CLASSIFICATION OF RAIL DEFECT BASED ON B-TYPE DISPLAY IMAGE USING DEEP LEARNING METHOD

LI JIE

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : DOH SHU ING

Position : ASSOCIATE PROFESSOR

Date : 16/06/2023

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

李杰

(Student's Signature)

Full Name : LI JIE

ID Number : MAH21011

Date : 03/06/2023

CLASSIFICATION OF RAIL DEFECT BASED ON B-TYPE DISPLAY IMAGE USING DEEP LEARNING METHOD

LI JIE

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

FACULTY OF CIVIL ENGINEERING TECHNOLOGY

UNIVERSITI MALAYSIA PAHANG

June 2023

ACKNOWLEDGEMENTS

My utmost gratitude goes to Associate Professor Dr. Doh Shu Ing, my supervisor for his remarkable patience and constructive suggestions that proved invaluable throughout this project. I may not have gone this far without his support and guidance.

I also owe a debt of gratitude to Dr Lim Kar Sing and Prof Md Abdul Mannan for their generous comments during the viva voce. Indeed, their knowledge and expertise are indispensable in enabling me to undertake this journey, and whose support and guidance were immensely appreciated.

I wish to express my appreciation to my lab technician and collaborator particularly my lab partner, for their valuable aid and technical expertise. I am also grateful to the university's librarians, research assistants, and study participants whose contributions had a profound impact on me and served as a source of inspiration.

Finally, I would like to acknowledge my family, most notably my parents and siblings, for their unwavering faith in me, which sustained my enthusiasm and determination throughout this endeavour.

ABSTRAK

Pengesanan kerosakan rel merupakan kaedah utama untuk memastikan pengangkutan kereta api selamat. Ketersediaan maklumat kerosakan rel membolehkan jabatan kereta api menentukan integriti rel keluli dan menyediakan pelan yang sesuai dalam proses pengoperasian dan penyelenggaraan kereta api. Bagaimanapun, pengesanan kerosakan rel pada masa kini masih bergantung kepada kaedah tradisional yang memerlukan intensiti tenaga kerja yang tinggi dan memakan masa. Tenaga kerja sedia ada tidak dapat menampung keperluan industri kereta api yang semakin meningkat. Tambahan pula, kaedah tradisional ini terdedah kepada kesilapan yang boleh mengurangkan ketepatan proses pengesanan kerosakan. Oleh itu, kajian ini bertujuan untuk mencadangkan kaedah pengecaman automatik berdasarkan pembelajaran mesin dan pemprosesan imej bagi menyediakan proses pengesanan kerosakan yang lebih cekap dan mampan di samping mengurangkan keperluan tenaga kerja yang tinggi. Untuk mencapai matlamat tersebut, objektif-objektif kajian adalah untuk: (1) Untuk mengklasifikasikan kerosakan rel keluli dengan menggunakan tenaga manusia; (2) Untuk membangunkan model pembelajaran mendalam untuk mengklasifikasikan kerosakan rel keluli berdasarkan imej paparan jenis B; dan (3) Untuk mengoptimumkan model pembelajaran mendalam dengan variasi yang berbeza. Dalam fasa 1, sejumlah 6000 imej kerosakan rel telah dikumpul dari Jabatan Kereta Api China Railway Hohhot. Kerosakan keluli tersebut telah diklasifikasikan dan dikenalpasti. Dalam fasa 2, model ResNet50 dibangunkan untuk pengesanan dan pengelasan kerosakan rel keluli. Kajian ini menggunakan 5000 imej kecacatan rel keluli sebagai data latihan untuk melatih model ResNet50, dan kemudian menggunakan 1000 imej rel keluli sebagai data ujian untuk mengesahkan struktur model. Dalam fasa 3, ResNet50 yang baru dibangunkan dioptimumkan dengan mengubah nilai parameter rangka kerja model, 14 keputusan analisis data akhir akhirnya diperolehi. Analisis kesesuaian dan penumpuan keputusan data menunjukkan model ResNet50 boleh memperoleh hasil yang optimum pada Epoch11. Kajian ini mendapati ketepatan keseluruhan model ResNet50 yang dicadangkan adalah 100% dalam set data ujian dan masa pengesanan satu imej kerosakan adalah 156 ms/imej, manakala baki tiga kaedah pembelajaran mendalam lain iaity GoogleNet, VGGNet dan AlexNet semuanya mencapai ketepatan <95 %. Keputusan perbandingan menunjukkan bahawa model ResNet50 yang dicadangkan berpotensi untuk digunakan pada pengenalpastian automatik dan klasifikasi kerosakan rel berskala besar.

