Visual communications of transportation system:

Using information design to strengthen the legibility of transit maps

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Abstract

This thesis developed design solutions to enhance the legibility of transit maps by using information design knowledge. The author followed a user-centred approach to observe participants' reading behaviour and provide design solutions that meet user needs and expectations.

In this study, the transit map is re-defined as an information design material rather than a cartographic map or a computerised diagram. The transit map design is divided into three main topics: information communication, visual design, and user performance. China's high-speed railway map is used as a case study where user performance tests are conducted to ascertain whether re-designing the map according to information design principles improves the map's legibility and makes it more user-friendly. The main focus is on information communication effectiveness, including map legend and instructional systems on the map; and on the visual design elements, including colour system, transit line layout, transfer signs and typography, etc. Finally, design guidance is established for transit maps based on literature review and on the research findings of this study. This guidance is aimed at providing designers and researchers with both theoretical and practical design suggestions.

Several research methods are included in this research study. Literature was reviewed to establish the theoretical basis for the empirical tests and relevant evaluation standards. Eye-tracking testing helped identify the map's strengths and potential design limitations in terms of information communication and visual design. It also assisted in observing users' reading strategy and habits based on the eye-movement data. The user performance tests helped evaluate the legibility of the existing map and the revised maps in terms of reading speed, information searching accuracy and route planning quality. The interviews and questionnaires helped collect users' opinions and suggestions, which reinforced the analysis of the experimental results.

The results indicate that information design plays a vital role in transit map design on many aspects. The information communication quality of the map legend can largely affect the legibility of transit maps; users showed a faster reading speed and better information searching accuracy after the necessary instructions were visualised. The colour system showed its unreplaceable advantage in transit map visual design, especially in distinguishing and grouping

different categories of travel information and map functions, such as different transit lines, services and icons, etc. In addition, a new colour-coding mode for transit lines that combines both qualitative and sequential schemes was created. Its effectiveness was then tested through usability testing. Users' reading speed and comfort was improved after the colour system was re-coded based on the new standard. This research also breaks Beck style (45°octolinear layout) in transit line schematical layout, widely recognised as "golden standard". The test results show that 60° octolinear layout could be the most suitable layout for the North-south direction middle-complex network. Moreover, the study shows that the visual design of micro visual elements (e.g., interchange icons, station labels) should always assist the information communication of the macro transit line layout. The test results would not be applicable to real life contexts if the design of individual elements was investigated separately from the whole information design structure.

The empirical research findings from this study are an essential contribution and a good demonstration that information design is of great importance to cartographic design. The study demonstrates a successful example that evaluated, improved and tested the legibility of a transit map by using existing information design principles and theories. The principles that then also emerge from this study are a strong contribution to knowledge in the field of information design and will provide valuable insight to researchers and designers. In addition, the methodologies used in the research can also support information design research beyond map design, such as information reading materials that contain various categories of instructions and data.

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1. Introduction

1.1. Context

Transit map design is a special topic in cartographic design and it has various design requirements that are different from a geographic map. Similar to all other maps, the basic function of a transit map is to guide the users in identifying their current location and looking for or arranging their destination routes (Passini, 1984). The first railway routes map was designed in 1874 to show the topographic surface of the railway lines (Ovenden, 2005). In 1932, Henry C. Beck, an engineer who worked in London Underground, created an epoch-making transit map that transformed the irregular curved lines into strict schematical alignment based on horizontal, vertical and diagonal 45° angles. This creation started a new era for transit map design (Bain, 2010). The design standard is also known as Beck's rule or octolinearity, which is the most widely used layout globally (Roberts, 2012). Some other schematical layouts were developed afterwards, such as multilinearity, hexalinearity, curvilinearity and concentric layout (Ovenden, 2003; Wu et al., 2020). Apart from the **macro** layout of the transit network, other **micro** design elements are also key factors that may affect the legibility of a map, such as signs, graphs, fonts and colours (Avelar and Hurni, 2006; Guo, 2011; Morgagni and Grison, 2019; Raveau, Guo and Munoz, 2012; Raveau, Muñoz and Grange, 2011; Roberts et al., 2013; Roberts and Rose, 2016; Xu, 2017, Guo et al., 2017).

A transit map consists of both **information** and **visual design elements**. The transit system can be understood as a network that allows passengers to enter, travel across and exist (Cartwright, 2014). The passenger needs to find a starting station to begin the journey and decide how to travel on the network to reach the destination (Keates, 1989). This process includes various decisions and specific information requirements at each stage of the trip (Bain, 2010). This brings to various main questions: What quantity and what quality of the information can meet users' travel needs? What layout of the transit lines can efficiently enhance users' route planning? And how can visual design elements be improved and manipulated to simplify users' information searching process?

There are researchers from different areas of expertise (including computer science, cartography, mathematics, even psychology) who investigated these questions (Roberts, 2012) and tried to simplify the map design process. For example, the research of automatic map producing technology (Nollenburg and Wolff, 2011; Stott and Rodgers, 2004). Most existing studies focused on a specific topic in terms of cartography, visual design, typography and user performance. These include, for example, the distortion of the topography (Roberts and Rose, 2016); the schematical layouts of transit lines (Roberts, Gray and Lesnik, 2017); the improvement of the station labelling (Yoeli, 1972; Imhof, 1975); the colour-coding of a transit system (Buard, Ruas, 2012); the users' reading behaviour when using maps (Netzel et al., 2016); the users' preference in map design (Grison, 2019); etc. In addition, some researchers (Dziekan, 2018; Monmonier, 2010; Roberts, 2019) investigated users' way-finding efficiency when using transit maps. In this research, both users' reading time and information searching accuracy are main factors when evaluating the legibility of a design example. Station finding or route finding is not always meaningful in usability tests, they have a considerable chance factor (Wu et al., 2020). Such as, the participant notices the target destination/line by chance, then the time or accuracy of the way finding tasks are not objective enough to support a specific conclusion.

In the existing studies, most researchers focused on transit maps' typographic features and network structures, even some geographic researchers defined transit maps as diagrams (Horne, 2012). There are very limited studies concerning information design aspects of transit maps, nor making connections with users' reading behaviour. A transit map is an information design material that involves various categories of related informative elements. This means that several information and instructional design topics need to be considered, such as data visualisation (map legend, visualised supplement description), infographics (visualised travel information), visual design elements (transit lines, instructional signs), typography (texts, station labels), etc. All these should therefore be designed systematically and as a whole to avoid a mismatch when combining elements that were designed separately (Roberts, 2012; Wu et al., 2020). In general, according to Avelar and Hurni (2006), visual information is either poor or insufficient for transportation users, one main reason being the lack of documentation and standardisation in transit map design. For conventional maps, there are a series of general rules for designers to follow, and the break of rules may cause a negative impact on map effectiveness. Similar to this, transit map designers also need some general guidance. As mentioned previously, most existing practical studies focused on specific design elements in transit map design and made improvements to each one individually, rather than treating the transit map as an overall piece of information design material and carrying out overall assessment and improvement.

A well-designed transit map should be neat and easy to understand, guiding users to wherever they plan to go on the transit network and be able to do so quickly and with no confusion (Philips and Noyes, 1982). In order to achieve this goal, in this research, China's high-speed railway map is selected as a case study to evaluate its legibility in terms of information structure and visual communication.

According to information from the Ministry of Transport of the People's Republic of China (2020), in 2019 around 60 million international tourists travelled to China by railway (95% of 63.1 million international tourists who visited China in 2019; the data of that in 2020 and 2021 are considered to lack representativeness due to the global epidemic). This indicates that the railway is the most popular transportation choice for international travellers and, therefore, this provides evidence of the need for a well-designed transit map of China's high-speed railway system. Due to such high demand and use, the Ministry of Transport (PRC) acknowledges the need to evaluate the design quality of China's current high-speed railway map. China's current high-speed railway map (English version) was updated in 2017 (Figure 1.1) and it has been widely promoted online and displayed in railway stations since then (Figure 1.2).

Apart from its considerable potential users, existing China's high-speed railway map is a particular design example that strictly follows the 45° octolinear layout principle, also known as Beck Style that was created in the 1930s. Beck simplified the shapes of London Underground lines on the map by using lines with 45° angle, this design style was widely used afterwards, more than half of the world's transit maps are designed based on this "golden rule" (Nollenburg and Wolff, 2011; Ovenden,2005; Roberts, 2012; Roberts et al., 2013). In addition, the existing map allocated the cities based on real topographic positions to keep geographic accuracy, and apply to users' mental models of the place, this method has been widely used in most transit maps, especially after the failure design case of New York Subway transit map in the 1970s. (Hochmair, 2009; Larkin and Simon, 1987; Marcus, 2016; Mollerup, 2015; Roberts, 2013; Roberts, Gray and Lesnik, 2017). Overall, existing China's high-speed railway map is an octolinear layout transit map based on topographic accuracy rules, which is a representative design example of the world's transit maps.

