- Condition-Based Maintenance:

  Shocks are successively monitored by supervisory control system.

- Preventive Maintenance:

  Degradation level is regularly inspected with a period ΔT.

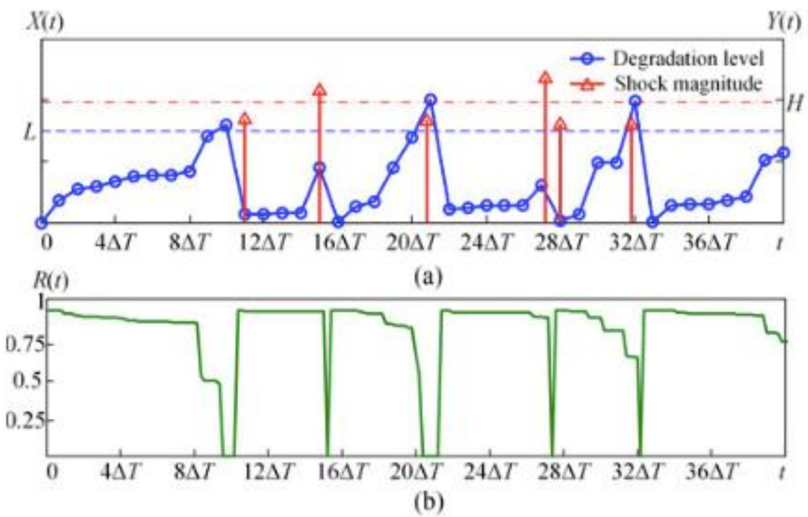

Figure 6. Multiple failure behavior and reliability evolution of GIS equipment under the maintenance strategy:(a)degradation process and shock process; (b)reliability

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Equipment Maintenance Planning (Wang et al. 2017)

long-run time span r → (randomness) → difficulty in counting whole maintenance cost

↓

finitely several renewal cycles | a renewal cycle:
as-good-as-new state-- deteriorating and failure --
maintenance activities-- as-good-as-new state

G: a renewal cycle length

Objective function:

reliability and economic efficiency:

$$RC = \frac{R_{av}}{C_{total}} = \frac{\int_0^r R(t)dt/r}{C_{ex} \cdot r}$$

R_{av}: average reliability during long run operation time

C_{total}: total maintenance cost during long run operation time

expected cost per unit time:

$$C_{ex} = \lim_{t\to\infty} \frac{C(t)}{t} = \frac{E[C(G)]}{E(G)}$$

expected cost in a renewal cycle length:

$$E[C(G)] = C_I E[N_1] + C_D E[T_D] + C_M$$

$C(t)$: maintenance cost by time t

C_I: each inspection cost

N_1: number of inspection

C_M: maintenance activity cost

C_D: downtime loss rate

T_D: equipment downtime

Plans for the coming years

- Exchanges
  - International conference
  - International workshops
  - International visitors
  - Workshops with industrial partners
- Education
  - Postdocs
  - PhDs
  - Masters
- Publications
  - Journal papers
  - Books
- Empirical validations
  - Industrial partners

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Thank you!