ABSTRACT

The rail defect detection is the main method to ensure that the railway transportation is safe. The availability of rail defect information enables the railway departments to determine the integrity of the steel rail and provide suitable plans for railway operation and maintenance. However, the current rail defect detection still relies on the traditional method which require high manpower intensity and time consuming. The high manpower at the current state is unable to cater for the growing need of the railway industries. Furthermore, the traditional method is prone to errors and mistake which reduces the accuracy of the defect detection process. Therefore, this study aims to propose an automated recognition method based on machine learning and image processing to provide more efficient defect detection process while reducing the need of manpower. To achieve that aim, the objectives are to: (1) To classify the steel rail defect by using manpower; (2) To develop deep learning models to classify steel rail defect based on B-type display image; and (3) To optimize deep learning models with different variations of epoch. In phase 1, a total of 6000 rail defect images has been collected from China Railway Hohhot Railway Department. The defects were classified and identified. In phase 2, a newly developed model ResNet50 has been developed for steel rail defect identification and classification. This study uses 5000 steel rail defect images as training data to train ResNet50 model, and then using 1000 steel rail images as testing data to validate model structure. In phase 3, the newly developed ResNet50 are optimized by varying the parameter values of the model framework, 14 final data analysis results were finally obtained. The analysis of the fit and convergence of data results shows that the ResNet50 model can obtain optimal results at Epoch11. This study found that the overall accuracy of the proposed ResNet50 model was 100% in the test dataset and the detection time of a single defect image was 156 ms/ image, while the remaining three deep learning GoogleNet, VGGNet and AlexNet methods were <95%. The comparative results show that the proposed ResNet50 model has the potential to be applied to the automatic identification and classification of large-scale rail defects.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ETR	Elettro Treno Rapido
TGV	Train à Grande Vitesse
CRH	China Railway High-speed
EU	European Union
RCF	Rolling Contact Fatigue
NDT	Non-destructive Testing
CNN	Convolutional Neural Network

LIST OF LABEL

LIST OF APPENDICES

REFERENCES

Abdelhafiz, D., Yang, C., Ammar, R., & Nabavi, S. (2019). Deep convolutional neural networks for mammography: advances, challenges and applications. *BMC bioinformatics, 20*(11), 1-20. doi:https://doi.org/10.1186/s12859-019-2823-4

Akhtar, S. W., Rehman, S., Akhtar, M., Khan, M. A., Riaz, F., Chaudry, Q., & Young, R. (2016). Improving the robustness of neural networks using K-support norm based adversarial training. *IEEE Access, 4*, 9501-9511. doi:https//10.1109/ACCESS.2016.2643678

Al-Haija, Q. A., & Adebanjo, A. (2020). Breast cancer diagnosis in histopathological images using ResNet-50 convolutional neural network. Paper presented at the 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS). doi:https://10.1109/IEMTRONICS51293.2020.9216455.

Alahakoon, S., Sun, Y. Q., Spiryagin, M., & Cole, C. (2018). Rail flaw detection technologies for safer, reliable transportation: a review. *Journal of Dynamic Systems, Measurement, and Control, 140*(2). doi:https://doi.org/10.1115/1.4037295

Aleshin, N., Grigor'ev, M., Shchipakov, N., Krys'ko, N., Krasnov, I., Prilutskii, M., & Smorodinskii, Y. G. (2017). On the possibility of using ultrasonic surface and head waves in nondestructive quality checks of additive manufactured products. *Russian Journal of Nondestructive Testing, 53*(12), 830-838. doi:https://doi.org/10.1134/S1061830917120026

Aydin, A., Salur, M. U., & Aydin, İ. (2021). *Fine-Tuning Convolutional Neural Network Based Railway Damage Detection.* Paper presented at the IEEE EUROCON 2021-19th International Conference on Smart Technologies. doi:https://10.1109/EUROCON52738.2021.9535585