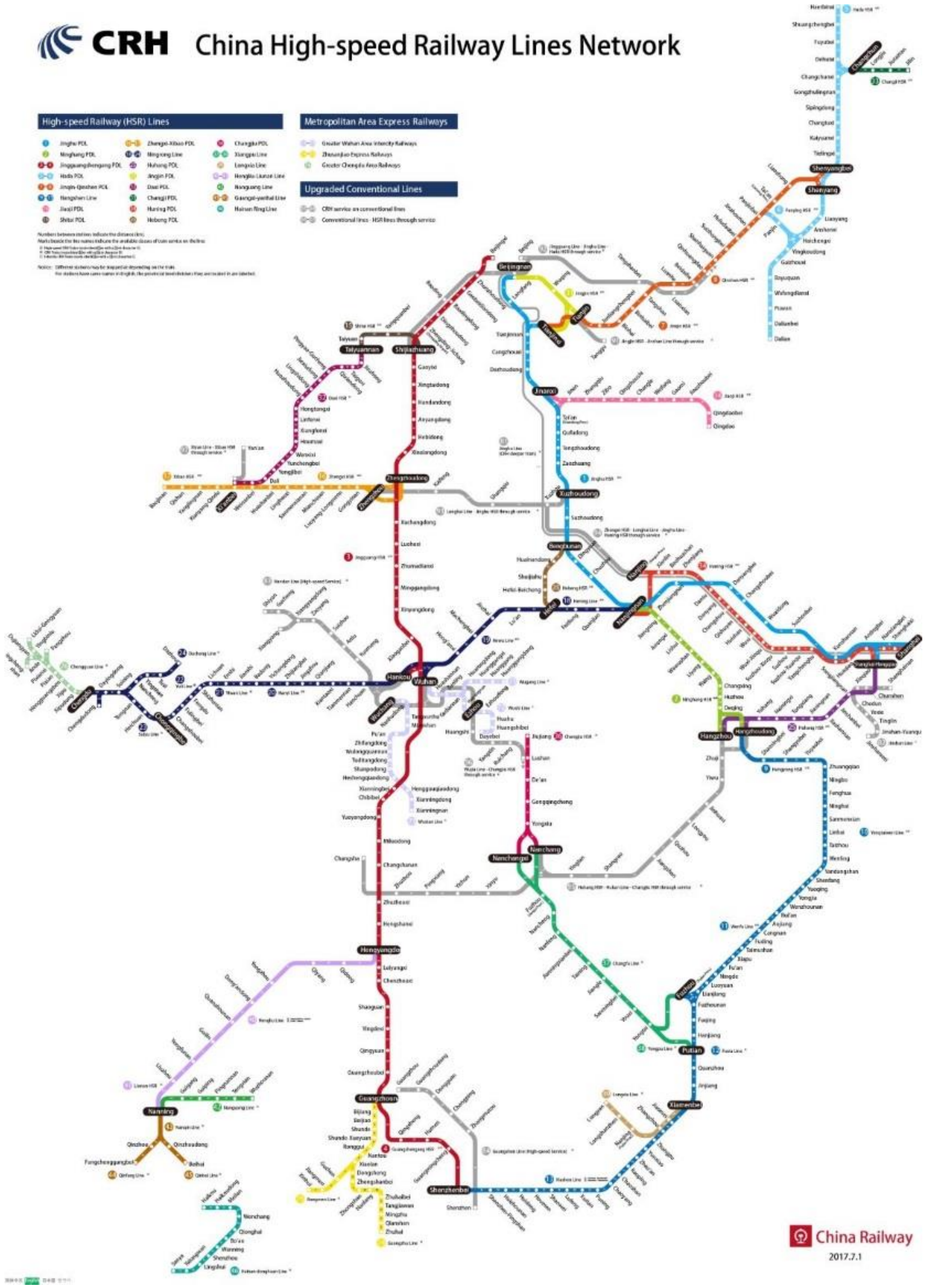


Figure 1.1: China's high-speed railway map

Figure 1.2: The high-speed railway station in Nanjing

To solve this problem and make design improvements, the identified design limitations China's current high-speed railway map that may affect the user's reading efficiency in terms of speed and accuracy will be improved based on information design principles and will be tested with suitable participants. At the end of the research, the design principles and findings from this study will be integrated to form a general transit map design guidance framework that can be used by designers and researchers.

1.2. Research aims, objectives and research questions

The **first** aim of this research is to investigate how information design as a whole (I.e., the combination of various features including visual design elements, data, typography, etc.) affects the legibility (factors that may affect the reading efficiency, accuracy, comfort and habit) of a transit map based on users' reading strategy, reading speed and information searching accuracy. This is a step forward and moves away from most map performance tests that only focused on individual features. The **second** aim is to develop effective design solutions to improve a transit map's information structure and visual design quality with a user-centred approach, which helps to strengthen the connection and consistency of different design features in a map, and lead to better legibility that guides readers to use the map more efficiently. The **third** aim is to develop a general map design guide that includes visual design examples, which provides designers and researchers with both theoretical and practical design suggestions that have been tested in this research study, as well as some other effective design solutions developed in relevant academic studies.

In order to achieve the research aims, the main objectives are:

1. To find out what design limitations in terms of information structure and visual elements affect the legibility of the map, and how they affect peoples' reading strategy, speed and accuracy.
2. To understand and strengthen the relationship between the information and visual features on the map, making them more systematic, relevant and mutually supportive.
3. To explore effective visual design solutions (e.g. data visualisation, colour-coding, typography and transit line schematic layout) that enhance the effectiveness and aesthetics of the map.
4. To investigate and analyse users' map reading strategy and habits, not only taking into account user-centred design solutions in transit map design, but also consider users' preference and performance when using the map (bearing in mind that some user preferences may conflict with certain design solutions that show to be effective in the performance test).
5. To build up design guidelines for transit map design based on experimental results and other empirical studies, not only limit to the map that is used in this study as the test material.

In this research, four key research questions are answered in the empirical tests:

- How do the macro information structure and transit line layout of the map affect users' map reading strategy and efficiency? What information design limitations of the map can be identified through user performance tests?
- How do the micro visual design and typographic design elements (e.g. instructional signs, station labels and informative explanations) affect users' route planning decisions and reading comfort?

- How does the colour system of the map affect users' reading speed and information searching accuracy? What colour-coding solutions can make the colour system more effective and aesthetically pleasant?
- What effective design approaches can enhance the legibility of a transit map through information and data visualisation?

Achieving these aims and objectives will contribute to transit map legibility research by providing empirical evidence on the influence of information structure, schematical layout and visual design elements on users' performance. The study will also provide practical design solutions and examples that may benefit the designers and researchers in relevant research areas for both information design and cartographic design.

1.3. Research methods and structure of the thesis

This section briefly introduces the key methods used in the study, applied to the content and research purpose of each chapter, and shows the empirical research process and the main achievements in each stage.

To achieve the aims described in the previous section, in this study all the methods follow a user-centred approach. This is a different approach from the traditional methods that map designers used previously to construct the information structure that was only based on its topography and functions, and then provide a large number of visual instructions to guide users in understanding and using different functions in different situations (Zoltowski, Oakes, and Cardella, 2012). This process may ignore the fact that users may not be able to process such a large amount of information when using the map, which could easily cause "information pollution" (Roberts, 2012). Information design materials designed only relying on functional requirements and the designer's own assumptions often lack a connection between elements and are poorly organised, consequently hindering how users read or operate (Kouprie and Visser, 2009). According to Roberts (2012) and Wu et al. (2020), designers' unwarranted assumptions in map design can cause problems in the quantity, quality, and visualisation of the information. To avoid this, performance tests based on the user's actual route planning can objectively evaluate the readability of a map and understand the user's needs and their reading difficulties (Roberts, 2012; Wu et al., 2020). Designers need to develop design solutions according to users' needs, goals, tasks and user habits as closely as possible (Endsley and Jones, 2012; Strickfaden and Devlieger, 2011). With this in mind, this study focuses on users' reading speed, information searching accuracy and reading habits to investigate how information design affects reading efficiency and user behaviour when using a railway map.

STAGE ONE

In the first stage, literature was reviewed to build up a theoretical basis for information design approaches in transit map performance in terms of information communication and visual design. As previously mentioned, the transit map is evaluated and investigated as an information design piece of material rather than scattered visual elements in the study.

Chapter 2: A review of the literature on information design theories that are applied to cartographic design, especially focused on general design principles for the construction of a transit map's information system and visual communication. This chapter takes the transit map as a whole information design material for in-depth interpretation and analysis, which builds up an initial evaluation framework for the map performance test that takes place in the next stage.

STAGE TWO

In the second stage, based on the academic principles reviewed in Chapter 2, the study focuses on how users access the information on a transit map and what design limitations may affect the legibility of a map. As Macdonald and Waller (1998) defended, information design is not only a process that transforms complex information into clear, well-organised and understandable information, but also needs to have an understanding of users' information needs, and how users access and make use of the displayed information. In order to understand this, an **eye-tracking** study that analyses users' information searching process is presented in Chapter 3. Data are collected and compared based on task time, accuracy and efficiency, as well as users' map using behaviour.

