Advances in Human Factors of Transportation, Vol. 186, 2025, 492–501
https://doi.org/10.54941/ahfe1006539

On Track for Safety: Redefining Color Vision Standards in U.S. Railway

Juksana Mai Ngam, Zander N. Miller, Ainsley N. Bernard, Corey A. Gregory, and Alex Chaparro

Department of Human Factors and Behavioral Neurobiology, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA

ABSTRACT

The U.S. railway industry faces growing concerns due to an aging workforce and rising demand for skilled personnel, particularly in safety-critical roles like locomotive engineers and conductors. Recruitment efforts are further challenged by outdated color vision assessments mandated by the Federal Railroad Administration (FRA), which rely on tests such as Ishihara and Hardy-Rand-Ritter plates. These methods often fail to detect subtle or acquired color vision deficiencies (CVDs), overlook non-red-green variations, and do not reflect the visual demands of real-world railway environments, increasing the risk of signal misinterpretation, operational delays, and accidents. This paper reviews current federal regulations and compares railway vision testing practices with those in other safety-critical fields, such as aviation. It also explores alterative assessments such as computerized tools, virtual reality, and augmented reality to enhance diagnostic accuracy and consistency. Effective implementation will require regulatory updates, staff training, and sustained investment in research. Considerations of these advancements will allow the railway industry to better identify and manage CVDs, ultimately enhancing safety across railway operations.

Keywords: Color vision deficiency, Color vision testing standards, Railway safety, Railway operations

INTRODUCTION

In the U.S., the demand for various services provided by the railway industry is steadily increasing, raising the demand for not just workers but specifically highly skilled workers. However, the U.S. already faces the issues presented by an aging workforce (Popkin et al., 2008). Within the railway industry, color vision deficiencies (CVDs) pose a significant challenge. Implementing modern standards can help prevent individuals with CVDs from safety-critical roles that require a certain threshold of color vision to ensure safe operations (Barbur & Rodríguez-Carmona, 2017). However, existing federal regulations, testing standards, and assessment tools used to evaluate color vision are problematic due to known limitations in reliability and validity. For example, while the Ishihara test can correctly diagnose whether an individual has CVD, it is unable to determine the type of deficiency or the severity (Van Staden et al., 2018). Additionally, those who fail standard CVD tests may be offered a field test as an alternative, and passing the field test qualifies them to work. However, there is little to no reliability or validity within these field tests (Raslear & Multer, 2015). This review analyzes the current practices for screening CVDs in the U.S. railway industry. Specifically, it will examine testing requirements in the industry and compare them to requirements in other regulated industries, present evidence that demonstrates the negative impacts that failing to detect CVDs has, examine why failures in detecting CVDs occur, and provide possible avenues for improving testing procedures.

COLOR VISION BACKGROUND

There are several types of CVD, including red-green, blue-yellow, and complete CVD. Difficulty discriminating between red, greens, and yellow is the most common and includes four different types: deuteranomaly, where greens appear more red; protanomaly, where reds appear more green; and protanopia and deuteranopia, where it is not possible to distinguish between red, green and yellow. Difficulty discriminating between blues and yellows is less common and includes two types: tritanomaly, where it is harder to distinguish blue from green and yellow from red, and tritanopia, where it is harder to distinguish blue from green, purple from red, and yellow from pink. The complete loss of color vision or achromatopsia is the rarest type of CVD. Red-green CVDs affect about 8–10 percent of men and 0.5% of women of European descent (Chaparro & Chaparro, 2017), and the severity of the condition can range from mild to severe. Deficiencies in blue-yellow color vision are much less common, affecting approximately 0.02% or less of the male population. CVD manifests either as genetically inherited, known as congenital or X-link CVD (Rodríguez-Carmona & Barbur, 2017), or may be acquired later in life due to injury or disease processes. As per the National Eye Institute (2024), most cases of CVD are congenital and remain stable without improvement or worsening over time. However, CVD can also develop later in life due to the development of cataracts, eye diseases such as macular degeneration and retinitis pigmentosa, eye or brain injury, and the use of some medications (e.g., Plaquenil).

