Project number: T32-101/15-R

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: *1 January 2016*
Project completion date: *31 December 2021*

1. Project Title:

Safety, Reliability, and Disruption Management of High Speed Rail and Metro Systems

2. Names and Academic Affiliations of Project Team Members[#]

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the current reporting period
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Co-Principal Investigator(s)	Kwok Leung TSUI‡	Data Science/CityU	8
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	Ngai Hang CHAN	Statistics /CUHK-Shenzhen †	4
	Wan Ki CHOW	Retirement †	4
	Chung Lun LI	Logistics Management /PolyU	4
	Nozer D SINGPURWALLA	Statistics/GWU, USA †	4
	Alain BENSOUSSAN	Data Science/CityU	4
	Siu Ming LO	Architecture and Civil Engineering/ CityU	8
	K.K. Richard YUEN	Architecture and Civil Engineering/ CityU	8
	Wai Tat Peter TSE	Advanced Design and Systems Engineering/CityU	4
	Biying SHOU	Management Sciences /CityU	8
	Yimin YU	Management Sciences /CityU	8
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	Kwai Sang CHIN	Advanced Design and Systems Engineering /CityU	2
	Qiang ZHOU	Systems and Industrial Engineering/Arizona	2
	Zijun ZHANG	Data Science/CityU	2
	Jin MURAKAMI	Urban Studies and Policy/SUTD, Singapore†	2

	Shui Yee Zoie WONG	St. Luke's International University, Japan	2
	Michael EDESESS	Environment and Sustainability / HKUST	2
	Shaobo LIU	Wuhan University of Technology	2
	Weili WANG	Shanghai Maritime University	2
	Sum Yee Selina NG	Gen. Life Ltd	2
	David GOLDSMAN	Stewart School of Industrial and Systems Eng./ Georgia Tech	2
	Matthias TAN	Data Science / CityU	2
	Zhou XU	Dept. of Logistics and Maritime Studies/ PolyU	2
	Jianxiang HUANG	Dept. of Urban Planning and Design/HKU	2
	Dan ZHANG	Leeds School of Business/U of Colorado	2
	Eric Wai Ming LEE*	Architecture and Civil Engineering/CityU	2
	Chi Kwong WONG*	Architecture and Civil Engineering/CityU	2
	Alpha Man Ho LING*	Mathematics and Information Technology/ The Education University of Hong Kong	2
	Jason Meng Cheng NI #	Wynn Research †	2
	Junwei WANG #	Industrial and Manufacturing Systems Engineering/ HKU	2
	Andy Ho Fai CHOW #	Advanced Design and Systems Engineering/CityU †	2
	Antoni B. CHAN✡	Computer Science/ CityU	2
	Lishuai LI✡	Data Science/CityU†	2
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	Wing Hong William LAM	Civil and Building Eng. Manager; MTR Corporation Limited	N.A.
	Vincent HO	China & International Business Safety Manager/MTR Corporation Limited	N.A.
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	Rafael GOURIVEAU	Automatic Control and Micro-Mecatronic Systems/FEMTO-ST Institute	N.A.

	Kamal MEDJAHER	Automatic Control and Micro-Mecatronic Systems/FEMTO-ST Institute	N.A.
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	Jian MA	College of Traffic & Transportation / Southwest JiaotongU	N.A.
	Xuesong JIN	State Key Laboratory of Traction Power/ Southwest JiaotongU	N.A.
	Hao YE	Rail Transit Control Technology R&D Center / Tsinghua University	N.A.
	John ANDREWS	Infrastructure and Geomatics Research Division / University of Nottingham	N.A.
	Anthony CHEN*	Utah State University	N.A.
	Xuesong ZHOU*	Arizona State University	N.A.
	Rex Yung-Cheng LAI #	National Taiwan University	N.A.

**Approved by RGC on 18 March 2016.*
#Approved by RGC on 14 July 2017.
✡*Approved by RGC on 5 October 2018.*
‡ *Approved by RGC on 14 October 2020.*
† *Updated affiliations due to change in employment universities/organizations.*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. Establish a consortium of international experts, consultants, and researchers in transportation safety, rail engineering, system informatics, and quality and reliability engineering to provide training and education programs to industry and government.	100	
2. Develop a centralized platform that manages a synergistic rail systems knowledge base, employs analytical models and algorithms, and provides real-time decision support.	100	
3. Achieve safety, dependability, and high-quality rail operation, performance, and service.	100	
4. Create fundamental science, theories, algorithms, and methodologies for rail safety, monitoring, control, and management, which will be documented and published in highly regarded journals and proceedings in appropriate science and engineering disciplines.	100	

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*
****** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

I) Fundamental and applied research

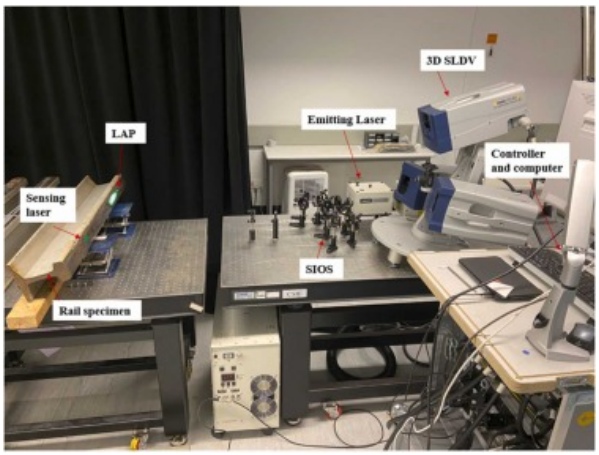
Closely aligned with the research goals and objectives, our project team had carried out various studies and activities to investigate rail safety, monitoring and management from different perspectives. Several major findings was summarized as follows.

RTA 1 Engineering Assets Health Monitoring, Diagnostics, and Prognostics

Task 1.1 Sensor-based Health Monitoring and Inspection Systems

- Non-contact Detection of Railhead Defect their Classification by using convolutional neural network

Railhead defects must be detected and classified intelligently in order for railway transportation systems to operate safely. Rail defect identification and categorization can be automated by using machine learning models to process rail image data acquired using cameras. However, such an automated method has significant drawbacks: it cannot detect subsurface defects, picture data requires a high-end GPU with a long computational time, and machine learning model training can be influenced by image quality, which is dependent on light intensity and shooting altitude. Rayleigh waves are a potential candidate for rail inspection because they can detect both surface and subsurface defects and travel long distances on curved surfaces (like a rail) at high speed. This article looks into the possibility of combining fully non-contact laser ultrasonic technology (LUT) and a deep learning approach for intelligent detection and classification of railhead surface and subsurface defects. The fully non-contact LUT was used to actuate and capture laser-generated Rayleigh wave signals on railhead specimens in order to create a database of A-scan signals from healthy, surface, subsurface, and edge defect railheads. The classification capabilities of a support vector machine (SVM), a fully connected deep neural network (DNN), and a convolutional neural network (CNN) were examined after they were applied to the pre-processed signals without extracting any statistical/signal processing-based characteristics. The comparative analysis demonstrates that CNN is robust in classifying railhead defects. As a result, when combined with CNN, the laser ultrasonic technology may ensure automatic defection and classification of railhead surface and subsurface flaws.