Chapter 3 (Experiment I): A scoping study and an eye-tracking test are conducted to identify the design limitations of China's high-speed railway map (e.g., information design structure, colour, visual elements, and typography) that affect users' information searching speed and accuracy. The results are analysed based on users' eye-movement data that explains how the map's legibility and people's reading behaviour is affected by the identified issues. This user-centred performance test shows that the main design limitations of the current map focus on information communication, colour system, transit line layout, and station labelling. These issues is then further investigated and improved via both theoretical principles and practical solutions.

STAGE THREE

In the third stage, based on the main design limitations of the map identified in Chapter 3, the colour system, information communication and transit line layout are investigated further. More detailed literature focusing on these topics is reviewed, and various design solutions to improve the map design are implemented according to empirical theories. The following tests compare users' reading speed, information searching accuracy, route planning efficiency and reading behaviour when using existing and revised map designs.

Chapter 4 (Experiment II): A thorough review of the literature on colour theories that mainly includes transit map colour-coding principles, colour harmony combinations, and design considerations that may benefit colour-deficient users. Further literature review analyses how colours can be used to enhance the legibility and aesthetics of the transit map, which provide valuable insights for the coming colour system redesign work. Then a new colour system is established based on the colour theories, and its effectiveness is evaluated by conducting map performance tests. The combination of both qualitative and sequential colour schemes shows to be effective, and the design also considers colour-deficient users. This experiment further investigates the effect of colours on a transit map's legibility and colour-coding design principles in cartographic design.

Chapter 5 (*Experiment* III): Relevant literature is reviewed on transit map design principles in terms of macro layout and micro designs, as well as on user performance studies. Various design examples are further analysed based on empirical studies. The extended literature review provides theoretical support for the revision work in map legend visualisation, line layouts and typography (e.g., information simplification principles, different transit line layout schemes, and visual instructions design principles). There are three different transit line layout schemes applied to the network based on design principles: the octolinear plan 45°, the octolinear plan 60°, and the curvilinear map. The legibility of the three redesigned maps is tested and made comparisons with the existing map. The impact of macro transit line layout and micro design elements (e.g. station labelling, visual examples, and trajectory angles) on map legibility is discussed in relation to users' reading behaviour. The 60° octolinear plan emerges as the most effective design for both reading speed and accuracy, which also showed its effectiveness in route planning.

STAGE 4

In the fourth stage, in **Chapter 6**, an information design guidance for transit maps is established that links the findings achieved in the study with other empirical design principles. Various visual design examples are also provided in different information and visual design categories related to a transit map (information structure, map legend, transit line layout, stations, interchanges, and colours). This guidance aims to provide empirical design solutions for designers or researchers that conduct interdisciplinary research on information design and cartographic design. More importantly, the design suggestions are provided based on the user-centred approach in this study, users' reading strategies, habits, preferences and potential biases are taken into consideration, relevant design solutions are demonstrated via visual examples.

Finally, **Chapter 7** of the thesis presents an overview of the research and discusses both theoretical and practical main research findings in each stage. The contribution to the knowledge and potential limitations of the study are also discussed, and possibilities for future research are proposed.

2. Information design principles in transit maps

Pettersson (2014) classified the design disciplines into six main categories: artefact design, message design, performance design, systems design, environment design, and design philosophy. Message design refers to conveying information from a sender to the receiver(s). The information should be transmitted accurately and interpreted correctly, to result in the desired behavioural outcome after it has been understood by recipients (Mullet and Sano, 1995; Bartusch and Porathe, 2011). Message design contains five main areas: graphic design, information design, instructional design, mass design, and persuasion design. In most cases, they are composed of words, visual designs or graphs, but can also include movement and sound (Pettersson, 2019).

Information design principles are essential to make the communication of different complicated systems accessible. It can be related to graphic design, interaction design, user experience, usability research, human factors, etc. (Baer and Vacarra, 2010). Different information design approaches can be used in the design process, such as information visualisation, systematisation of data and simplification of information. All these approaches have one purpose: to make information easy for users to access and understand (Lipton, 2007; Pettersson, 2016). Pettersson (2016) also mentioned that a well-designed information design material would satisfy aesthetic, economical, ergonomic, and subject matter requirements. Therefore, information design is the art and science that prepare information for users and effectively enable them to use it (Horn, 1999). Based on this, information design is also recognised as simplification design. It does not mean only simplifying the design outcome, but also simplifying the design process (Waller, 2011). This idea is supported by Monmonier (1996) concerning transit map design by simplifying complex transit lines and allocating them effectively into a schematic network.

Information design knowledge has been widely used in transportation services to support travellers with valuable and timely information (Dragoicea et al., 2016). According to Liu and Ho (2012), well-designed information and instructional visual materials and maps in central rail hubs in Taiwan, significantly enhanced recognition of the different services, and helped users to plan their trips efficiently. On the other hand, poor information communication confuses travellers and causes potential misunderstandings (Broome and Boldy, 2011). Thus, the quality of information communication is essential in transportation systems. A good information design material should contain a clear information structure, accurate information, a well-organised layout and high-quality graphic design. All these factors will make the information material relevant, legible and reliable, and users will also feel that it is easier to access the information (Pettersson, 2014).

Information design is inter-disciplinary and multi-disciplinary. Various academic areas are related closely to information design, especially art and aesthetic disciplines, cognitive disciplines, communication disciplines, design disciplines, information disciplines, and language disciplines. Information design is not an isolated academic discipline, and it works together with knowledge and experience from other subjects (Pettersson, 2016). In this research, information design knowledge is used to solve legibility problems in cartographic design, which shows a good example of an inter-disciplinary information design study.

Although there are no firm rules in information design (Pettersson, 2016), some basic principles can be followed when preparing and demonstrating the information, as described next.

Visual language: text-based materials are not the only format to present information. If a reading material only follows one visual approach (e.g., just text or visuals), it may lead to low reading efficiency (Laberge and Samuels, 1974). Well-designed reading materials should combine different communication elements by including words, images and symbols to enhance reading efficiency and memory (Tetlan and Marschalek, 2016). To enhance people's understanding and memory of the information, visual materials (perception) and text (concept) can be combined (Horn, 1998), which is helpful for quick reading and for building up a long-term memory (Simon and Harlford, 1995).

High-quality information: the information should be credible and accurate, relevant to the topic and easy for people to access, interpret and understand (Pettersson, 2010).

Suitable quantities of information: when too much information is presented together, it is difficult for users to process and remember. Overload of information can easily cause readers to miss the key information (Wurman et al., 2001).

A clear hierarchy: information with a well-organised structure will make it easy to understand the relevance and priority of the information. It is also helpful for users to construct their own understanding system (White, 2002).

Appropriate layout: the location of the information should be relevant and accurate. It will be challenging to look for associated information from various places (Sweller and Chandler, 1994).

In addition, users will also feel confused when information is not at the place they expected or assumed it would be (Harris, 2007).

Providing simplicity: simplifying complex and technical knowledge in information design is necessary. It is advisable not to use too many terminologies. Instead, supporting material can be provided to explain them. Using visual symbols that people are familiar with can help users to understand unknown or unfamiliar information from known knowledge (Bransford et al., 1999).

Avoiding scattered information: texts, images and other scattered data need to be summarised and grouped into meaningful and systematic information chunks, as this can help users to remember and recall the information (Shedroff, 2001).

For transit map design, visual elements like point, line and shape are basic visual elements that represent the stations, interchange points and railway lines. Some symbols can be used to instruct services and locations, or assist user's travel plans (Meirelles, 2013). The information that can support passengers to complete their journeys should be provided, such as travel time, the distance between stations, where to transfer, etc. (Bain, 2010). In addition, unnecessary information such as boundaries of cities and green areas are not needed on the map, as they may simply overload and cause difficulties for users to figure out the key travel information they need (Robinson et al., 1995). The map legend is a essential component of a transit map to explain visual elements and instructions displayed on a map. It is, therefore, necessary to have a clear hierarchy for users to find information quickly (Burch, 2018).

Moreover, **simplicity** is also a priority for transit map design. The complex trajectories of routes should be schematised into a simple network, and the various travel information needs should be grouped and demonstrated in a simple way (Roberts, Gray and Lesnik, 2017). Detailed transit map design principles are explained further in the following sections and chapters with specific research topics. This basic review explains how information design knowledge supports the cartographic design, which again shows the inter-disciplinary nature of information design.

There are two main considerations in transit map design: **information communication** and **visual design**. A transit system can be understood as a network that passengers enter, travel across and exist. The passenger needs to find a starting station to begin the journey and decide how to travel on the network to reach the destination (Slocum, 2014). This process includes various decisions and specific information requirements at each stage of the journey (Kruger and Dunning, 1999). Then it leads to a guiding question when constructing the information system for a transit map: what information does a passenger need?