CURRENT PRACTICES FOR DETECTING COLOR VISION DEFICIENCIES

The 1875 Lagerlunda train collision in Sweden was the first accident to prompt the introduction of color vision testing in railway operations after ophthalmologist Frithiof Holmgren speculated that CVD among train personnel may have been a contributing factor (Mollon & Cavonius, 2012). While investigations pointed to multiple factors, including miscommunication and human error, Holmgren convinced officials to implement mandatory color vision screening for railway workers, setting a precedent for safety regulations worldwide. Over time, additional incidents where CVD was identified as a possible cause (Frey, 1975; NTSB, 1997; NTSB, 2013) led to further refinements in testing standards. Today, the

Federal Railroad Administration (FRA) mandates color vision testing under Safety Advisory 98–01, focusing on signal discrimination, specifically, the ability to "recognize and distinguish among the colors used as signals in the railroad industry" (Qualification and Certification of Locomotive Engineers, 1991). Examiners administer tests such as the Dvorine and Ishihara, and candidates who fail may take a practical field test with an emphasis on yellow signal recognition. Examiners also have the authority to restrict candidates to work environments that do not hinder their vision.

It is useful to compare FRA practices to other government organizations where color vision testing is mandated, such as the Federal Aviation Administration (FAA). One of the tests used by the FAA is the City Occupational Color Assessment and Diagnostic (CAD) test. The CAD consists of tasks that require color naming and color arrangement that evaluate both color recognition and discrimination abilities under controlled conditions. It serves as an alternative for individuals who do not pass standard color vision screening tests, such as the Ishihara plates, and provides a more comprehensive assessment of functional color vision. If an applicant successfully completes the CAD, they may be eligible for an unrestricted medical certificate, allowing them to perform aviation duties without limitations related to color vision. Initial screening may be performed using the "fast" version of the CAD test, which is a streamlined variant designed to reduce the testing time while maintaining accuracy in assessing color vision. It uses a subset of the full test's stimuli to quickly measure an individual's ability to discriminate colors along key chromatic axes (red-green and blue-yellow). This version is particularly useful in high-throughput or time-constrained environments, such as aviation medical assessments, where rapid and reliable determination of color vision sufficiency is needed. The fast version retains the precision necessary for ensuring compliance with aviation safety standards. If the operator fails the fast version of the CAD test, however, a more in-depth examination is conducted using the full set of test stimuli.

The FAA also approves the use of the Waggoner Computerized Color Vision Test (CCVT) (FAA, 2024). This test is similar to the Ishihara test, which has letters or shapes of one color embedded in a background of a different color. The CCVT uses a series of computer-based tasks to determine an individual's ability to distinguish colors essential for aviation operations. The test accurately measures red-green and blue-yellow color discrimination thresholds, providing precise and reliable results (Gao, 2022). Its automated and standardized format also allows for consistent evaluation, making it a convenient and effective tool for assessing color vision in pilots and air traffic controllers. In addition, the CCVT is able to identify the type of CVD (e.g., protanopia, deuteranopia, or tritanopia) an operator may have (FAA, 2024). As of January 1, 2025, the FAA mandates all color vision tests be conducted using computer-based methods, replacing traditional paper-based pseudoisochromatic plate (PIP) tests like the Ishihara and Dvorine color vision tests (FAA, 2024). This is an effort to increase standardization throughout the industry and ensure more accurate tests without the possible impacts of color fading and inconsistent lighting.

IMPACTS OF UNDETECTED COLOR VISION DEFICIENCIES

A railroad train operator's ability to accurately interpret signals is foundational to railway safety. Undetected CVDs can lead to operational inefficiencies, economic costs, and long-term consequences for the railway industry (Multer et al., 2019). The critical role of color-coded signals must be considered when establishing regulatory benchmarks. Much like traffic lights, these signals guide train movements to prevent collisions. For instance, three vertical red lights indicate a stop, while the introduction of a single yellow light conveys a cautionary warning (NTSB, 1997). Misinterpretation of these signals can increase crash risks, making undetected CVDs a significant safety concern.

Despite the FRA's mandatory screening requirements, some operators may still bypass detection, as seen in the New Jersey Transit (NJT) commuter train collision, which prompted the current railway regulations (NTSB, 1997). This case highlights an experienced engineer with diabetic retinopathy whose color vision impairment went undetected by NJT due to inadequate testing and underreporting. The engineer was administered a Dvorine PIP test by an NJT physician, which he failed. He then underwent a second Dvorine test, focused on color naming rather than discrimination, which revealed a moderate handicap due to CVD. While this was sufficient for non-color-dependent tasks, accurate color vision is crucial for train operators. Unfortunately, the engineer relied on light intensity to discriminate between the signal lights, resulting in misreading a stop signal as caution, which contributed to the collision (NTSB, 1997). This incident demonstrates the dangers of inadequate CVD regulations in safety-critical roles.