Azimy, H., Meghdadi Isfahani, A. H., & Farahnakian, M. (2022). Investigation of the effect of ultrasonic waves on heat transfer and nanofluid stability of MWCNTs in sono heat exchanger: an experimental study. *Heat and Mass Transfer, 58*(3), 467-479. doi:https://10.1007/s00231-021-03126-6

Aleksić, D., Marković, M., Vasiljević, M., Stojić, G., Pavlović, N., & Tanackov, I. (2018). Analysis of impact of meteorological conditions on human factors in estimating the risk of railway accidents. Transport, 33(5), 1121-1134. doi:https://doi.org/10.3846/16484142.2017.1332684

Bailey, J. (2022). The steam age—Evolution of steam engines and the 1st steam locomotive. *In Inventive Geniuses Who Changed the World*. 23-36: Springer. doi:https://10.1007/978-3-030-81381-9_3

Cao, X., Xie, W., Ahmed, S. M., & Li, C. R. (2020). Defect detection method for rail surface based on line-structured light. Measurement, 159, 107771. doi:https://doi.org/10.1016/j.measurement.2020.107771

Cao, Y., An, Y., Su, S., Xie, G., & Sun, Y. (2022). A statistical study of railway safety in China and Japan 1990–2020. Accident Analysis & Prevention, 175, 106764. doi:https://doi.org/10.1016/j.aap.2022.106764

Carvalho, S., Partidario, M., & Sheate, W. (2017). High speed rail comparative strategic assessments in EU member states. Environmental Impact Assessment Review, 66, 1-13. doi:https://doi.org/10.1016/j.eiar.2017.05.006

Chen, Z., Wang, Q., Yang, K., Yu, T., Yao, J., Liu, Y. He, Q. (2021). Deep learning for the detection and recognition of rail defects in ultrasound B-scan images. *Transportation Research Record, 2675*(11), 888-901. doi:https://doi.org/10.1177/03611981211021547

Chen, Z., Wang, Q., He, Q., Yu, T., Zhang, M., & Wang, P. (2022). CUFuse: Camera and ultrasound data fusion for rail defect detection. IEEE Transactions on Intelligent Transportation Systems, 23(11), 21971-21983. doi:https://10.1109/TITS.2022.3189677

Cherubini, S., Iasevoli,Gennaro,Michelini,Laura. (2015). Product-service systems in the electric car industry: critical success factors in marketing. *Journal of Cleaner Production, 97*, 40-49. doi:https://doi.org/10.1016/j.jclepro.2014.02.042

Chotzoglou, A., Pissas, M., Zervaki, A., Haidemenopoulos, G., & Pissas, T. (2019). Visualization of the Rolling Contact Fatigue Cracks in Rail Tracks with a Magnetooptical Sensor. *Journal of Nondestructive Evaluation, 38*(3), 1-8. doi:https://doi.org/10.1007/s10921-019-0606-5

Dong, G., Sun, S., Wang, Z., Wu, N., Huang, P., Feng, H., & Pan, M. (2022). Application of machine vision-based NDT technology in ceramic surface defect detection–a review. *Materials Testing, 64*(2), 202-219. doi:https://doi.org/10.1515/mt-2021-2012

Dwivedi, S. K., Vishwakarma, M., & Soni, A. (2018). Advances and researches on non destructive testing: A review. *Materials Today: Proceedings, 5*(2), 3690-3698. doi:https://doi.org/10.1016/j.matpr.2017.11.620

Fengshou, L. (2018). Research on Early Defect and Defect of High-speed Railway Rails in China. *Rail Construction, 58*(01), 138-140.

Freimanis, A., & Kaewunruen, S. (2018). Peridynamic analysis of rail squats. *Applied Sciences, 8*(11), 2299. doi:https://doi.org/10.3390/app8112299

Goel, P., & Ganatra, A. (2022). *A Pre-Trained CNN based framework for Handwritten Gujarati Digit Classification using Transfer Learning Approach. Paper presented at the 2022 4th International Conference on Smart Systems and Inventive Technology (ICSSIT).,* pp. 1655-1658. doi: https://doi.org/10.1109/ICSSIT53264.2022.9716483.