Passengers may weigh the perceived convenience of alternative start points and endpoints and may have to select among various routes. Typical judgments include estimating the time needed for travel, distance to the destination, and planning which transfers to make. A transit map that provides information to support these travel needs can be considered as an informative design example of good practice (Bain, 2010). On the other hand, when a user knows where the destination is and understands how to plan the trip, too much detailed topographical information such as mountains and rivers may distract the user from the task, and affect the trip planning speed and accuracy (Roberts, 2012). It is essential to balance travel information and topographical information with the awareness that a good transit map should be neat and easy to understand, guiding users to wherever they plan to go on the transit network quickly and with no confusion (Philips and Noyes, 1982). In addition, it can be counter-productive to ask users what information they need or whether it is useful. Information people believe they need may not be relevant to what they need when planning a trip (Chabris and Simons, 2010; Kruger and Dunning, 1999). As a result, two main factors need to follow when preparing information for a transit map:

1. Keep a suitable **information quantity** and avoid information pollution. The fundamental function of the map for trip planning can be hindered when there is information overload because people's cognitive capacity is limited and it will result in poor information searching efficiency (Everett, Andeson and Makranczy, 1977). The designer also needs to group the information in clear chunks so that users can quickly see the information they need (Roberts, 2012).
2. Make sure the **information quality** is good. Poor quality information increases cognitive load (Roberts, 2012). Information on the map should be accurate, clear, complete, relevant, unambiguous and consistent (Manktelow, 2012). Information that does not meet these criteria can lead to confusion and results in potential route planning errors.

In the visual design aspect of a transit map, three basic graphic elements have been widely used in map design: point, line, and shape. These three elements have their own special visual representation and provide people with different feelings of space: a point has no dimension and provides a sense of place; a line has one dimension and provides a sense of length and direction; a shape has two dimensions and provides a sense of space and scale (Meirelles, 2013). Beck's London underground designed in 1931 set a near-ubiquitous template for the design of schematic maps, at least for transit systems (Cheng, 2014). In Ovenden's (2015) collection of the schematic maps worldwide, more than 100 design examples use the same generic format: stations are represented by labelled nodes, tracks are shown as lines between them; symbols (textual labels or icons) are associated with the nodes. Although some researchers questioned if this Node-Line-Symbol (NLS) format is the best design for transit maps and tried to explore possibilities of alternative designs, NLS format is still the most common and successful design format for transit maps and is widely accepted by users globally.

The visual appearance of a schematic map depends not only on graphic symbology but also on the choice of map elements, their position in the map space, the interrelationships among all map elements, and the perception of map users (Avelar and Hurni, 2006). The more the designer relates schematic maps to the critical elements of the environment represented, the more easily users can find an orientation solution (Casakin, Barkowsky and Freksa, 2000). Ware (2008) explains: "Good design optimises the visual thinking process. The choice of patterns and symbols is important so that the intended viewer can efficiently process visual queries; this means choosing words and patterns each to their best advantage."

When designing a transit map, Roberts, Gray and Lesnik (2017) summarised five main factors that need to consider: simplicity, coherence, balance, harmony, and topography.

Simplicity: Converting the complex trajectories of routes into simple line trajectories is the fundamental requirement of transit map design (Roberts, 2012; Wu et al., 2020). This can make the lines, interconnections, and broad pathways easier to identify and follow, which enhances the legibility of the overall structure of the network. But one thing that needs to be more carefully considered is that, while the increase in the number of angles may be useful to make the line trajectories simpler, it may compromise coherence. In this case, the octolinear layout offers a good compromise between complexity in terms of line trajectories versus complexity in terms of the number of line angles (Roberts, Gray and Lesnik, 2017).

Coherence: Well-designed shapes of each line, trajectory, and specific objectives on the map contribute to coherence. There are many visual design solutions to meet this criterion, such as maximizing parallel lines, symmetrical divergence, and aligning stations and termini (Roberts, 2012; Roberts, Gray and Lesnik, 2017). The regular shapes of the lines, such as circles, equilateral triangles and horizons, are also helpful to achieve coherence. In this aspect, the octolinear layout provides regular shapes of lines, and the lines are as parallel as possible, which keeps a stronger coherence (Wu et al., 2020).

Balance: It is always better to keep the density of stations evenly on a transit map, or at least keep a gentle density of gradients, so the empty spaces are not adjacent, which avoids leaving large margins on the map. However, most maps do not fulfil this requirement because of the complexity of the topography (Lindell & Mueller, 2011). A design solution commonly used by designers is where the central area is enlarged, and the suburb areas are expressed to make more space for the central areas. However, it is important to control the distortion; otherwise, the distances between stations may differ from reality (Roberts, Gray and Lesnik, 2017).

Harmony: There are some individual differences between maps, and different design solutions can help to achieve the optimum design (Palmer, Schloss and Sammartino, 2013). But some shapes and patterns have advantages over others and can make people feel more pleased. For example, angles that permit equilateral triangles (e.g., hexalinearity) may be preferred by users over tall thin isosceles triangles (Lindell & Mueller, 2011). The steep or shallow angles should be avoided in design, as they can make transit lines difficult to intersect, and the station labels are then difficult to accommodate as well (Roberts, 2012). In addition, the layout such as octolinearity, which allowed perpendicular line crossings, maybe better than those that do not allow such an approach.

Topography: Distortion is always used in map design, but extreme distortions can significantly conflict with the reality and users' mental models of the place. A few studies investigated how distortion affects the usability of a map (Roberts, Gray and Lesnik, 2017). Guo (2011) found that a region of the London underground map with poor topography increased 30% more chance of users choosing ineffective routes. Forrest (2014) counterargument that although there are individual differences in reported tolerance for poor topography, this problem does not seem to be a big issue for most users.

These basic criteria identify the factors in terms of macro layout and visual demonstration that designers need to pay more attention to when designing a transit map. Once these criteria are specified in the design, the usability of the map can be evaluated (Roberts, Gray and Lesnik, 2017). In most cases, the simplicity and the balance of a map design are not difficult to be quantified. However, the coherence is harder to quantify because it looks at the relatedness between transit lines, which needs more measurements to evaluate, such as observing users' map reading performance and habits, and collecting users' feedback to identify any potential limitations that make the whole design unsystematic (Wu et al., 2020). Similar research methods were taken in the following empirical tests (Chapter 3, Chapter 4 and Chapter 5). In addition, although the distortion of the lines can be quantified by the size of the deviation of station locations on the map from what they are in reality (Lindell & Mueller, 2011), the effect of the method is difficult and complicated to evaluate because some users may have limited tolerance for topographical distortion Forrest (2014). As a result, the over-distorting of the topography should be avoided. Overall, these criteria are essential for a transit map's usability and legibility.

2.1. Information communication theory

In this section, literature on infographics and data visualisation principles that are applied to transit map design is reviewed. Overall design guidance in information simplification and visualisation that may benefit the cartographic design are analysed. Based on this, the information structure of a transit map and the map legend (the central information of a map) design principles are summarised and discussed.

2.1.1. Infographics in transit map design

Infographics can be understood as the combination of "information" and "graphic", which is, using graphic visuals to present information, data, or knowledge more clearly and understandably (Smiciklas, 2012). As previously mentioned, information design contains analysis, planning, presentation and understanding of the messages (content, language, and form). Information design aims to provide better information communication that readers need to learn specific knowledge or perform particular tasks (Pettersson, 1998; Pettersson, 2019). Graphic design is a process and a result that provides aesthetic, functional, and organised structure to all kinds of information sets (Pettersson, 2019).

Infographic design has always been used to convey complex information and data in a visual format. The purpose of infographic design is to inform, entertain and persuade the readers (Pettersson, 2019). In most cases, infographics end with conclusions and calls to action. People learn from infographics and realise what they should do by using the knowledge they acquired (Dunleavy, 2015). The main advantage of infographics is that people can view and understand visual materials with a combination of text and images, instead of reading and summarising lengthy texts or data documents (Bekhit, 2009).

Nowadays, media organisations create infographics as a way of news and communicating messages, and it has been used as an efficient approach of storytelling. An infographic presents a story by visualising the complex information or the process of a specific subject; this helps to attract readers' attention and interests, then tells a complete story or conveys a piece of complete knowledge (Dunleavy, 2015). In this case, a transit map can be understood as an infographic; it tells a detailed story of people’s travel process by using visual designs to demonstrate topographic information and travel service information, which guides users to their destination and helps them plan trips effectively. Taking Amsterdam’s underground map (partial) as an example (Figure 2.1), the complex underground lines are visualised by schematic lines with different colours, transfer signs are designed to instruct where passengers can transfer between lines, and illustrations display the famous tourist attractions in Amsterdam, which may help travellers reach their target destinations quickly.

Figure 2.1: underground transit map of Amsterdam (partial)

Some basic principle can be followed in infographic design, specifically for transit maps:

Problem addressed: infographics aim to deal with typical issues or resolve specific problems (Mollerup, 2015). Designers blend data with design to help individuals or organisations communicating information to their audiences and solve certain problems (Smiciklas, 2012). The main aim of a transit map is to help passengers plan and finish their travel correctly and effectively.

Descriptive and prescriptive: an infographic is descriptive or prescriptive, sometimes both. Descriptive information shows the pure fact of certain subjects, while prescriptive information provides instructions to guide the readers about what to do (Mollerup, 2015). A transit map should show both descriptive and prescriptive information, a detailed description of the rail route network, and an instructional system that guides readers when travelling to different locations.