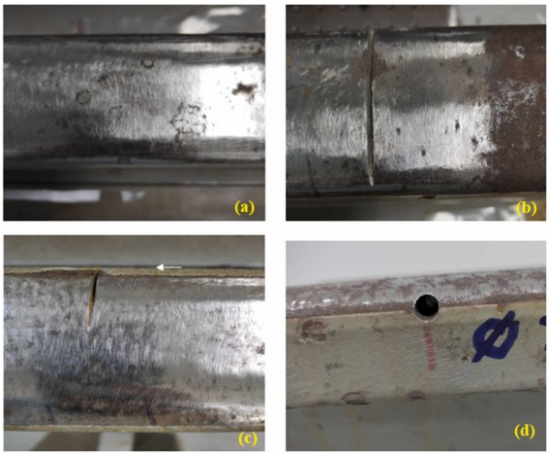


Fig. 1. (Left) Experimental setup for non-contact inspection of rail
Fig. 2. (Right) Railhead specimens; (a) healthy (b) surface defect (c) edge defect (d) subsurface defect

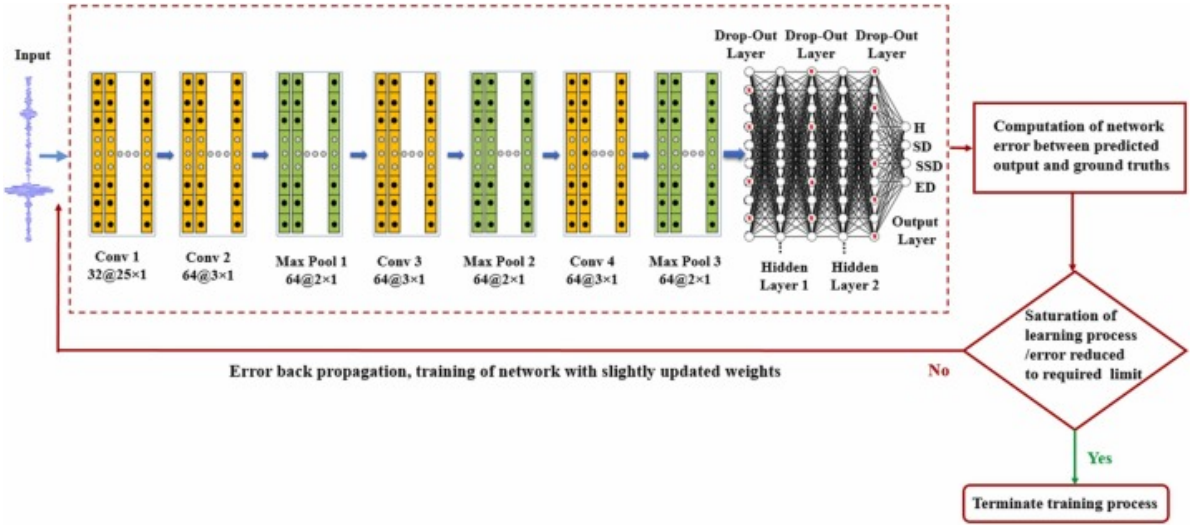
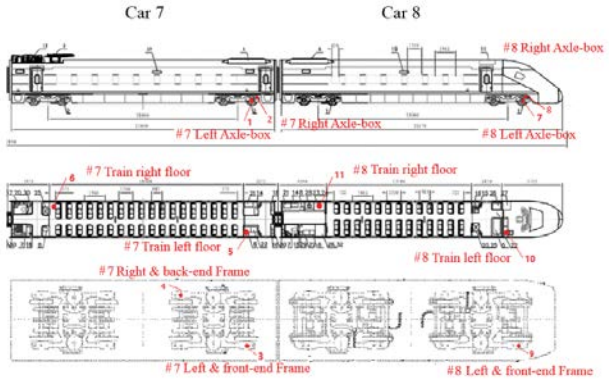


Fig. 3. Flow diagram of training process of CNN

Task 1.2 Anomaly Detection, Failure Discrimination, and Fault Diagnostic Systems

➢ High-Speed Rail Suspension System Health Monitoring Using Multi-Location Vibration Data

A novel data-driven framework to monitor the health status of high-speed rail suspension system by measuring train vibrations is proposed herein. Unlike existing methods, this framework does not rely on sophisticated dynamic models or high-fidelity simulations; it combines the power of data and domain knowledge to generate a model that can be trained quickly and adapted easily to different rail systems. In addition, the framework includes a module to generate a training dataset, tackling a typical challenge in real-world system monitoring, namely, the lack of labeled data due to practical limits. Based on the multi-output support vector regression (MSVR), the proposed framework can monitor the stiffness and damping coefficients of the suspension system using vibration signals measured on trains in real time. The framework comprises three modules. First, a simple suspension system dynamics model is built to generate a training dataset. Furthermore, key features are extracted from frequency response curves to reflect the impact of spring and damper degradation. Subsequently, a supervised learning model based on the MSVR is built to predict the stiffness and damping coefficients of suspension systems from features extracted in the second module. Once the model is built, real-time monitoring can be achieved by feeding the vibration signals as they are collected during operations. The proposed framework was evaluated on simulation data for its accuracy and tested on real-world operational data for its practicability.



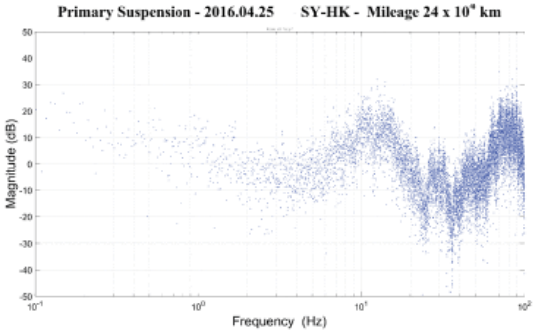


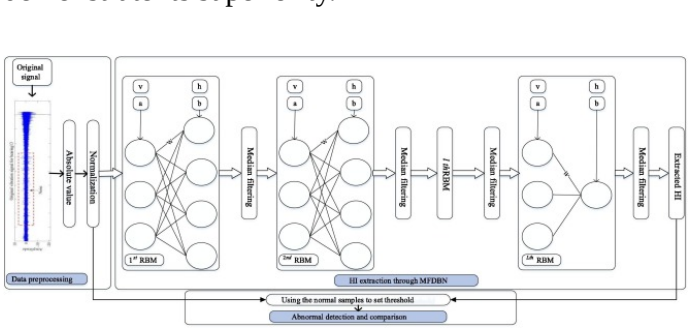
Fig. 4. ((Left) Position of 11 sensors on trail car and motor car
Fig. 5. (Right) Samples of magnitude frequency response curves for the primary suspension system

Task 1.3 Reliability Degradation Modelling and Failure Prediction

➢ Deep Belief Network for Bearing Performance Degradation Assessment

An improved unsupervised deep belief network, namely median filtering deep belief network (MFDBN) model is proposed in this paper through median filtering for bearing performance degradation. MFDBN has the following advantages. First, MFDBN uses the absolute amplitude of the original vibration signal as direct input to extract health indicator (HI) and reduce dependence

on manual experience. Second, unlike the bearing failure signal, the degradation signal is continuously changing; hence it is difficult to label the data. To solve this problem, MFDBN is used to extract HI without an output layer. Third, because the noise of the vibration data, the smoothness of the extracted HI is poor, it is easy to misjudge the bearing health status. The multiple hidden layers with the median filtering model can denoise the HI curve layer by layer. Finally, this is verified by comparing other models and using multiple bearing datasets to demonstrate its superiority.