Undetected CVDs not only pose safety risks but also lead to operational inefficiencies and economic impacts. As noted above, operators with CVDs may rely on light intensity to differentiate signals, which can be problematic and inaccurate in poor lighting or adverse weather conditions (Pridmore, 1999). This can result in slower operations, disrupted schedules, and reduced network efficiency (Versluis et al., 2024), creating delays that spill across both passenger services and freight systems, affecting the reliability of rail transport. Moreover, train collisions or derailments caused by misinterpreted signals can incur substantial costs for the party found at fault, including repairs to infrastructure, litigation fees, and compensatory payouts (Funk, 2023). Without reliable, efficient, and medically relevant standards for assessing color vision, employers must allocate extra resources to mitigate these risks, such as additional training, automatic stop systems, or supplementary warning systems. While implementing these practices may aid the performance of color-deficient individuals, the approach redirects resources, funds, and training efforts from other crucial areas.

The aging workforce also presents a challenge to railway safety due to the increased prevalence of age-related eye conditions affecting color vision. According to the Centers for Disease Control and Prevention (2024), 12 million Americans over 40 experience vision issues. This places many railway workers in a demographic at risk for vision impairments, as the average age of railway workers is 42.8 years (Bureau of Labor Statistics, 2024). Acquired CVD is more common than congenital forms and often stems from eye conditions such as glaucoma, macular degeneration, diabetic retinopathy, and retinitis pigmentosa. These conditions affect 5 to 15% of the population and primarily impact blue-yellow color discrimination (Simunovic, 2016). The natural aging process also contributes to color vision challenges as the eye's crystalline lens yellows over time, absorbing more short-wavelength light and making it harder to distinguish between yellow, blue, and white signals. This change can have serious implications for railway safety. For instance, an operator with blue-yellow CVD may mistake a yellow signal (caution) for white signal (proceed at restricted speed) on a bright day. Less common signals, such as blue (indicating workers on a track), may also appear dim or resemble green depending on the type of CVD. Additionally, cataracts are commonly developed after the age of 40 due to protein breakdown in the eye's lens, which reduces sensitivity to short-wavelength light, exacerbating these color vision challenges (Mehta et al., 2020). As the railway workforce expands to meet increasing demand, addressing these color vision-related safety concerns becomes crucial for maintaining operational safety and efficiency. Implementing reliable and valid testing protocols for identifying CVDs is essential to preserve public trust in rail travel as a safe and sustainable transportation option.

EXPLANATIONS FOR FAILURES TO DETECT COLOR VISION DEFICIENCIES

Despite established CVD detection practices and the significant safety risks of undetected cases, CVDs often go unnoticed in the railway sector. PIP tests, like the Ishihara and Hardy-Rand-Rittler (HRR) tests, are widely used for screening but have notable limitations. The Ishihara test identifies only 50% of males with inherited red-green CVD and is ineffective for detecting blue-yellow deficiencies and acquired CVD related to aging or ocular diseases (Shin et al., 2007; Green, 2007). The HRR test, while including both red-green and blue-yellow plates, may still miss subtle variations in color perception (Cole et al., 2006). Additionally, the Farnsworth hue test, which requires individuals to arrange colored caps in sequence, often fails to detect mild or complex CVD cases, such as anomalous trichromacy (Evans et al., 2020). Furthermore, its reliability can be affected by test administration factors, including test administrators' allowance for minor errors and the potential for improved performance with practice, which can mask underlying deficiencies, according to Ng & Liem (2018). These limitations underscore the need for more comprehensive and precise methods for assessing CVD in critical fields such as transportation and safety-sensitive industries.