Simplicity: simplify complicated knowledge or information by using visualisations, typography, and imagery. The aim is to present information digestively to readers who do not have sufficient knowledge of certain areas (Barnes, 2016). In transit map design, using simple visual elements and shorter texts to convey transportation information may help to enhance people's reading efficiency.

Objectivity: infographics should be objective, i.e., the information describing facts should not be influenced by the feelings or preferences of the creator or designer (Mollerup, 2015). This emphasises the importance that all information on the transit map must be authoritative, specific, and objective.

Understandable description: language plays a significant role in infographic design, as well as document design. The explanation language should be understandable with as few professional terminologies as possible. The language in infographics needs to be accessible to the majority (Mollerup, 2015). In transit maps, terminologies of topography or railway can be simplified or transformed into visual examples.

Functional and aesthetic: appearance and explanation are two basic attributes of an infographic (Stone and Hall, 1997). In other words, the infographics should be not only factual, objective, and functional, but also be beautiful, simple, and effective. According to Viera (2012), there is a direct correlation between visual aesthetics and function in reading effectiveness. Roberts (2012) mentioned that an effective transit map in terms of function is more likely to be good-looking, as function and aesthetics complement each other in infographics. The good appearance of infographics can capture the readers' attention and enhance readers' memory of the information they learned (Borkin et al., 2013). However, according to Reavy (2003), the overuse of visual decorations intended to enhance the attractiveness of an infographic may increase users' visual burden and reduce the efficiency of information communication. Overall, balancing both visual aesthetic and function is important in transit map design. A successful map should be both effective in information communication and attractive in visual design.

Data visualisation is an external visual representation of certain patterns and trends contained within quantitative data, like graphs, tables, charts, maps, etc. It may have some similarities with infographics, as both provide a visual presentation of complex and irregular information in a well-organised format. But data visualisation cannot be seen as a complete infographic; it can only be considered as a useful tool for designers to visually tell stories in infographics using data (Krum, 2013).

An infographic is composed of different visual elements, with data visualisation being part of an infographic for the purpose of specificity and description (Yau, 2013). According to Iliinsky and Steele (2011), visualisations are explanatory and exploratory, and data visualisation can be seen as a necessity for creating an infographic. On a transit map, data visualisations are important components that explain every detail of topographic or travel data in an infographic design work (the map itself), which is also a key research question in Experiment I (Chapter 3) and Experiment III (Chapter 5).

2.1.2. Data visualisation in transit map design

According to Vanhamaki et al. (2017), data visualisation focuses more on data information. Compared with infographics, data visualisation can be defined as a visualisation of numeric values using charts, tables and graphics and as the transformation of raw data information into visual presentations, which is a very effective approach to make technical and complex raw data easier to understand (Chen, 2017). Visualisation can help to make data information more legible after being summarised, analysed and simplified into different types of charts or images to replace big chunks of text. Simplification of data is especially helpful for those who are unfamiliar with the content (Vanhamaki et al., 2017). However, over-simplified information will also cause problems, such as missing important points or making users feel that the information is not reliable (Lipton, 2007).

The visual elements should be closely relevant to the corresponding data to avoid any possible misunderstandings in the data visualisation process. Good design can promote people's visual thinking process. It is conducive to choosing suitable symbols or patterns to make all data meaningful and show its advantages (Ware, 2008).

Taking the travel time from London to the rest areas of the U.K. by train (Figure 2.2) as an example, the designer used different colours to represent different travel time slots by train from London, from dark purple-blue (less than 2 hours) to light brown (less than 14 hours). Users can easily estimate their potential travel time simply based on the corresponding colour of the area where their destination is located. Using colourful shapes on the map to visualise travel time makes this infographic more accessible than a table that only includes city names and their corresponding travel time.

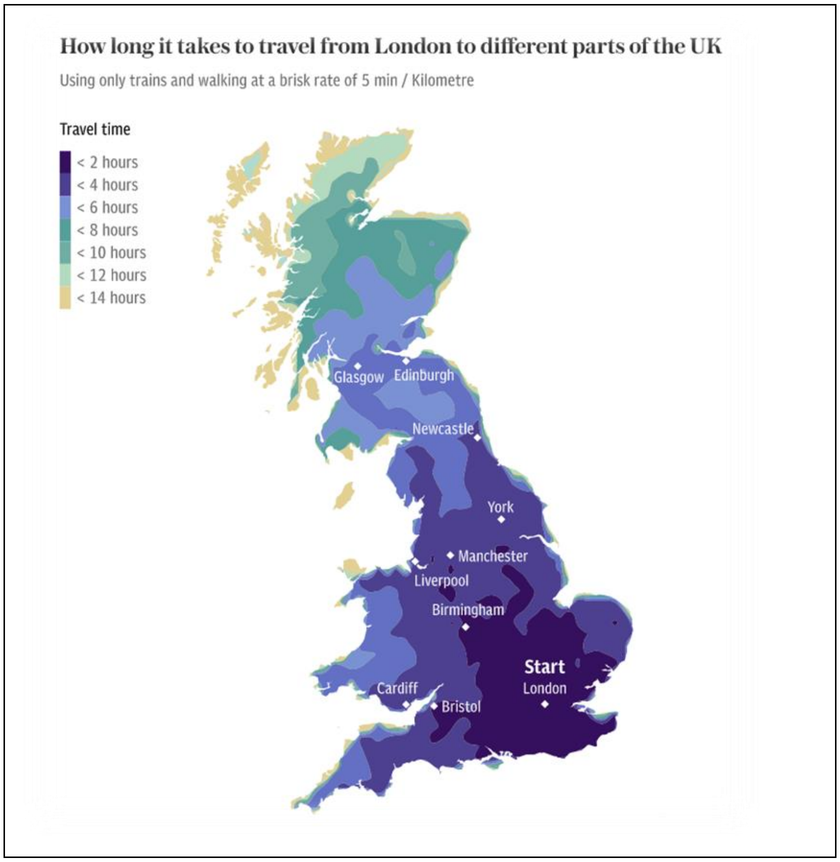


Figure 2.2: travel time from London to the rest areas of the U.K. By train, available from: https://www.telegraph.co.uk/travel/destinations/europe/united-kingdom/articles/uk-travel-map-rail-journey-times-isochronic/

Data visualisation has three main goals: to help readers to communicate, to record and to understand information based on measurable statistic data (Dunleavy, 2015; Mollerup, 2015). . According to Chen (2017), "*data visualisation is the science of visual representation of data, which has been abstracted in some schematic form, including attributes or variables for the units of information*." When constructing data visualisations, some principles can be followed:

High understandability: visual displays present qualitative and quantitative relationships in different ways to make them easier and faster to understand than text and numbers alone (Mollerup, 2015). Providing correct and a suitable amount of information in data visualisation is helpful for audiences to get access. The information should be accurate, complete and relevant as well (Few, 2012).

Outstanding insight: it could be tough for readers to observe the relationships and trends of data when explained only in text. The advantage of the well-design data visualisation is to show the transformation and comparison of the raw data (Mollerup, 2015).

Attractive: well-crafted visual displays can attract and hold the readers' attention; the attractive data visualisation can provide the readers with a basic reason to spend time getting through the data (Mollerup, 2015). An attractive data visualisation material also enables audiences to be more interested in certain contents, even if they are not directly relevant to their specific information needs (Few, 2012).

Memorable and intuitive: simplicity and elegance can make a data visualisation more memorable. Compared with other approaches of expression, good visual displays simplify information in terms of quantity and quality (Finke and Manager; Mollerup, 2015). In addition, choosing a suitable form of display accompanied by simple instructions can make data more intuitive for users to understand and compare (Few, 2012).

From these principles, some similarities between data visualisation and infographic can be observed, as previously emphasised. Both data visualisation and infographic aim to visually present intense and intricate information in a more comprehensive approach, and data visualisation can increase the credibility of infographics (Dunleavy, 2015). Both provide information by visual transfer and well-designed outcomes in terms of visuality, content and usefulness. They are useful tools to persuade, direct and mobilise readers (Pettersson, 2016).

Moreover, when data visualisation and graphic design meet, their own advantages and characteristics will fill the absent traits of each other. Graphic design emphasises its arguments with objective data, and data visualisation strengthens visual aesthetics by using the principle of graphic design. Combining both can make data meaningful, insightful and influential (Tanyoung and Disalvo, 2010). This topic is further investigated in Experiment 3 (*Chapter 5*).

2.1.3. The information structure of a transit map

A transit map is a schematic diagram that depicts the locations, directions, and connections of stations and lines in a public transit system. Normally, it does not include service information, such as travel time or crowding (Guo, 2011). But in the 1980s, researchers started to suggest adding representative landmarks of the area to help tourists understand the surroundings (Bain, 2011). There are significant differences between designing topographically accurate conventional maps and schematic transportation maps. For transit map design, the distortion of stations and topography helps to satisfy the requirements of line layouts and omit any unnecessary details to enhance the map legibility for quicker wayfinding (Avelar and Hurni, 2006; Roberts, 2012). However, designers can still indulge their ability to innovate, because a transit map is not only a cartographical representation of reality, but also an artwork with creations and meticulous designs (Guo, 2011; Wu et al., 2020). In order to design a transit map that suits the users, it is always necessary to understand users' needs and their perceptions in the first place. Compared with conventional map design, more criteria may need designers to follow because the information and relevant visual designs on a transit map should be more specific and simplified (Avelar and Hurni, 2006).