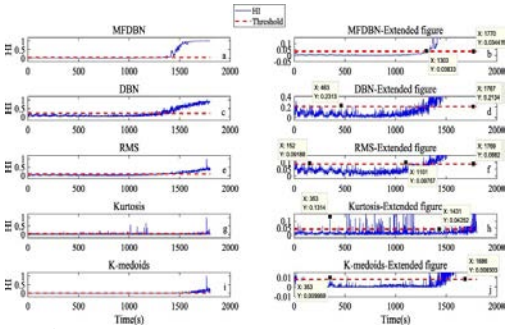


Fig. 6. (Left) Structures of restricted boltzman machine and median filtering deep belief network
Fig. 7. (Right) Result of the extracted health indicator for a bearing

RTA 2 Crowd Safety Management in a Big Data Environment

Task 2.1 Hazard Mitigation in Stations and Allied Facilities

- Simulation Study of Tenability for Passengers in a Railway Tunnel with Arson Fire

Arson fire occurring inside railway tunnel with a crowded train could give rise to serious consequences. The severity of tunnel fire increases with the length of tunnel, the fire size and the presence of obstructions inside the tunnel. Thus, investigation of different aspects of tunnel fire is important in tunnel design, fire safety, and rescue. While real-scale experimental study of tunnel fire is in general too demanding in terms of resources and feasibility, simulation has an important role to play in such studies. The present study employs the Fire Dynamic Simulator to perform simulation of arson fire in front of a train in an underground tunnel. The arson fire occurs in an underground tunnel of length 500 m, which resembles some subway tunnels in Hong Kong. The scenario consists of a metro train stopping inside the tunnel when an arson fire is set in front of the train. In addition, the worst scenario in which the mechanical ventilation system inside the tunnel is not functioning, either due to malicious damage or power failure, is assumed. In the simulation, temperature inside the train car and smoke layer height, temperature, visibility and concentration of carbon monoxide at important locations outside the train are investigated. Most importantly, analysis of tenability in such a tunnel fire scenario is performed. The simulation results show that inside the train and near to the train front temperature could be a threatening factor while outside the train visibility and carbon monoxide concentration are threatening factors. Provided that the train compartment is not too crowded and that the passengers are not in great panic, it would be safer to move inside the train to locations further away from the train front than to escape from the train and move in the tunnel where the geometrical environment is not favorable. In addition, the effect of longitudinal ventilation is investigated by comparing the results of simulation for an unventilated tunnel and a tunnel under a ventilation velocity of 2 m/s. The results of the present study could be of importance in drafting plans of rescue and evacuation in tunnel fires.

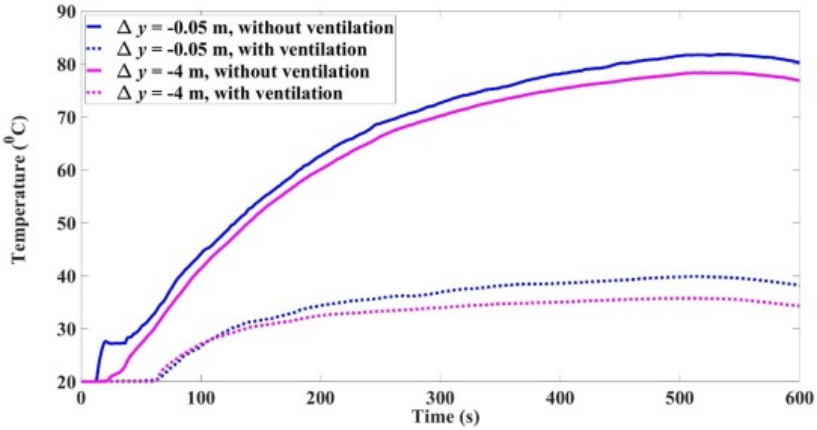


Fig. 8. Temperature at different locations along x = 0 m inside train compartment, at the characteristic height of 1.5 m, with and without ventilation for a fire size of 16 MW

Task 2.2 Big Data Analytics for Passenger Flow Dynamics

- Adapted Geographically Weighted LASSO Model for Predicting Subway Ridership

Ridership prediction at station level plays a critical role in subway transportation planning. Among various existing ridership prediction methods, direct demand model has been recognized as an effective approach. However, direct demand models including geographically weighted regression (GWR) have rarely been studied for local model selection in ridership prediction. In practice, acquiring insights into subway ridership under multiple influencing factors from a local perspective is important for passenger flow management and transportation planning operations adapting to local conditions. In this study, we propose an adapted geographically weighted LASSO (Ada-GWL) framework for modelling subway ridership, which involves regression-coefficient shrinkage and local model selection. It takes subway network layout into account and adopts network-based distance metric instead of Euclidean-based distance metric, making it so-called adapted to the context of subway networks. The real-world case of Shenzhen Metro is used to elaborate our proposed model. The results show that the proposed Ada-GWL model performs the best compared with the global model (ordinary least square, GWR, GWR calibrated with network-based distance metric and geographically weighted LASSO (GWL) in terms of estimation error and goodness-of-fit. Through understanding the variation of each coefficient across space (elasticities) and variables selection of each station, it provides more realistic conclusions based on local analysis. Besides, through clustering analysis of the stations according to the regression coefficients, clusters' functional characteristics are found to be in compliance with the policy of functional land use in Shenzhen, indicating the high interpretability of Ada-GWL model from the spatial angle. In other words, the regression coefficients of different stations can provide us the local prospective to understand the influence of factors on stations' ridership.

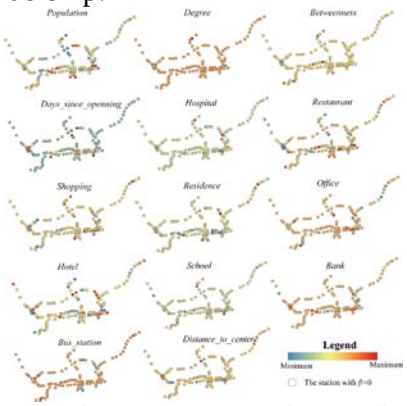


Fig. 9. (Left) Spatial distribution of local coefficients (elasticities) of Ada-GWL model for non-rush hour ridership
Fig. 10. (Right) Clusters by coefficients of stations for non-rush hour ridership with the method of k-means

Task 2.3 Crowd Safety Management

- Tracking Traffic Accidents Using Social Media Data: A Case Study of Shanghai

Traffic congestion and accidents take a toll on commuters' daily experiences and society. Locating

the venues prone to congestion and accidents and capturing their perception by public members is invaluable for transport policy-makers. However, few previous methods consider user perception toward the accidents and congestion in finding and profiling the accident- and congestion-prone areas, leaving decision-makers unaware of the subsequent behavior responses and priorities of retrofitting measures. This study develops a framework to identify and characterize the accident- and congestion-prone areas heatedly discussed on social media. First, we use natural language processing and deep learning to detect the accident- and congestion-relevant Chinese microblogs posted on Sina Weibo, a Chinese social media platform. Then a modified Kernel Density Estimation method considering the sentiment of microblogs is employed to find the accident- and congestion-prone regions. The results show that the 'congestion-prone areas' discussed on social media are mainly distributed throughout the historical urban core and the Northwest of Pudong New Area, in reasonably good agreements with actual congestion records. In contrast, the 'accident-prone areas' are primarily found in locations with severe accidents. Finally, the above venues are characterized in spatio-temporal and semantic aspects to understand the nature of the incidents and assess the priority level for mitigation measures. The outcomes can provide a reference for traffic authorities to inform resource allocation and prioritize mitigation measures in future traffic management.