He Kaiming, Z. X., Ren Shaoqing,Sun Jian. (2016). *Deep residual learning for image recognition.* Paper presented at the Proceedings of the IEEE conference on computer vision and pattern recognition.

Hua, L., Zheng, W., & Gao, S. (2019). *Extraction and analysis of risk factors from Chinese railway accident reports.* Paper presented at the 2019 IEEE Intelligent Transportation Systems Conference (ITSC). doi:https:doi:10.1109/ITSC

Huang Mengying, L. J., Wang Wenxing. (2020). Research on rail damage classification algorithm based on image processing. *Locomotive Electric Drive*(04), 41-46+53.

Huang Xiaoyan, S. Y., Zhang Yuhua. (2018). Research on classification technology of B-display data damage pattern of ultrasonic rail flaw detector. *CHINA RAILWAY*(3), 82-87.

Kumar, B. R. (2022). Case 1: The Chuo Shinkansen Project, *Japan. In Project Finance , Springer*, 87-90. doi:https://10.1007/978-3-030-96725-3_5

Khalid, N. I. M., Najdi, N. F. N., Adlee, N. F. K., Misiran, M., & Sapiri, H. (2019). *Assessing railway accident risk through event tree analysis.* Paper presented at the AIP Conference Proceedings.

Kim, G., Seo, M.-K., Kim, Y.-I., Kwon, S., & Kim, K.-B. (2020). Development of phased array ultrasonic system for detecting rail cracks. *Sensors and Actuators A: Physical, 311*, 112086. doi:https://doi.org/10.1016/j.sna.2020.112086

Khalid, N. I. M., Najdi, N. F. N., Adlee, N. F. K., Misiran, M., & Sapiri, H. (2019). *Assessing railway accident risk through event tree analysis.* Paper presented at the AIP Conference Proceedings. doi:https:// doi.org/10.1063/1.5121060

Kyriakidis, M., Majumdar, A., & Ochieng, W. Y. (2015). Data based framework to identify the most significant performance shaping factors in railway operations. *Safety science, 78*, 60-76. doi:https://doi.org/10.1016/j.ssci.2015.04.010

Luo, Q., Fang, X., Liu, L., Yang, C., & Sun, Y. (2020). Automated visual defect detection for flat steel surface: A survey. IEEE Transactions on Instrumentation and Measurement, 69(3), 626-644. doi:https://doi: 10.1109/TIM.2019.2963555

Law, S., Seresinhe, C. I., Shen, Y., & Gutierrez-Roig, M. (2020). *Street-Frontage-Net: urban image classification using deep convolutional neural networks. International Journal of Geographical Information Science*, 34(4), 681-707. doi:https://doi.org/10.1080/13658816.2018.1555832

Li, C., Tang, T., Chatzimichailidou, M. M., Jun, G. T., & Waterson, P. (2019). *A hybrid human and organisational analysis method for railway accidents based on STAMP-HFACS and human information processing. Applied ergonomics, 79,* 122-142. doi:https://doi.org/10.1016/j.apergo.2018.12.011

Lei, C. (2016). Talking about the daily application of GCT-8C digital rail flaw detector in rail flaw detection. *Shandong Industrial Technology* (19), 201.

Lesiak, P., & Sokołowski, A. (2017). Evaluation of Head Defect Images of Railway Rails in Laser Scatterometry. *Problemy Kolejnictwa.*

Li, W., & Zhang, H. (2017). *A FPGA based ultrasonic rail flaw detection system.* Paper presented at the 2017 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT).

Liu, X., Saat, M. R., & Barkan, C. P. (2014). Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation. *Journal of Hazardous Materials, 276*, 442-451. doi:https://doi.org/10.1016/j.jhazmat.2014.05.029

Luo Jiangping, Y. X., Cao Jingwei. (2021). Rail damage intelligent identification system based on deep learning and support vector machine. *Locomotive Electric Drive*(02), 100-107.