LITERATURE EXAMPLES AIMED AT ENHANCING COLOR VISION TESTING

The CAD test is currently the most widely used assessment across various industries due to its ability to distinguish normal color vision from congenital or acquired CVD, as well as identify the severity of blue-yellow and red-green color loss (Ballard, 2013; Rodríguez-Carmona, 2022). However, to enhance color vision testing for railway employees, Birch & Rodríguez-Carmona (2014) recommend combining traditional methods like the Ishihara and Farnsworth tests with modern technologies to enhance accuracy, as integrating multiple testing modalities can improve diagnostic accuracy by cross-validating results and detecting cases that a single test might miss. For instance, traditional color vision tests require consistent lighting, a limitation computer-based assessments can overcome. These digital platforms also offer higher resolution, improving the reliability of CVD assessments, and eliminate examiner variance, ensuring consistent pass/fail decisions that are fairer to all candidates (Birch & Rodríguez-Carmona, 2014). Additionally, Arnegard et al. (2022) found that genetic testing using the MassArray genotyping system, which analyzed participants' saliva samples, detected twice as many color-deficient individuals as PIP tests alone, highlighting the traditional tests' inability to identify mild red-green deficiencies. Their study revealed that combining genetic testing with PIP tests improved diagnostic accuracy and reduced false negatives, with Hardy-Weinberg equilibrium calculations confirming the validity of the findings.

Advancements in technology are paving the way for more immersive and realistic assessments, which have the potential to lead to more accurate results. For instance, Cárdenas-Delgado et al. (2021) proposed a study to assess CVDs using virtual reality (VR) devices. The authors are developing a visual color test (VR-test ViKi) based on the Ishihara test, including visual and kinesthetic stimulation. The virtual environment will include 3D objects, a short path, and a virtual task under sunny, rainy, and night conditions, using two types of head-mounted displays. The virtual task involves driving and identifying numbers that appear randomly, where participants must say and remember the numbers they see. The study will compare the performance between the Ishihara test and the VR-based ViKi test to improve the visual evaluation process in access to aviation schools (Cárdenas-Delgado et al., 2021). Additionally, VR technology may be leveraged to simulate dynamic, real-world railway operation scenarios, which allows candidates to experience and respond to color-related tasks in a controlled yet realistic space. By replicating railway operations, this approach can help understand how candidates perceive colors in the context of their specific job tasks and help identify subtle CVDs that may go undetected through other testing methods.

Significant advancements have also been made in wearable technologies aimed at improving color perception for individuals with CVDs. One leading technology is a wearable augmented reality system developed by Melillo et al. (2017). This device was designed to enhance color vision and was validated in a clinical study. The study found that participants saw an improved Ishihara test score (from 5.8 $\pm$3.0 to 14.8 $\pm$5.0) with the device's correction. Nearly all participants experienced enhanced color vision, and notably, 50% of them were able to pass the color vision test as normal vision subjects. This initial validation suggests that wearable augmented reality technology could be a valuable tool for improving color vision in individuals with deficiencies

(Melillo et al., 2017). These studies demonstrate that integrating multiple methods (traditional and computer-based assessments, genetic testing, and VR and wearable technologies) can lead to more accurate evaluations and help color-deficient individuals perform tasks that would otherwise be challenging. As these technologies continue to make headway, ongoing advancements have the potential to increase their effectiveness and aid color-deficient individuals in the transport industry, opening up opportunities that were previously out of reach.

FUTURE DIRECTIONS

Given the lack of reliability and validity of the current tests and CVD assessments used in the railway industry, it is crucial to explore the implementation of new technologies and methodologies to address this problem. Although new assessment tools may allow for more reliable and valid measures of CVD, their use requires several changes. First, regulatory frameworks will need updating, as they typically specify the tests used to assess individuals for CVDs. As new tests and strategies are adopted, these frameworks must adapt to include the newly utilized methods. Additionally, developing and implementing new training for test administrators will be necessary. Establishing effective training protocols requires both training specialists and subject matter experts, which can be costly. Investment in research is also crucial for successfully developing and integrating these technologies. Implementing computer and VR systems requires careful consideration of the time and costs associated with calibration of display hardware, ease of use, and efficiency of testing procedures. Lastly, while combining traditional tests with genetic testing offers more accurate results, this method is costly, time-consuming, and intrusive for test candidates, making it unideal for diagnosing CVDs.