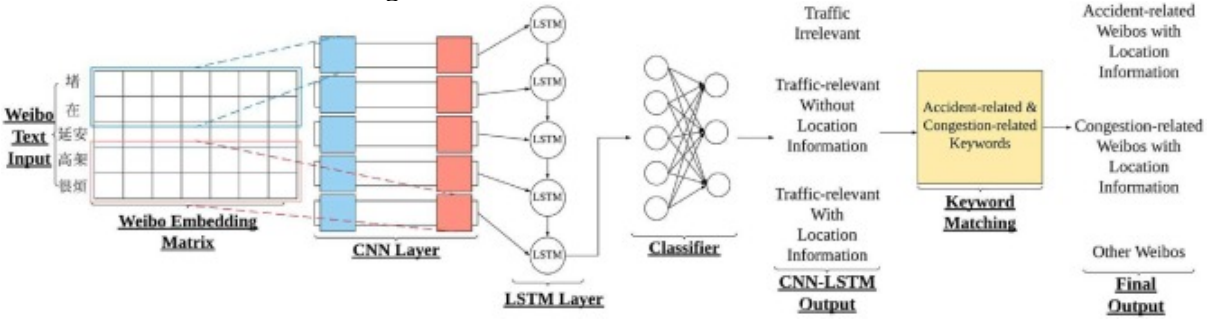


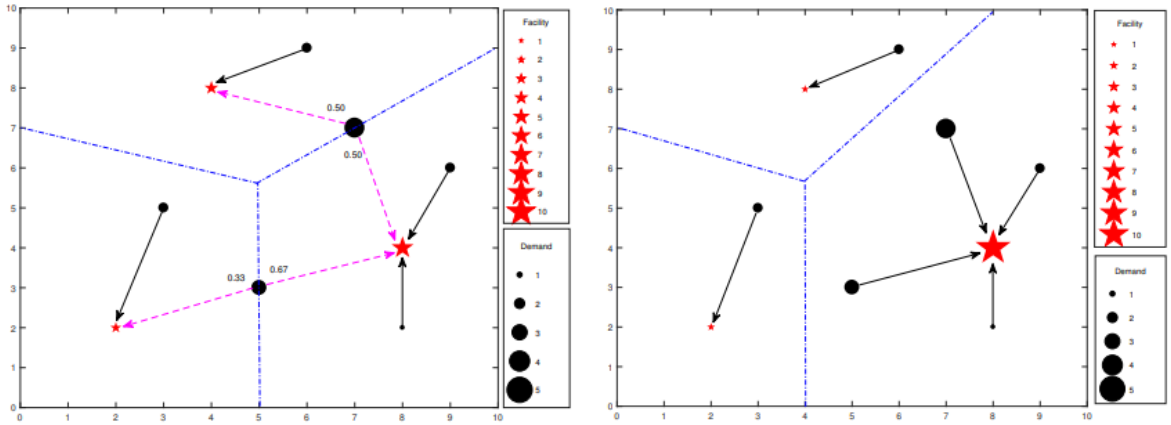
Fig. 11. Overview of the Traffic Information Detection Module

RTA 3 Demand, Capacity, and Disruption Management

Task 3.1 Demand Modelling and Capacity Management

- Price-Directed Cost Sharing and Demand Allocation Among Service Providers

We study capacity sharing through demand allocation in service systems in the presence of service-fulfillment costs. Our problem is motivated by service collaboration in healthcare involving public–private partnerships. Methodology: We formulate the problem as a cooperative game and identify a cost allocation that is in the core. Results: The cost-allocation scheme we identify is price-directed, and the cost of each firm consists of three components: The delay cost incurred within the firm; a cost paid for the capacity used by the firm at facilities owned by other firms; and a payment received for fulfilling demand of other firms at facilities owned by the firm. Interestingly, we show that the cost-allocation scheme is equivalent to a market equilibrium—that is, it can be implemented in a decentralized fashion. We extend our analysis to settings where the capacity of each facility is endogenously determined and to settings where a service-priority policy is deployed. Our results are robust to a variety of generalizations: partial sharing, partial transfer, facilities modeled as general queueing systems, and convex delay costs.



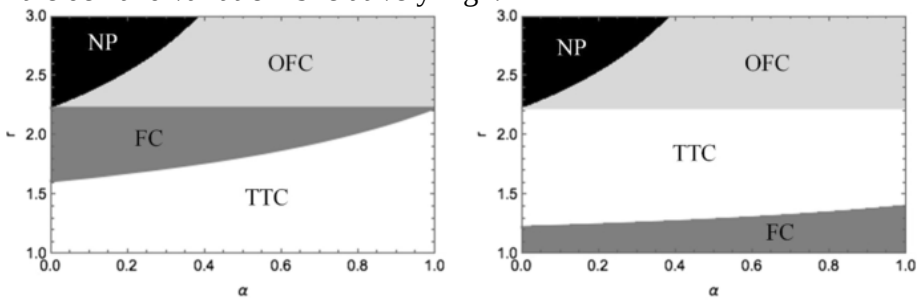
(a) Demand Allocation with Fixed Capacities (b) Demand Allocation with Optimal Capacities

Fig. 12. Optimal demand allocation under fixed and optimal capacity

Task 3.2 Supply Chain Management for Critical Components

- Contract Design for Sustainable Supply Chain Practices

A game-theoretic model is developed that captures the most crucial factors in market entry stage, such as market uncertainty, competition, contract design, distribution channel, and sustainability. we study how the supplier optimally designs the contract for the retailers under asymmetric information to make the supply chain more efficient and sustainable. Subsequently, we investigate the preference of contractual forms between a franchise contract and a two-part tariff contract, from the perspectives of the supplier, the incumbent retailer, and the whole supply chain, respectively. It turns out that the supplier prefers the TTC while the incumbent is better off under the FC when the demand variation is relatively high.