Lam, C. Y., & Tai, K. (2020). Network topological approach to modeling accident causations and characteristics: Analysis of railway incidents in Japan. Reliability Engineering & System Safety, 193, 106626. doi:https://doi.org/10.1016/j.ress.2019.106626

Muhamedsalih, Y., Hawksbee, S., Tucker, G., Stow, J., & Burstow, M. (2021). Squats on the Great Britain rail network: Possible root causes and research recommendations. *International Journal of Fatigue, 149*, 106267. doi:https://doi.org/10.1016/j.ijfatigue.2021.106267

Mićić, M., Brajović, L., Lazarević, L., & Popović, Z. (2023). Inspection of RCF rail defects–Review of NDT methods. Mechanical Systems and Signal Processing, 182, 109568. doi:https://doi.org/10.1016/j.ymssp.2022.109568

Milo, D., Principe, L., Deng, J., Zhou, K., & Liu, X. (2018). *A Literature Review of Rail Defect Causal Factors. Paper presented at the ASME/IEEE Joint Rail Conference.* doi:https://doi.org/10.1115/JRC2018-6162

Nath, S., & Raganata, G. (2020). An Assessment of Economic and Financial Impacts of Jakarta-Bandung High-Speed Railway Project. *Journal of Business and Political Economy: Biannual Review of The Indonesian Economy, 2*(1), 45-55. doi:https://doi.org/10.46851/27

Nonaka, N., Muraoka, K., Okuyama, T., Suyama, S., Okumura, Y., Asai, T., & Matsumura, Y. (2020). *28 GHz-Band experimental trial at 283 km/h using the Shinkansen for 5G evolution.* Paper presented at the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring).

Pietikäinen, M., & Silven, O. (2022). Challenges of Artificial Intelligence--From Machine Learning and Computer Vision to Emotional Intelligence. *arXiv preprint arXiv:2201.01466*. doi:https://doi.org/10.48550/arXiv.2201.01466

Punyaratabandhu, P., & Swaspitchayaskun, J. (2018). The political economy of China–Thailand development under the one belt one road initiative: Challenges and opportunities. *The Chinese Economy, 51*(4), 333-341. doi:https://doi.org/10.1080/10971475.2018.1457326

Ray, S. (2019). *A quick review of machine learning algorithms.* Paper presented at the 2019 International conference on machine learning, big data, cloud and parallel computing (COMITCon).

Sen, P. K., Bhiwapurkar, M., & Harsha, S. (2022). Parametric features of an UIC60 rail at weld bottom crack in transverse direction under weld-wheel contact forces. *Materials Today: Proceedings, 56*, 717-721. doi:https://doi.org/10.1016/j.matpr.2022.01.282

Shultz, J. M., Garcia-Vera, M. P., Santos, C. G., Sanz, J., Bibel, G., Schulman, C., Rechkemmer, A. (2016). Disaster complexity and the Santiago de Compostela train derailment. *Disaster health, 3*(1), 11-31. doi:https://doi.org/10.1080/21665044.2015.1129889

Simonyan, K., & Zisserman, A. (2014). Very deep convolutional networks for large-scale image recognition. *arXiv preprint arXiv:1409.1556*. doi:https://doi.org/10.48550/arXiv.1409.1556

Song, Y., Hua, L., Wang, X., Wang, B., & Liu, Y. (2016). Research on the detection model and method for evaluating spot welding quality based on ultrasonic A-scan analysis. *Journal of Nondestructive Evaluation, 35*(1), 4. doi:https://10.1007/s10921-015-0319-3

Su F, L. Q., LUO Renze. (2019). Review of image classification based on deep learning. *Review, 35*(11), 58-74.

Tu, Z., Wu, S., Kang, G., & Lin, J. (2021). Real-time defect detection of track components: Considering class imbalance and subtle difference between classes. IEEE Transactions on Instrumentation and Measurement, 70, 1-12. doi:https://10.1109/TIM.2021.3117357

Tao, X. (2018). Discussion on the Sectional Shape of Train Rails Based on the Knowledge of "Mechanics of Materials". South Agricultural Machinery, 49(12), 198.