CONCLUSION

The U.S. railway industry currently faces challenges in effectively detecting and managing CVD despite their crucial role in ensuring safe and efficient operations. This review details current practices and their shortcomings and compares them to standards in other regulated industries, such as the FAA's use of the CAD and Waggoner tests. This illustrates the lag in utilizing modern and technologically advanced solutions by the railway industry. The review also outlined the consequences of failing to detect CVDs, including operational inefficiencies, economic costs, and, in severe cases, fatalities and injuries to workers and passengers. These failures can result from tests only examining specific CVD types, improper administration of tests, incorrect analysis of data, and workers learning to bypass the tests. To address these issues and improve CVD detection in the U.S. railway industry, traditional methods such as the Ishihara and Farnsworth tests should be combined with modern technology to increase accuracy and overcome their limitations. The integration of multiple test modalities, including evidence-based tests such as the CAD, along with new technology like VR for simulation-based training, should be prioritized and utilized more frequently. Ultimately, the U.S. railway industry must keep up with current technologies, literature, and best practices utilized in other regulated industries to allow for continuous improvements in the detection and management of CVDs.

REFERENCES

Arnegard, S., Baraas, R. C., Neitz, J., Hagen, L. A., & Neitz, M. (2022). Limitation of standard pseudoisochromatic plates in identifying colour vision deficiencies when compared with genetic testing. *Acta ophthalmologica, 100*(7), 805–812.

Ballard, J. (2013). Colour-vision safety on track. *Occupational Health at Work, 10*(1), 20–23.

Barbur, J. L., & Rodríguez-Carmona, M. (2017). Colour vision requirements in visually demanding occupations. *British medical bulletin*, *122*(1), 51–77.

Birch, J., & Rodríguez-Carmona, M. (2014). Occupational Color Vision Standards: New prospects. *Journal of the Optical Society of America A: Optics, Image Science & Vision (JOSA A)*, *31*(4).

Cárdenas-Delgado, S., Loachamín-Valencia, M., & Rodríguez-Reyes, B. (2021). VR-test viki: VR test with visual and kinesthetic stimulation for assessment color vision deficiencies in adults. *Smart Innovation, Systems and Technologies*, 295–305.

Center for Disease Control and Prevention. (2024, May 15). *Fast Facts: Vision loss*. Vision and Eye Health. https://www.cdc.gov/vision-health/data-research/vision-loss-facts/index.html

Chaparro, A., & Chaparro, M. (2016). Applications of color in design for color-deficient users. *Ergonomics in Design: The Quarterly of Human Factors Applications*, *25*(1), 23–30.

Cole, B. L., Lian, K. Y., & Lakkis, C. (2006). The new Richmond HRR pseudoisochromatic test for colour vision is better than the Ishihara test. *Clinical and Experimental Optometry*, *89*(2), 73–80.

Evans, B. E., Rodríguez-Carmona, M., & Barbur, J. L. (2020). Color vision assessment-1: Visual signals that affect the results of the Farnsworth D-15 test. *Color Research & Application*, *46*(1), 7–20.

Federal Aviation Administration. (2024). Guide for Aviation Medical Examiners. *Item 52 Color Vision.* https://www.faa.gov/ame_guide/app_process/exam_tech/item52/et

Frey F. G. (1975). Ein Eisenbahnunglück vor 100 Jahren als anlass für systematische Untersuchungen des Farbensehens [A railway accident a hundred years ago as reason for systematic testing of colour vision (author's transl)]. Klinische Monatsblatter fur Augenheilkunde, 167(1), 125–127. German. PMID: 1104986.

Funk, J. (2023, October 25). *Derailment costs grow for Norfolk Southern but railroad's trains moving more smoothly.* Associated Press News. https://apnews.com/article/norfolk-southern-earnings-railroad-east-palestine-derailment-10f01782a697d887684dfff744379493

Gao, H., Kirkendall, C. D., Kinney, M. J., Preston, A. M., & Reddix, M. D. (2023). Color Vision Testing, Standards, and Visual Performance of the U.S. Military. *Military Medicine*, *188*(1–2), 49–57.

Green, K. (2007). Acquired Colour Vision Assessment - Is Ishihara Really Enough? *Australian Orthoptic Journal, 39*(1), 24–30. https://www.aojournal.com.au/static/uploads/files/aoj20073907-wfjsqtdqxedl.pdf

Mehta, U., Diep, A., Nguyen, K., Le, B., Yuh, C., Frambach, C., Doan, J., Wei, A., Palma, A. M., Farid, M., Garg, S., Kedhar, S., Wade, M., Marshall, K. A., Jameson, K. A., Cristina Kenney, M., & Browne, A. W. (2020). Quantifying color vision changes associated with cataracts using cone contrast thresholds. *Translational Vision Science & Technology*, *9*(12), 11.