When designing a transit map, similar to a geographic map, three basic areas need to be considered before inserting any visual elements: projection, scale and symbolisation (Meirelles, 2013).

The **map projection** is a mathematical method to transform the curved three-dimensional surface of the land to a flat two-dimensional visual material. All map projections include transformations that could cause the distortions of geometric properties of angles, areas, shapes, distances, and directions (Meirelles, 2013).

It is almost not possible to establish a map projection that is both conformal and equivalent. The choice of map projection depends on the specific design needs. The accuracy of land areas needs to be higher when the designer needs to compare land areas, which means the ocean areas can be distorted to emphasise the land areas (Monmonier, 2010). But when the designer needs to show an overall picture of both land and ocean areas, a low-distortion projection will be suitable to display both areas objectively (Monmonier, 1993; Robinson et al., 1995). In transit map design, topographic information is less important than that in a geographic map. Keeping a basic geographic accuracy will be sufficient to build up a systematic network for a large number of stations and stops. Some topographic details can be distorted and even hidden, because a transit map focuses more on the transportation networks. A transit map is normally less accurate in terms of the depicted distance and direction, such as displaying the distance between two stations longer or shorter than its actual length. A line depicted as straight on a transit map may contain many changes in directions. It is very common that if the central area of the transit system is expanded, then more station labels can be accommodated, and the outer area is compressed accordingly. Such distortion can easily emphasise the main areas and speed up the process of information searching and decision making (Larkin and Simon, 1987; Hochmair, 2009).

Map scale is the ratio of a distance on the map and the corresponding distance in reality. In other words, the degree of reducing the actual earth (Robinson et al., 1995). The map's objective and the expected output need to be considered when choosing the map scale, as both factors will primarily affect the geographical range of the map. According to Keates (1989), a map is a reduced representation of the topographic surface, and the scale of a map determines the amount of information that can be shown. When the scale of a map reduces, more generalisation will increase correspondingly, and the smaller the scale, the greater the degree of generalisation (Keates, 1989). The map scale is usually present by a simple word statement or a graphic bar on the map, which is also needed in a transit map, depending on the size of the area it displays (Wi et al., 2020).

Visual encoding is a big topic in map design and refers to the process of visualising the data with suitable types of representations, usually through visual approaches or graphical features. If we compare the underground maps of the three famous cities: London, New York, and Paris, many similarities can be found. All three maps include the essential components of each network: station indicators, station names, lines, line identifiers or names, and interchanges (Figure 2.3). In addition, distinctive colours are used to distinguish different lines or groups of services on all three maps. Other services such as nearby airports or connecting buses are included, as well as the links to these services. Since all the three cities are all developed on navigable waterways, the representations of rivers or bodies of water areas are demonstrated on the maps (Bain, 2010).

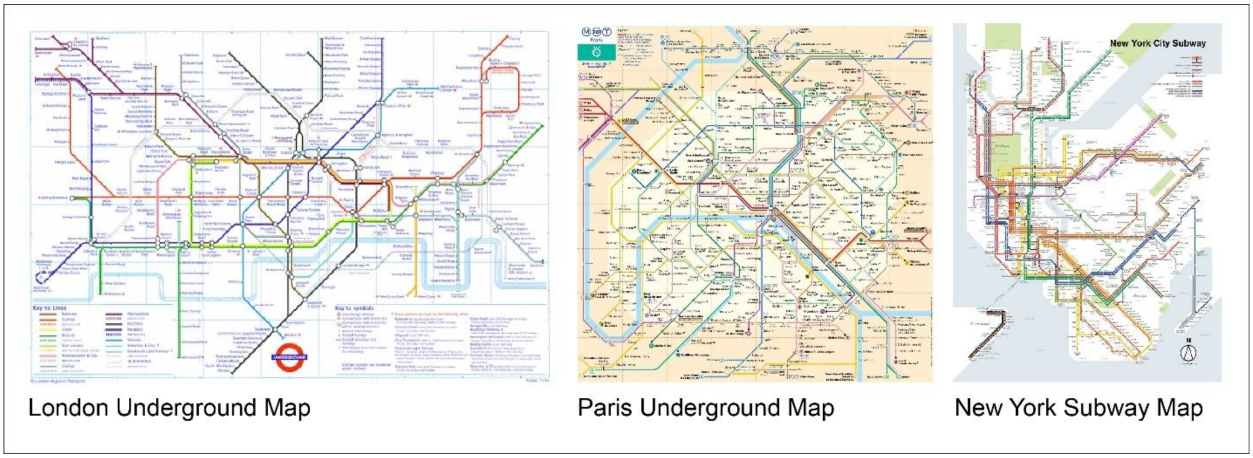


Figure 2.3. London Underground Map, Paris Underground Map, and New York Subway Map

In cartographic design, visual encoding is called symbolisation in some literature (Meirelles, 2013). According to Monmonier (1996), the generalisation of a map is due to the fact that it is impossible to simplify a realistic area without losing all details. In order to generalise and simplify the topographic details, different symbols have been widely used in map design. Taking transit lines as an example, lines with different thicknesses could have different meanings, including political borders, rail lines or latitude, etc. In transit map design, lines are usually used to represent transit lines (Roberts, 2012). Symbol exaggeration is very common in map design, such as thickening the width of certain lines or enlarging certain signs to make them stand out; This helps readers notice and understand the meaning of the elements they represent more quickly and easily (Monmonier, 1996). Symbols can represent almost all the information on a map, and therefore devising symbols is an important task requiring cartographers to display the information clearly and logically (Keates, 1989).

The following list shows common symbols and features on a transit map:

Map legend: the key part of the map, demonstrates and explains necessary symbols and instructions displayed in the transit system (Burch, 2018).

Transit lines: the topographical layout of transportation lines and their colours can provide a first impression of the system; it also largely influences the map's legibility (Coltecin, Fabrikant and Lacayo, 2010).

Stations: key information to show the users' specific locations, and where to start and end the journey (Kiefer, Giannopoulos and Raubal, 2014).

Interchange points: showing where passengers can transfer to other transit lines or services, which is especially important when planning long journeys (Burch, 2018).

Other transportation signs: airport or underground signs provide additional transportation information for users, which may help users to make their trips more effectively and economically (Ooms et al., 2015).

Rivers (Water): water areas include rivers, lakes or oceans, can provide more geographic information, and they are helpful to restrict the distortion of lands in the design process (Burch, 2018).

Sight symbols: Tourist attractions are interested and wanted information when travellers planning trips (Coltecin, Fabrikant and Lacayo, 2010).

Dense regions: dense regions can show busy zones of the area in larger cities, mainly in the city centres (Ooms et al., 2015).

Sparse regions: outside areas or the corner regions also need to be displayed, such as parks, golf courses, etc. (Burch, 2018).

Labels: some additional labels can help to interpret the map effectively, such as special notices include travel time, ticket price and service ending time, etc. (Coltecin, Fabrikant and Lacayo, 2010).

The suitable number of symbols on a transit map can help users find out their target information efficiently. However, the overnumbered symbols may lead to visual clutter and a mass of additional unwanted information. Inversely, the insufficient symbols may easily cause misunderstandings and force some users to spend more time searching for the missing symbols they believed should appear on the map (Netzel et al., 2016).

In addition, both map title and map legends are important components of a map. The title provides a basic context to explain the purpose of all the subjects presented on the map, including geographical information, temporal or topical context. As a result, the title should be short and brief, accurate and direct (Meirelles, 2013). A well-designed map legend is helpful to enhance the structure of information on the map; it is an important database for users to understand and select the information they need (Buard and Ruas, 2009). The information in the map legend usually needs to be grouped, which is helpful to make them well-organised and reduce the possibility of misunderstandings (Meirelles, 2013). Sometimes, map legends can be replaced by simple descriptions or labels. They can be allocated in visualisations on the map separately to conduct similar functions of map legends. Burch's (2018) research showed that the map legend is a key component of a transit map; users read the map legend very frequently and spent longer time reading it than other components of the map. Users also read the map legend very carefully, tried to find out needed transit lines, and looked back to the map legend to double-check the information (Burch, 2018). More details about map legend design are introduced in the next section (*Section 2.1.4*).

In the cartographical and geo-informatic study, the geographic data is divided into spatial data (e.g. size, shape and locations) and non-spatial data (e.g. names, area, volume, population), they can also be summarised as thematic data. All the data resources should be marked on the map, but sometimes are displaying in map legends as well. Moreover, the verification and references of the resources can strengthen the accuracy, authority and reliability of the map (Delaney, 2012).