Theckedath, D., & Sedamkar, R. (2020). Detecting affect states using VGG16, ResNet50 and SE-ResNet50 networks. *SN Computer Science, 1*(2), 1-7. doi:https://doi.org/10.1007/s42979-020-0114-9

Voulodimos, A., Doulamis, N., Doulamis, A., & Protopapadakis, E. (2018). Deep learning for computer vision: A brief review. *Computational intelligence and neuroscience, 2018*. doi:https://doi.org/10.1155/2018/7068349

Wang, G., Xie, L., Jiang, C., Liu, X., Li, Y., Yu, F., & Zhao, X. (2022). High performance piezoelectric crystal cut designed using LiNbO 3 for high temperature acoustic emission sensing application. *CrystEngComm*. doi:https://doi.org/10.1039/D1CE01521D

Wang, B., Zhong, S., Lee, T.-L., Fancey, K. S., & Mi, J. (2020). Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review. Advances in mechanical engineering, 12(4), 1687814020913761. doi:https://doi.org/10.1177/1687814020913761

Wu, F., Li, Q., Li, S., & Wu, T. (2020). Train rail defect classification detection and its parameters learning method. *Measurement, 151*, 107246. doi:https://doi.org/10.1016/j.measurement.2019.107246

Wu, F., Xie, X., Guo, J., & Li, Q. (2021). Internal Defects Detection Method of the Railway Track Based on Generalization Features Cluster. doi:https://doi.org/10.21203/rs.3.rs-399710/v1

Xiaoming, T. (2017). Experimental Study on Frequency Spectrum Component Model of Noise Source outside CIT500 Train. *Journal of the China Railway Society, 39*(7), 32-37. doi:https://10.3969/j.issn.1001-8360.2017.07.005

Xiaowei, L. (2021). Analysis of the Reasons for the Inconsistent Flaw Detection of the Rail Head. *Journal of Wuhan Engineering Vocational and Technical College, 33*(03), 18-20.

Xu, Q., Zhao, Q., Yu, G., Wang, L., & Shen, T. (2020). *Rail defect detection method based on recurrent neural network.* Paper presented at the 2020 39th Chinese Control Conference (CCC).

Xu, W. (2012). Analysis on the Cause of High-speed Railway Accidents and Discussion on Rescue. *China Emergency Rescue, 2012*(4), 34-37.

Xu, Q., Zhao, Q., Yu, G., Wang, L., & Shen, T. (2020). Rail defect detection method based on recurrent neural network. Paper presented at the 2020 39th Chinese Control Conference (CCC). doi:https://10.23919/CCC50068.2020.9188823

Zerbst, U., Lundén, R., Edel, K.-O., & Smith, R. A. (2009). Introduction to the damage tolerance behaviour of railway rails–a review. *Engineering fracture mechanics, 76*(17), 2563-2601. doi:https://doi.org/10.1016/j.engfracmech.2009.09.003

Zhang, W., Zhang, Q., & Cao, W. (2021). Study on Stress and Deformation of Bolt Joints of Shield Tunnel under Static and Seismic Action. *KSCE Journal of Civil Engineering, 25*(8), 3146-3159. doi:https://doi.org/10.1007/s12205-021-1339-4

Zhao, H., Liang, J., & Liu, C. (2020). High-speed EMUs: characteristics of technological development and trends. *Engineering, 6*(3). doi:https://doi.org/10.1016/j.eng.2020.01.008

Zhiwei, W. (2022). Research and Application of Dual Rail Ultrasonic Flaw Detector in Plateau and High Altitude Area. *N D T, 46*(1), 31-36. doi:https://10.13689/j.cnki.cn21-1230/th.2022.01.008

Zhouxin, W. (2020). Study on Rail Service Status and Disease Treatment of Rail for High Speed Railway. *Rail Construction, 60*(08), 126-129+142. doi:https://10.3969/j.issn.1003-1995.2020.08.29

Zhao, Y., Liu, Z., Yi, D., Yu, X., Sha, X., Li, W. (2022). A review on rail defect detection systems based on wireless sensors. Sensors, 22(17), 6409. doi:https://doi.org/10.3390/s22176409

Zemin, J. (2012). Criminal Law of the People's Republic of China. Chinese L. & Gov't, 45, 53. doi:https://10.2753/CLG0009-4609450104

Zhang, Z., Turla, T., & Liu, X. (2021). Analysis of human-factor-caused freight train accidents in the United States. Journal of Transportation Safety & Security, 13(10), 1157-1186. doi:https://doi.org/10.1080/19439962.2019.1697774