Melillo, P., Riccio, D., Di Perna, L., Sanniti Di Baja, G., De Nino, M., Rossi, S., Testa, F., Simonelli, F., & Frucci, M. (2017). Wearable improved vision system for color vision deficiency correction. *IEEE Journal of Translational Engineering in Health and Medicine*, *5*, 1–7.

Mollon, J. D., & Cavonius, L. R. (2012). The Lagerlunda collision and the introduction of color vision testing. *Survey of Ophthalmology, 57*(2), 178–194.

Multer, J., Safar, H., Roth, E. M., & France, M. (2019). Why do passenger trains pass stop signals? A systems view. (No. DOT/FRA/ORD-19/19). *Federal Railroad Administration*. https://rosap.ntl.bts.gov/view/dot/40900

National Eye Institute. (2024, December 6). *Causes of color vision deficiency*. U.S. Department of Health and Human Services, National Institutes of Health. https://www.nei.nih.gov/learn-about-eye-health/eye-conditions-and-diseases/color-blindness/causes-color-vision-deficiency

National Transportation Safety Board. (1997). *Near Head-On Collision And Derailment Of Two New Jersey Transit Commuter Trains Near Secaucus, New Jersey, February 9, 1996*. Railroad Accident Report NTSB/RAR-97/01. Washington, DC.

National Transportation Safety Board. (2013). *Head-On Collision of Two Union Pacific Railroad Freight Trains Near Goodwell, Oklahoma, June 24, 2012*. Railroad Accident Report NTSB/RAR-13/02. Washington, DC.

Ng, J. S., & Liem, S. C. (2018). Can the Farnsworth D15 color vision test be defeated through practice? *Optometry and Vision Science*, *95*(5), 452–456.

Popkin, S. M., Morrow, S. L., Di Domenico, T. E., & Howarth, H. D. (2008). Age is more than just a number: Implications for an aging workforce in the US transportation sector. *Applied ergonomics*, *39*(5), 542–549.

Pridmore, R. W. (1999). Bezold–Brucke Hue-shift as functions of luminance level, luminance ratio, interstimulus interval, and adapting white for aperture and object colors. *Vision Research*, *39*(23), 3873–3891.

Raslear, T. G., & Multer, J. (2015). *Railroad signal color and orientation: Effects of color blindness and criteria for color vision field tests* (No. DOT/FRA/ORD-15/03). United States. Federal Railroad Administration. Office of Research and Development.

Rodríguez-Carmona, M. (2022). Advances in colour vision assessment. In *XIII Congreso Nacional del Color: Terrassa, 29–30 juny-1 juliol, 2022* (p. 14). Universitat Politècnica de Catalunya.

Rodríguez-Carmona, M., & Barbur, J. L. (2017). Variability in normal and defective colour vision: Consequences for occupational environments. In *Colour design* (pp. 43–97). Woodhead Publishing.

Qualification And Certification Of Locomotive Engineers, 49 C. F. R § 240 (1991). https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-240

Shin, Y. J., Park, K. H., Hwang, J.-M., Wee, W. R., & Lee, J. H. (2007). A new color vision test to differentiate congenital and acquired color vision defects. *Ophthalmology*, *114*(7), 1341–1347.

Simunovic, M. P. (2016). Acquired color vision deficiency. *Survey of Ophthalmology*, *61*(2), 132–155.

United States Bureau of Labor Statistics. (2024) . *Labor Force Statistics from the Current Population Survey.* https://www.bls.gov/cps/cpNsaat18b.htm

Van Staden, D., Mahomed, F. N., Govender, S., Lengisi, L., Singh, B., & Aboobaker, O. (2018). Comparing the validity of an online Ishihara colour vision test to the traditional Ishihara handbook in a South African university population. *African Vision and Eye Health*, *77*(1), 1–4.

Versluis, N. D., Quaglietta, E., Goverde, R. M. P., Pellegrini, P., & Rodriguez, J. (2024). Real-time railway traffic management under moving-block signalling: A literature review and research agenda. *Transportation Research Part C: Emerging Technologies*, *158*, 104438.