Conventional maps usually contain many features: major rivers, lakes, political boundaries or latitude-longitude lines (Robinson et al., 1995). Cartographers emphasised that the elements they decide to use in maps depend on the map's purpose, and the map scale determines the details of the elements used. Therefore, the main information of the maps should be strictly related to the purpose and eliminate unnecessary information. For example, a bus transit map should include information about the route system and bus stops, other information such as the temperature of different areas is irrelevant to user needs (Meirelles, 2013).

It could be difficult to maintain the high details of all layers of visual information represented in a map (Bertin, 2010). MacEacgren (2014) indicated that the data visualisation methods in map design should be distinct according to the different needs and purposes. In visualisation, there are three basic graphic elements for maps: point, line, and plane. For a transit map, the dimension of a visual element may relate to the actual dimension of the corresponding feature (Meirelles, 2013). Colour variation is also an extensive aspect of symbol variation, colours can create a huge range of visual differences (Keates, 1989), which is detailly analysed in *Section 2.2.5* and Experiment II (*Chapter 4*).

The **point** has no dimension and provides a sense of place. When points are used to present locations, their sizes depend on two factors: the minimum sizes visible on the map, and the sizes required to demonstrate the level of importance of represented locations (Meirelles, 2013). Colour variations in point symbols depend on the contrast between hues; it is also affected by the size of the symbol; if the point is small, a strong hue that can be used to create an outstanding contrast, which is helpful to make the point more perceptible (Keates, 1989).

The **line** has one dimension and provides a sense of length and direction. The size of a line means its length and width; the wider lines are normally used to highlight wider routes or important routes (Meirelles, 2013). Similar to points, the colour of a line also needs to keep a sufficient contrast with white background and other lines.

The **plane** has two dimensions and provides a sense of space and scale (Meirelles, 2013). When selecting colours to represent area symbols, there are two variations: colours of the surface and colours of the components that created the area, such as points and lines (Keates, 1989). Areas can be distinguished clearly on the map by using fully saturated colours and decreased saturated colours, it is a very practical method in map design, but it is not suitable to use a highly saturated colour to represent a large area on the map, it will make the area too intense and outstanding. Small areas can display with more saturated colours to prevent the areas from being ignored because of the tiny sizes (Brewer, 1994).

The combination of points and lines is a key factor in a transit map design's success, they can help to display a thorough transportation network of a certain area in the simplest way. On a transit map, there are three symbols that display three types of key information: segments representing railway lines, points representing stations (with station name), and transfer points representing connections between lines. Intersected areas between lines or transportation modes are often not well represented and can be interpreted wrong, this is a common design problem in transit map design (Grison et al., 2016), which is observed in Experient I (*Chapter 3*) when participants searching for specific stations or panning trips.

As previously emphasised, **colour** is always a key factor and an important research topic in transit map design. In almost all visual materials that include maps, people distinguish nine visual properties: shape, size, colour hue, colour value, colour saturation, orientation, texture arrangement, texture density and texture size (Ware, 2004), colour relevant factors occupied three out of nine visual properties in visual design, this indicates how influential the colour is in visual design legibility. Garland et al. (1979) found that the better colour coding of a transit map led to greater trip planning accuracy, less perceived difficulty, less frustration and higher confidence. On the contrary, when the quality of colour coding is not satisfied or even no colour coding, it led to lower trip planning accuracy, greater perceived difficulty, greater frustration, and lower confidence. Their research (Garland et al., 1979) showed how the colour system affected the effectiveness of a transit map. Based on this, the colour is discussed as a unique and vital visual element in separate sections to show more details of transit map colour design principles and relevant colour theories (*Section 2.2.5*).

2.1.4. Map legend

A map legend is a description, explanation, or table of symbols displayed on a map or charts to permit a better understanding or interpretation of it. It usually includes a sample of each symbol (e.g., point, line, area, etc.), and a brief description of the meaning of symbols, which is considered as the information centre of a map (Slocum, 2014). A well-designed map legend has to group the information into themes that structure the cartographic message (Buard and Ruas, 2009). The relationships between legend lines following three main relations: association, order and difference. In addition, colour is a key factor in the map legend to distinct different themes. Some rules that can be followed when constructing information that belongs to different categories in the map legend (Buard and Ruas, 2009):

- A legend is composed of several object legend themes, and an object theme contained a set of legend lines.
- A legend line is described by an object legend text and an object sign, while an object colour represents the object sign.
- If two legend lines belong to the same theme, which means both lines are in the association that their signs should be visually close, such as representing by same/similar hues or same/similar shapes.
- If two legend lines are ordered, but still belong to the same theme, they have to show differences in design according to their importance level. E.g., the colour of the more important line is more outstanding than the less important one.
- If two lines belong to different themes, their signs should be very visually distinct to show their differences, such as distinct colours or shapes.
- Sometimes, if a theme is more important than another, then the signs of the more important theme group should be more visible than another theme.
- All descriptions of the instructions and functions should be clear, detailed, understandable but short and brief, visual signs are encouraged to simplify the information and enhance the legibility.

In addition, the signs used in the map legend can follow some complementary rules:

- Signs should be associate with the meaning of the objects, and conventional association should be followed as much as possible. E.g., using green colour to represent large areas of grassland, forests ore mountains are helpful to optimise users' understanding of the map, because the greens normally associate with plants/vegetation in people's mind (Roberts and Rose, 2016; Wu et al., 2020).
- The size of signs in map legend should not be too large to accommodate the limited space, the design should follow the minimum size criteria that all the perception and recognition (Spiess, 1995). However, the colours of the smaller items should be darker than larger items, such as buildings should be darker than forests.

When constructing a map legend, it is important to organise the information (E.g., transit lines, service information) into **themes** and clearly describe the relationships between them. The signs can link users' association with the objective meaning to enhance users' understanding of the map. The design quality of the tested map's map legend was evaluated in Experiment I (Chapter 3), and the identified design limitations were improved in *Section 5.3* based on the design principles listed in this chapter.

2.2. Visual design theory

The visualisation design of maps and routings has a long history, Tabula Peutingeriana was one of the earliest transit maps, it showed the layout of the cursus publicus, the road network of the Roman Empire in the 4th century. With the explosion of the world's population and the growth of urban areas over the last two centuries, people's needs for public transportation are significantly increasing. After the appearance of railways, the first railway routes map has been designed in 1874, it was one of the first maps which discard almost all real surface topography, more design examples were further improved by distorting the actual geographic distances (Ovenden, 2005).

Henry Charles Beck, an engineer who worked in London underground created a pioneering transit map for London Underground networks in 1932. He transformed the curved underground lines into strict vertical or horizontal alignment, his underground map has soon become a design standard for transit maps (Bain, 2010). Even today, most transportation transit maps contain his original design ideas. Some researchers suggested that Beck's design was inspired by George Dow, who designed the schematic maps for the London & North-eastern Railway Company (Garland & Beck, 1994). George may less famous, but he made various creating designs in diagrammatic railway maps preceding Beck, especially the interchange signs which help to tell the passengers where to get off and transfer to another train to the destination (Dow, 2005). Although we call the transportation schematic maps “transit maps”, but some commentators argued that they are not even maps and they should be called diagrams (Horne, 2012).

Traditionally, transit maps were printed and still used and preferred by many users today, the history of transit maps experienced a long history from grey-scale to colourful, from print to digital (Black et.al, 2017). The contemporary digital geographic information system transformed the complicated design process of paper transit maps, designers can create more design possibilities even custom building a travel information system according to specific needs.

Transit map design is a special topic in cartographic design study, it has many design requirements different from a commercial geographic map. A map is a graphic description of reality and shows the relative positions of objects (Cartwright, 2014). A map aims to guide the users in identifying their current location and looking for or arranging their destination routes (Passini, 1984). There are three main groups of maps: special-purpose topographic maps, special-subject maps of the physical environment, and special-subject maps of the human environment. The transit maps are belonging to special-subject maps of the human environment (Keates, 1989).

When establishing the visual design system of a transit map, some basic elements should be presented. Primary elements include map title, subtitle, legend, North/South arrows, date, scale bars, authorship, etc. Secondary elements include neat lines, graticules, network path, disclaimer, data sources, data citations, logos, graphs, photographs, graphics, tables and inset maps, etc. (Petersen, Vakkalanka and Kuzniarz, 2015). Designers also need to consider typographic features in a map, such as font types, font sizes, line spaces, colours and margins, etc. These requirements are almost the same for both geographic map and transit map design.

There are some different geometric and aesthetic standards used to present public transportation networks in different countries. However, all the transit maps should fulfil the requirements of graphic simplicity and make sure the network is legible (Avelar,2006). Morrison (1996) summarised and suggested the following four representative transit map design styles (Figure 2.4):

Classic style: commonly used in the U.K., the U.S., Italy and China. Using one line to represent each service of each transportation mode, each route of individual service is instructed by a service number besides.

French style: each service of each transport mode is identified by a different line shown in a different colour. The service number is normally displayed at both ends of each line. This style is mainly used in France, also seen in some Sweitzer cities and Belgian cities.

Scandinavian style: similar to the classic style, but some services may subdivide out two or three separate lines to display more detailed routes, they are shown in different colours. This style is commonly used in Scandinavian big cities, also some cities in Germany, Austria and Spain.