(a) Incumbent profit **(b)** Supplier profit

Fig. 13. Regions where incumbent and supplier are better off under two contractual forms

Task 3.3 System Responses in the Event of Disruptions

- Energy-efficient High-speed Train Rescheduling during a Major Disruption

Disruptions are inevitable in daily train operations, and can cause high-speed trains to deviate from their official schedules. Therefore, the efficient rescheduling of disrupted trains is critical for ensuring smooth daily operations. We sought to determine the appropriate arrival and departure times and orders of trains at each station during a disruption, and the speed profile of each train, to reduce the delay costs and energy consumption. To embed the train speed profile corresponding to energy saving into the train rescheduling problem, a space–time–speed network is applied for problem formulation. Thus, the energy-efficient train speed profile is embedded in the speed dimension in the space–time–speed hypernetwork. The detailed train speed profile between two stations is formulated as a multiple-phase optimal control model, which is solved using a pseudospectral method. Then, an integer linear programming model based on multicommodity flow is built to solve the train rescheduling problem. We decompose it via the alternating direction method of multipliers into a series of easy-to-solve shortest path subproblems. Each subproblem is then efficiently solved using a dynamic programming algorithm. Finally, the Xi'an–Chengdu high-speed railway line is used to test our model and algorithms, thereby demonstrating the atrade-off between passenger-service quality and energy efficiency.

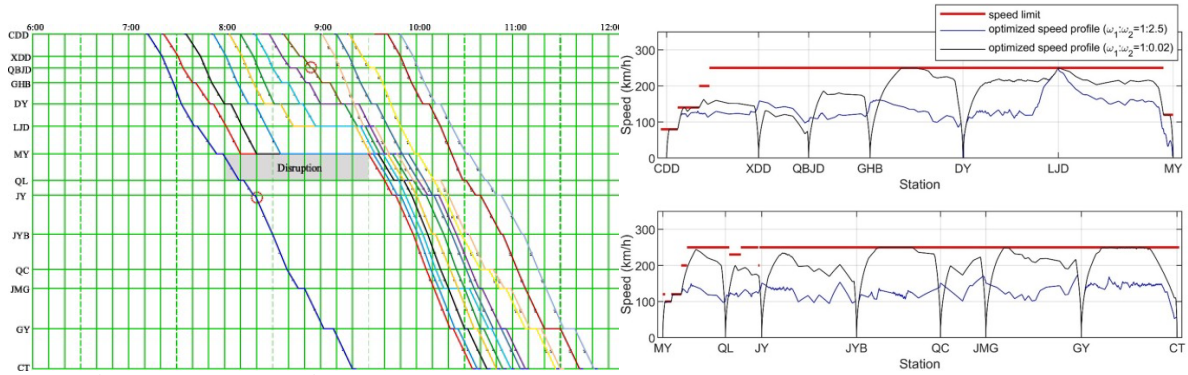


Fig. 14. (Left) Disposition timetable for disruption scenario
Fig. 15. (Right) Train speed profile

➢ Train Rescheduling on Double-track High-speed Railway Lines

We develop a method of real-time train rescheduling on double-track high-speed railway lines undergoing major disruption. As a result, trains approaching the disrupted area cannot use the blocked tracks and must be efficiently rescheduled. As most tracks in a high-speed railway station can be shared by trains arriving from both directions, we reschedule both inbound and outbound trains simultaneously by allowing them to share sidings. Based on a space-time network, an integer linear programming (ILP) model is formulated to minimize the train-deviation cost. As the ILP model is difficult to solve for real-world problems, we decompose it into many easy-to-solve subproblems by the alternating direction method of multipliers (ADMM) algorithm. Our model is tested on an abstract representation of the Chinese high-speed railway system to illustrate both the benefit of rescheduling trains in both directions simultaneously and the efficiency of the ADMM algorithm in train rescheduling.

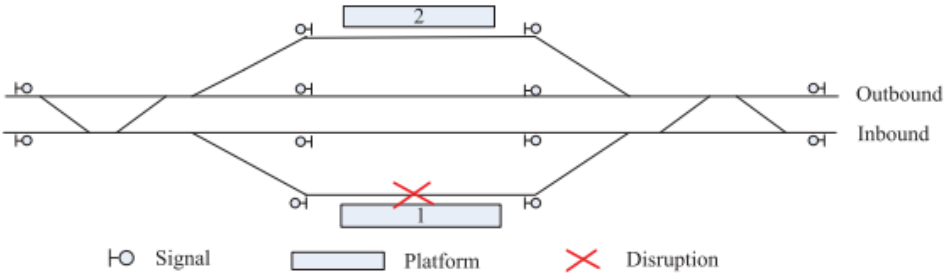


Fig. 16. Disruption scenario in Tengzhou East Station

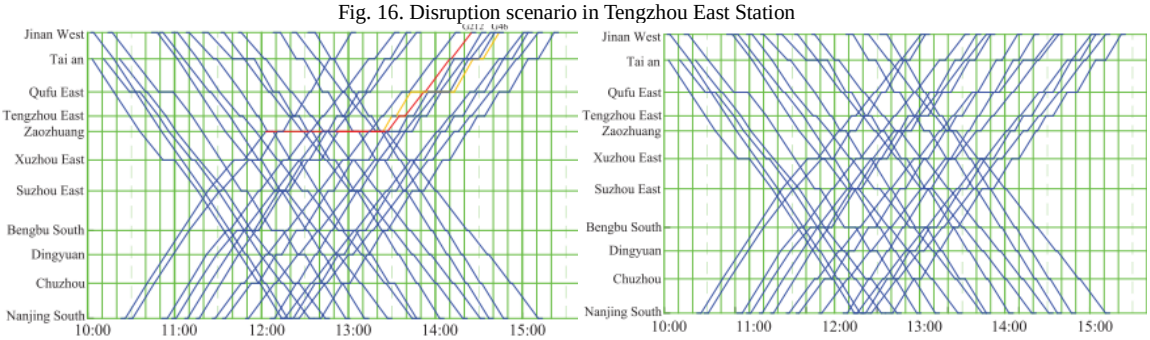


Fig. 17. (Left) Disposition timetable for disruption scenario without sharing sidings
Fig. 18. (Right) Disposition timetable for disruption scenario with sharing sidings

II) Intellectual merit across disciplines

Project team produced a total of 226 of peer reviewed papers, among which, over 50 were published in A+ tier journals (top 10% in respective field). Here are the examples:

- Cheng, C. H., Chow, C. L., & Chow, W. K. (2021). A simulation study of tenability for passengers in a railway tunnel with arson fire. Tunnelling and Underground Space Technology, 108
- He, Y., Zhao, Y., & Tsui, K. L. (2021). An adapted geographically weighted LASSO (ada-GWL) model for predicting subway ridership. Transportation, 48(3), 1185-1216.
- Hong, N., Li, L., Yao, W., Zhao, Y., Yi, C., Lin, J., & Tsui, K. L. (2020). High-speed rail

suspension system health monitoring using multi-location vibration data. IEEE Transactions on Intelligent Transportation Systems, 21(7), 2943-2955.
- Liang, R., Wang, J., Huang, M., & Jiang, Z. -. (2020). Truthful auctions for e-market logistics services procurement with quantity discounts. Transportation Research Part B: Methodological, 133, 165-180.
- Xu, F., Tse, W. T. P., & Tse, Y. L. (2018). Roller bearing fault diagnosis using stacked denoising autoencoder in deep learning and Gath–Geva clustering algorithm without principal component analysis and data label. Applied Soft Computing Journal, 73, 898-913.
- Xu, X., Li, C. -., & Xu, Z. (2021). Train timetabling with stop-skipping, passenger flow, and platform choice considerations. Transportation Research Part B: Methodological, 150, 52-74.
- Ying, C. -., Chow, A. H. F., & Chin, K. -. (2020). An actor-critic deep reinforcement learning approach for metro train scheduling with rolling stock circulation under stochastic demand. Transportation Research Part B: Methodological, 140, 210-235.
- Zhan, S., Wang, P., Wong, S. C., & Lo, S. M. (2022). Energy-efficient high-speed train rescheduling during a major disruption. Transportation Research Part E: Logistics and Transportation Review, 157
- Zhan, S., Wong, S. C., Shang, P., Peng, Q., Xie, J., & Lo, S. M. (2021). Integrated railway timetable rescheduling and dynamic passenger routing during a complete blockage. Transportation Research Part B: Methodological, 143, 86-123.
- Zhuang, L., Wang, L., Zhang, Z., & Tsui, K. L. (2018). Automated vision inspection of rail surface cracks: A double-layer data-driven framework. Transportation Research Part C: Emerging Technologies, 92, 258-277.

The project advanced knowledge and created scientific impact on multiple disciplines including engineering, computer science, decision science, mathematics, management, and relevant cross-disciplinary research. Here are the examples of highly cited publications.

- Wang, D., Tsui, K.-L., Miao, Q. (2017) Prognostics and Health Management: A Review of Vibration Based Bearing and Gear Health Indicators. IEEE Access, 6, pp. 665-676. *[cited 213 times]*
- Wang, D., Zhao, Y., Yi, C., Tsui, K.-L., Lin, J. (2018) Sparsity guided empirical wavelet transform for fault diagnosis of rolling element bearings. Mechanical Systems and Signal Processing, 101, pp. 292-308 *[cited 126 times]*
- Kang, D., Ma, Z., Chan, A.B. (2019) Beyond Counting: Comparisons of Density Maps for Crowd Analysis Tasks-Counting, Detection, and Tracking. IEEE Transactions on Circuits and Systems for Video Technology, 29 (5), art. no. 8360001, pp. 1408-1422. *[cited 78 times]*
- Zhou, Y., Wang, J., Yang, H. (2019) Resilience of Transportation Systems: Concepts and Comprehensive Review. IEEE Transactions on Intelligent Transportation Systems, 20 (12), art. no. 8602445, pp. 4262-4276. *[cited 63 times]*
- Chow, W.K., Gao, Y., Zhao, J.H., Dang, J.F., Chow, N.C.L. (2016) A study on tilted tunnel fire under natural ventilation. Fire Safety Journal, 81, pp. 44-57. *[cited 59 times]*

III) Industrial impact

Innovation and Technology Fund partnership research programme with MTR. Collaboration between academia and industry partners had produced promising result. MTR and our team stepped up to co-apply and secured an ITF project on “Escalator Health Condition Analytics and Monitoring Models”. The project is an extended research based on results arising from the pilot studies under TRS.

Electrical and Mechanical Services Department. The Railway Branch of EMSD, the regulatory authority on railway safety in Hong Kong, had designated our project team member for a two-year consultancy service for POC project on AI Analysis for Prediction of Risk of Permanent Way Related Incidents, which applied data analytics, machine learning and AI models on permanent way data for smart and predictive maintenance and system optimization.

Training programme for Seoul Metro. Our team was invited by Seoul Metro to deliver a 3-day training program at CityU in 2019 for their directors and managers with over 60 delegates in total. The program aimed to close the research-industry gap and enable both sides

to build a broader base of knowledge and expertise.

IV) Knowledge dissemination

To promote our research project in railway research field, we had been spending effort in organizing annual workshops and invited sessions in major international conferences in PHM, statistics, transportation, safety management, and supply chain management, such as IAFSS, INFORMS, POMS, JSM, WCEAM.

Annual Workshop on High-speed Rail Operation for Safety and Reliability. Our project team, together with Beijing Jiaotong University and National Taiwan University, co-organized workshops yearly. The workshops featured influential speakers from the industry, academia, and regulatory agency to share and exchange their experiences in a wide range of topics to improve rail safety, reliability and efficiency. World renowned speakers included Prof Christopher P.L. Barkan of UIUC, Prof Tao Tang of BJTU, Prof Pierre Dersin of Luleå UT, Prof Clive Roberts of Birmingham, Prof Ingo A. Hansen of UTDelft, etc.

Asia Pacific Rail. Our team had proactively promoted the project to stakeholders in various occasions. We were invited to showcase our research project in the largest railway exhibition in the region, Asia Pacific Rail 2018 and 2019. The events brought together major rail operators, including MTR, JR, SNCF, etc., which allowed project team to demonstrate our research work to the industry and open up collaboration opportunities.

HK TECH Forum: Reliability and Safety of Intelligent System. The HK Tech Forum on Reliability and Safety of Intelligent Systems is organized by Prof Xie to provide a platform to discuss some of the important and challenging issues of complex systems that incorporate various kinds of artificial intelligence. Several leading experts, including Turing Award recipient, academicians and industry leaders, will give presentation on various aspects of reliability and safety of intelligent systems. As a highlight of the TRS project, Dr Tony Lee, Operations Director of MTRC and our honorary advisor of the project, is invited to discuss issues of transportation systems.

V) Nurture future talents

This project gave a tremendous opportunity and research connections. Some students had directly engaged in working groups of industrial collaborative projects. Yuxin He and Ben Lin, CityU research students, were recruited as summer interns at MTR. Yuxin was conferred second place in INFORMS 2018 Railway Applications Section Student Paper Award for her work “Short-term forecasting of Origin-Destination matrix in rail system via a deep learning approach”.

TRS Project Student Presentations Workshop. A half day workshop with students from different disciplines was held in CityU. Students shared lots of ideas in diverse topics in relation to railway research. In the project, student's presentation becomes an important element in delivering positive learning experiences and receiving feedback from team members and fellow students.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?

TRS funding is critical to creating a solid interdisciplinary platform. This project has brought together more than 30 professors from engineering and management disciplines to work together in a coherent manner to cover the emerging research topics from system health monitoring, engineering asset diagnostics, crowd safety management, logistics, and disruption management. Both the intra- and inter-communication and the cooperation between the various sub-thematic groups were made much easier by this large-scale project. Without this funding, such intensive cooperation would have been difficult. At the same time, the relatively long project duration has provided sufficient time for the project team members to develop

their research base through the training of research staff and students.

6.3 If the project has not met its original objectives, why?

N/A

6.4 (a) Peer-reviewed journal publication(s) arising directly from this project:

The research progress was promising. We had produced numerous journal publications, conference papers and book chapter in various disciplines, including engineering, computer science, operations research management science, etc. Details of each publication were enclosed in Annex 1.

(b) Recognised international conference(s) in which paper(s) related to this project was/were delivered:

Our team actively presented research findings in international conferences. A list of conferences was attached in Annex 2.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

N/A

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

Southwest Jiaotong University and Shenzhen Metro. Project team had obtained data for empirical research that focused on geographically modeling and understanding factors influencing transit ridership and forecasting short-term passenger flow. Two papers had been published in this reporting period.

Beijing Jiaotong University and China Railway Shanghai Group. Joint research on object detection and track warning through image processing was conducted. The aim of the project was to develop an automatic and robust system to detect approaching train, track-side maintenance workers, and other unwanted objects. CRSG shared surveillance camera video data from Beijing-Shanghai high-speed railway to project team.

National Taiwan University. NTU had long-term collaborative relationship with various rail operators in Taiwan. Through this connection, we had established closer collaboration with Taipei Metro. A joint study with Prof Rex Lai on 'Development of rail maintenance task generation and scheduling model for Taipei Metro system' was completed, which aimed to develop a decision-support process to efficiently generate and schedule annual rail maintenance plans according to degradation models for rail component.

Nihon University. Zitong Li, research student, was selected for a three-month immersion with Prof Norio Tomii and Prof Hitoshi Tsunashima in College of Industrial Technology, Nihon University.

Research on agent-based pedestrian simulation model and application on passenger flow management in Japan railway stations were discussed. Several field surveys were conducted in JR East and JR West stations to observe passengers' alighting and boarding management in morning peak hours. A joint study with Prof Norio Tomii on "Evaluation of timetable robustness of Japan Railway" was completed.

Internal collaboration. Collaboration had been an integral part of our research, and our team

had expanded the necessary partnerships across departments and disciplines. Examples were as follows.

- KL Tsui (CityU) and NH Chan (CUHK): Passenger forecasting, time series modeling
- Alpha Ling (EduU) and KL Tsui (CityU): Reliability and degradation modeling
- Eric Lee (CityU) and Alpha Ling (EduHK): Axle bearing health monitoring
- SC Wong (HKU) and SM Lo (CityU): Crowd movement and flow modeling
- WK Chow (PolyU) and Richard Yuen (CityU): Fire hazards & evacuation modeling
- Eric Lee (CityU) and Antoni Chan (CityU): Crowd management through image processing
- Zijun Zhang (CityU) and Xiaowei Luo (CityU): ORIS for rail crack identification
- Lishuai Li (CityU) and KL Tsui (CityU): Escalator asset life prediction and management

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
At HKU			
Yaoming Zhou	PhD	Aug-14	Jul-18
Yan Wang	PhD	Aug-16	Jul-20
Yue Gao	PhD	Jul-17	Jun-21
Jiemin Xie	PhD	Sep-15	Aug-19
At CUHK			
Ng Wai Leong	PhD	Aug-16	Jul-19
Ying Tao	PhD	Aug-13	Jun-17
Zhelin Huang	PhD	Aug-14	Jun-18
Shan Dai	PhD	Aug-15	Jun-19
Dong Wang	PhD	Aug-15	Jun-19
Linhao Gao	PhD	Aug-15	Jun-19
Wenbin Ye	PhD	Aug-15	Jun-19
Yuxin Li	PhD	Aug-15	Jun-19
Zhong. Chen	PhD	Aug-16	Jun-20
Han, Chenyu	PhD	Aug-17	Jun-21
At PolyU			
Jan To	PhD	Jun-14	Dec-18
At CityU			
Liu Yu	PhD	Sep-14	Aug-17
Ning Hong	PhD	Sep-16	Aug-20
Chen Liang	PhD	May-14	Apr-17
Zitong Li	PhD	Sep-16	Aug-20
Liping Lian	PhD	Sep-14	Aug-17
Taiwo Joel Omoleye	PhD	Sep-16	Sep-19
Ben Lin	PhD	Sep-16	Aug-20
Fangfang Yang	PhD	Sep-13	Aug-17

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Peiwen Xu	PhD	Jun-16	May-19
Huihui Wang	PhD	Sep-11	Jul-16
Yihang Yang	PhD	Sep-16	Aug-20
Long Wang	PhD	Sep-14	Oct-17
Li Zhuang	PhD	Sep-16	Aug-20
Wei Fan	PhD	Sep-15	Aug-18
Seher Razzaq	PhD	Sep-16	Aug-20
Di Zhang	PhD	Sep-14	Jul-18
Rui Zheng	PhD	Sep-14	Oct-17
Faeez Masurkar	PhD	Sep-17	Jul-20
Kin Ming Ng	PhD	Sep-17	Jul-22
Di Kang	PhD	Sep-14	Jul-18
Yuxin He	PhD	Sep-17	Jul-20
Yi Li	PhD	Sep-16	Aug-20
HOU Zeyu	PhD	Sep-18	Jul-22
Imran Ghafoor	PhD	Sep-18	Jul-22
KHAN Moshin	PhD	Sep-18	Jul-22
Tiange Wang	PhD	Sep-18	Jul-22
Zicheng Fei	PhD	Sep-19	Jul-23
Yunyie Zhang	PhD	Sep-20	Jul-24
ZHAO Weizun	PhD	Oct-17	Jul-20
Weihong Ren	PhD	Sep-16	Nov-19
Tianyu Yang	PhD	Sep-15	Nov-19
Ying Chengshuo	PhD	Nov-17	Oct-21
Zhang Yunjie	PhD	Sep-19	Aug-23

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

- A Sagnac interferometer-based optical system (SIOS). The SIOS was a modified Sagnac interferometer with specially designed lens so that it could actuate Rayleigh waves in a rail specimen and then estimated the intrinsic nonlinearity of the rail material, thereby, SIOS was able to predict the current health status of the rail specimens.
- An experimental transduction system was designed to act as a non-destructive testing device for rails, I-beam and plates. The transduction system was embedded with virtual instruments and MATLAB codes.
- Collaborated with MTRC, we have developed a dashboard management system for crowd counting analysis and a frontend to display the results. We improved the system by retraining the crowd counting algorithm. The backend system is designed to count crowds in the camera streams, predict count in 5 minutes, predict passenger waiting time and detect congestion in certain regions. A front-end interface to view the data was developed, as well as a dashboard to view the situation in real-time.

6.8 Other education activities and/or training programmes developed:

The items are discussed in 6.1.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

N/A

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

The PC had played a significant role in coordination, leadership, and supervision. The PC consulted the management team to plan a long-range strategy in relation to the project mission and objectives. The PC was responsible for making a development plan and financial plans, promotion of the project, and fostering internal and external collaborations between academics and industry.
PC actively reached out to industry and research groups to foster collaborative partnerships at regional and international levels. The goals were to facilitate and encourage collaborative research on a grand scale, and to allow team members to learn from experts in diverse yet relevant disciplines.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

- Dr Lishuai Li and Prof Tsui secured over $1.44M in funding through ITC for a collaborative project with MTR (50% industrial contribution) and subsequent funding for research talent hub programme on "Escalator Health Condition Analytic Model"
- Dr KS Chin and Dr Yang Zhou were award 面上项目 "考虑行动方案优先级与协同机理的铁路应急预案评估模型" and 青年科学基金项目 "面向地铁客流大数据的统计机器学习关键技术研究", with direct project funding of $490,000 and $180,000 respectively.
- With the research experience earned from the TRS project, Prof YQ Ni of PolyU (PC), Prof Tsui (Co-PI) and Prof SM Lo (Co-PI) had collaborated and secured a Research Impact Fund titled "Enhancing Safety, Punctuality and Ride Comfort of Railway Transportation: From Local Metro System to Global High-speed Rail Network" amounted HK$5.89M.
- Prof S.C. Wong was awarded the "Mainland – Hong Kong Joint Postdoctoral Fellows Program under Hong Kong Scholars Program" to recruit Dr. Shuguang Zhan (SWJTU) to conduct postdoctoral research in Hong Kong for two years, amounted to HK$300,000.
- Masurkar Faeez Aziz, research student of Ir Dr. Peter W. Tse, was awarded the Outstanding Academic Performance Award and a Research Tuition Scholarship. His research interest is on fault detection using ultrasonic guided waves in RTA1.

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

Prof Xie and Prof Tsui actively organized international workshop and special session to discuss various issues including but not limited to system modelling, prediction and estimation, system maintenance, and the use of artificial intelligence approaches. We organized a Special Session on *Safety and Reliability of Intelligent Transportation Systems* in the 31st European Safety and Reliability Conference (ESREL2021); Keynote Panel on *Management of Intelligent Transportation Systems* in 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM2020), etc. In addition, as mentioned in 6.1, our project team, Beijing Jiaotong University and National Taiwan University co-organized Workshop on High-speed Rail Operation for Safety and Reliability annually to share and exchange their experiences in a wide range of topics to improve rail safety, reliability and efficiency.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

Editorship:

- Prof Kwok L Tsui, Department Editor, Quality and Reliability Engineering, IIE Transactions
- Prof Alain Bensoussan, Editor in Chief of Asymptotic Analysis Journal (IOS Press)
- Prof NH Chan, Managing Editor, International Journal of Theoretical and Applied Finance
- Prof WK Chow, Editor-in-Chief, International Journal on Engineering Performance-Based Fire Codes, and International Journal on Architectural Science
- Prof SC Wong, Editor-in-Chief, International Journal of Sustainable Transportation, Transportmetrica A
- Prof Min Xie, Editor of Book Series on Quality, Reliability and Engineering Statistics for World Scientific Publisher, and Department Editor of IIE Transactions

In addition, our members are fellows and academicians for various professional bodies, including American Statistics Association, French Academy of Sciences, Academia Europae, Asia-Oceania Association for Fire Science and Technology, Institute of Mathematical Statistics, Institution of Civil Engineers, IEEE, American Society of Mechanical Engineers (ASME), Hong Kong Institute of Engineers (HKIE), etc.

7.4 Any documentary proof of the application of technologies arising directly from this project?

Several patents are granted under the project as follows. Prof Antoni Chan, System and Method for Counting Objects (US11,048,948). Dr Zijun Zhang, A System And Method for Monitoring A Device (16/592,815), Dr Peter Tse, Apparatus for Magnetostrictive Sensor for Guided-Wave-Based Inspection, and its Associated System and Method (US10,181,371).

7.5 Other awards and recognitions as a result of this project (please specify):

Project PC and Co-PIs (Prof Xie, Prof Tsui, Prof Wong, Prof Chow, Prof Li, Prof Lo, Dr Tse) were listed as World's Top 2% Scientists by Stanford. This recognition acknowledged the research strength of our team.

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8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of

Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Our project team had strong links with industry and external organizations. As mentioned above, collaboration with industry and external research groups had enabled to deliver high impact applied work tailored to the project on high-speed rail and metro systems. Through our annual board meeting, project team channelled research insight to management level of rail operators and regulatory authority. To generate economic and social impacts, project teams had taken up consultancy service with EMSD and ITF project with MTR.

8.2 Others (please specify):

N/A

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

The project team had gained vast knowledge in extremely rapidly developing interconnected fields of remote sensing and monitoring, real-time probabilistic and statistical analysis of large, high-velocity data streams, and decision-theoretic techniques for economical operation of safe and reliable engineering systems.

Reliability modeling is performed using fault tree analysis, event tree analysis, failure mode, effect, and criticality analysis. Fusion modeling and filtering estimate components' remaining useful life and optimize condition-based maintenance. Anomaly detection, failure discrimination and fault diagnostics develop a healthy system baseline model under normal working conditions, and fault signatures extracted from fault data. Quality and reliability engineering methods have been successfully applied to many manufacturing and service industries to enable process improvement in dynamic systems, product performance optimization, and product and process re-engineering.

Hazards mitigation in stations and allied facilities will model the control of fire and smoke spread, and provide hazard control and management, egress planning and strategies, and emergency responses. Passenger demand analysis and passenger flow prediction model can predict crowding risk. CCTV data and gate records will track individual passengers through pattern recognition and simulate rail systems passenger mobility. Disruption management is studied to optimally plan and dynamically manage the recovery from a disruption to ensure the best cost-effective services. Many of the studies are validated with real data.

9.2 Whether there are new projects evolved directly from this project?

CityU, as the coordinating unit, leads way on industry-academic collaborative proof-of-concept projects. Details are discussed in 6.1.

MTR Corporation	- Permanent rail crack detection - Axle bearing failure diagnostics - Car roof top crack detection - Condition monitoring for escalators - Crowd management and people counting
CRRC Qingdao Sifang Co., Ltd. Southwest Jiaotong University	- Bearing fault diagnosis - High-speed train tracking data analysis
Shenzhen Metro Southwest Jiaotong University	- Passenger flow forecasting for disruption management, traffic scheduling and maintenance planning - Passenger traveling behaviour analysis

Taipei Metro National Taiwan University	- Condition-based maintenance for rail infrastructure - Monitoring system for train operation and driver behaviour - Replacement planning strategies for signal system
Taiwan High Speed Rail Corporation National Taiwan University	- High-speed train delay duration estimation

9.3 Whether there are new collaborations developed directly from this project?

Southwest Jiaotong University, Beijing Jiaotong University, National Taiwan University, Nihon University, The Railway Branch of Electrical and Mechanical Services Department, MTR Corporation, Shenzhen Metro, China Railway Shanghai Group, Taipei Metro, Seoul Metro, etc. Details are discussed in 6.1 and 6.5.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

Dr Lishuai Li and Prof Tsui secured over $1.44M in funding through ITC for a collaborative project with MTR (50% industrial contribution) and subsequent funding for research talent hub programme on "Escalator Health Condition Analytic Model".

10. Statistics on Research Outputs

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	211	15 papers & 136 presentations	1	3	Dataset	3

11. Public Access of Completion Report

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons
N/A	N/A

12. The Layman's Summary

Large network systems for electricity transmission, passenger transport, supply chain management, internet connectivity, finance and other applications may be increasing in complexity faster than we can ensure their safe, reliable and efficient operation. Monitoring technologies have developed just as rapidly, yielding large quantities of data. Massive challenges loom, however, in the synthesis of monitoring techniques with effective ways to mine the resulting data for information that can be acted on quickly and effectively.
Hong Kong has a reputation for innovation, dependability, efficiency and accountability in business services. Our proposal seeks to extend Hong Kong's advantages by establishing it as a center of expertise in the safety, reliability, and efficient management of complex network systems. We will focus specifically on high-speed rail (HSR) and urban (metro) train systems. It is anticipated that project results will be transportable to other complex network systems.

Our world-class team has expertise in the rapidly developing interconnected fields of remote sensing and monitoring, real-time probabilistic and statistical analysis of large, high-velocity data streams, and decision-theoretic techniques for economical operation of safe, reliable engineering systems. The proposed research is in two areas: ensuring the safety and reliability of HSR and metro engineering systems; and ensuring the safe and efficient management of passenger capacity, demand, scheduling and pricing. We will also prescribe decision processes for disaster management and rescheduling in the event of disruptions.