Dutch style: similar to the classic style, but using different symbols to represent different transportation modes, such as a double line represents a light rail route, and a single line represents a high-speed rail route. This style is used mostly in the Netherlands.

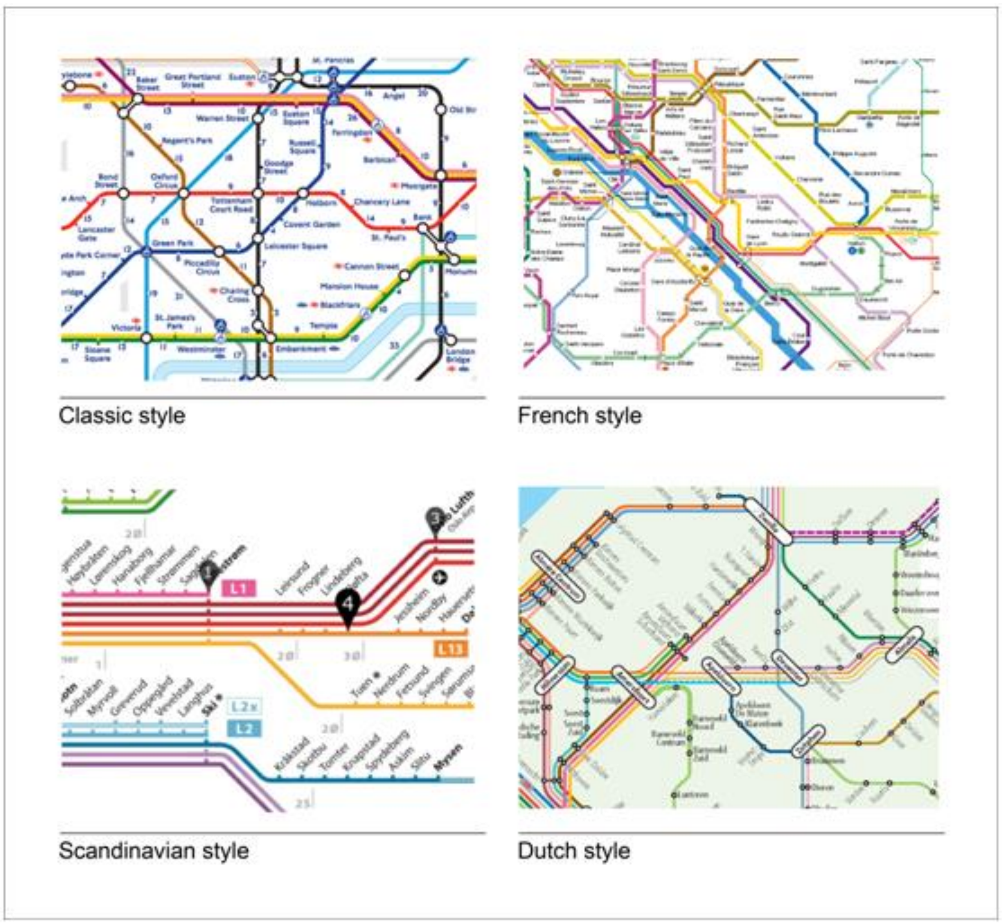


Figure 2.4: Classic, French, Scandinavian and Dutch style

China’s high-speed railway map is considered as a classic style railway map, each route is represented by a unique number and a colour different to other lines, which is similar to Beck’s design standard, but the line layout and other visual designs needed to be tested and evaluated further, which was detailly analysed in the eye-tracking test (Experiment !, *Chapter 3*).

2.2.1. Topographic distortion

The topographic distortion can make a transit map more schematic. The irregular positions of train stations are adjusted, the zigzag route paths are simplified, the central areas are expanded, and the marginal areas are compressed (Guo, 2011; Roberts, 2012). Without these interventions, it could be impossible to build an effective transit network that makes each line displayed in the appropriate position and has a clear travel connection with other lines (Bain, 2010). Almost all transit maps' topographies are distorted to at least some extent, this may conflict with some users' mental model if they know the area displayed on the map well. Still, users who are not familiar with the place may not be able to notice any distortion of the network (Roberts, 2010). The moderate distortion of topography is always permitted, but it is also necessary to maintain the correct communication between lines (Roberts, 2012).

In order to reduce the complexity of the map, most transit maps are schematised according to some principles that to simplify the geographic environment, distorting the topographic environment of the area is an initial work in transit map design (Roberts, 2012; Roberts and Rose, 2016; Wu et al., 2020).

1. The details of the surface are omitted except for the most important landmarks. This method can make stations and transit lines look outstanding on the map, rather than other topographic information.
2. The winding transit lines need to be smoothed and simplified, especially for complicated curves and sharp twists. The most common simplification scheme is octollinearity, which display the transportation network by using horizontal, vertical and 45° angle straight lines, it was created by the designer of the first London Underground transit map, Henry Beck in the 1930s. This distortion standard was widely used globally.
3. Global and local scale distortion can expand or compress some areas, normally the central areas need to be expanded and the suburbs is required to be expressed, this helps to emphasise the busiest transit networks and provide better legibility. Sometimes, the station positions, lines, directions and distances between stations may need to be altered to accommodate station labels or simplify line trajectories.

In most cases, when the topographical accuracy for one particular location is specified to preserve some very necessary information, then the topographic accuracy is required for all other areas. The reason is that users do not aware of which parts on the map are distorted to assist users, they may assume that the map demonstrates all topographic surfaces accurately (Roberts, 2013; Wu et al., 2020). Distortion is widely used to present transit systems, Guo (2011) made a comparison between the London Underground map and the actual distances between stations, and calculated their correlation, the value is only 0.22, which means the map only showed around 4% of the London underground system's actual spatial distances between stations, such as the distance between Piccadilly Circus and Leicester Square, it looks far away from each other on the map, but it is just a five minutes walking distance in reality.

In some cases, minimising topographic distortion could conflict with the main purpose of establishing a schematic map, which is providing an effective legible design with simple line trajectories (Roberts, 2012; Roberts, 2013). But there is a potential risk that topographic distortion may influence user's trip plan, e.g., when the distance between two stations is exaggerated, users may think that both stations are far away from each other and choose another inappropriate travel plan to get some time benefit that according to their imagination (Wu et al., 2020). It happened in many underground systems where the stations looked far away from each other after the central area expanded, which made many passengers give up walk between stations. Still, many neighbour stations are within walking distance. Adversely, the places been expressed may make stations in real far away from each other look close on the map, this issue frequently happened to stations located at margin areas of the map (Guo, 2011). Moreover, some alternation on distances and directness of competing options may make inappropriate roundabout routes look viable, this may waste user's time and lead to traffic problems on some routes (Guo, 2011). Too much distortion is unacceptable in utilise, a well-known example is the 1972 New York Subway map, the narrow and runs north-south Central Parks was drawn as a wide and runs west-east rectangle, it received a large number of complaints and was finally abandoned nine years after its introduction (Roberts, 2013).

2.2.2. Transit line layout

Building the macro layout of transit lines is a preliminary but complicated work when constructing a network system; the macro layout mode for a network has been investigated and argued along with the development history of the transit map (Ovenden, 2003). Individual differences are important topics that cannot be ignored; different networks may have their own best-matched line layout schemes. This needs thorough usability tests to find out and improve them until an efficient plan is achieved. Roberts (2012) mentioned that different transportation networks are structured differently. Still, no matter which design rule is applied, it should follow the criteria for effective design, e.g., simple line trajectories and less distorted topography.

Stations and transit lines construct the transportation network on a transit map, no matter for railway networks, bus networks, airline networks, or ferry routes, the layout of transit lines is always a critical factor that needs to be considered carefully (Ovenden, 2015; Garland, 1994; Ovenden, 2003; Roberts, 2012). Different line styles represent services along routes that include various types of trains, regularity, frequency and capacity, etc. The typical examples include adjusting the width of lines, choosing between solid, hollow, and dashed patterns. The transit Iines under repair or construction can be displayed by broken lines or assigned colours (Avelar and Hurni, 2006). In order to enhance the legibility of the network, abstracted displays of curved and complicated transit lines are commonly used, e.g., straightening lines and distributing stations evenly; this process transforming a topographical map into a standard network system is called schematisation in map design (Wu et al., 2020). **Simplification** is a vital topic in transit map design, by using visual elements include symbols for stations, interchange points, station/city names and coloured lines, linking the stations and displaying relevant services. The layout of transit lines is a macro (global) layout parameter; the purpose of a well-designed transit network is to facilitate users' orientation and navigation of the transit network; in order to fulfil this requirement, there are many styles to demonstrate the layout of transit lines. Figure 2.5 shows six different transit line layout styles of London Underground, which are Spatially representative (Curvilinear), Schematised Curvilinear, Concentric circles, Multilinear, Octolinear (Octilinear) and Hexalinear, from less to more constrained curves or polylines in each row (Roberts, 2012). Some layout schemes are optimised for usability, and some are for decoration or visual entertainment (Wu et al., 2020).

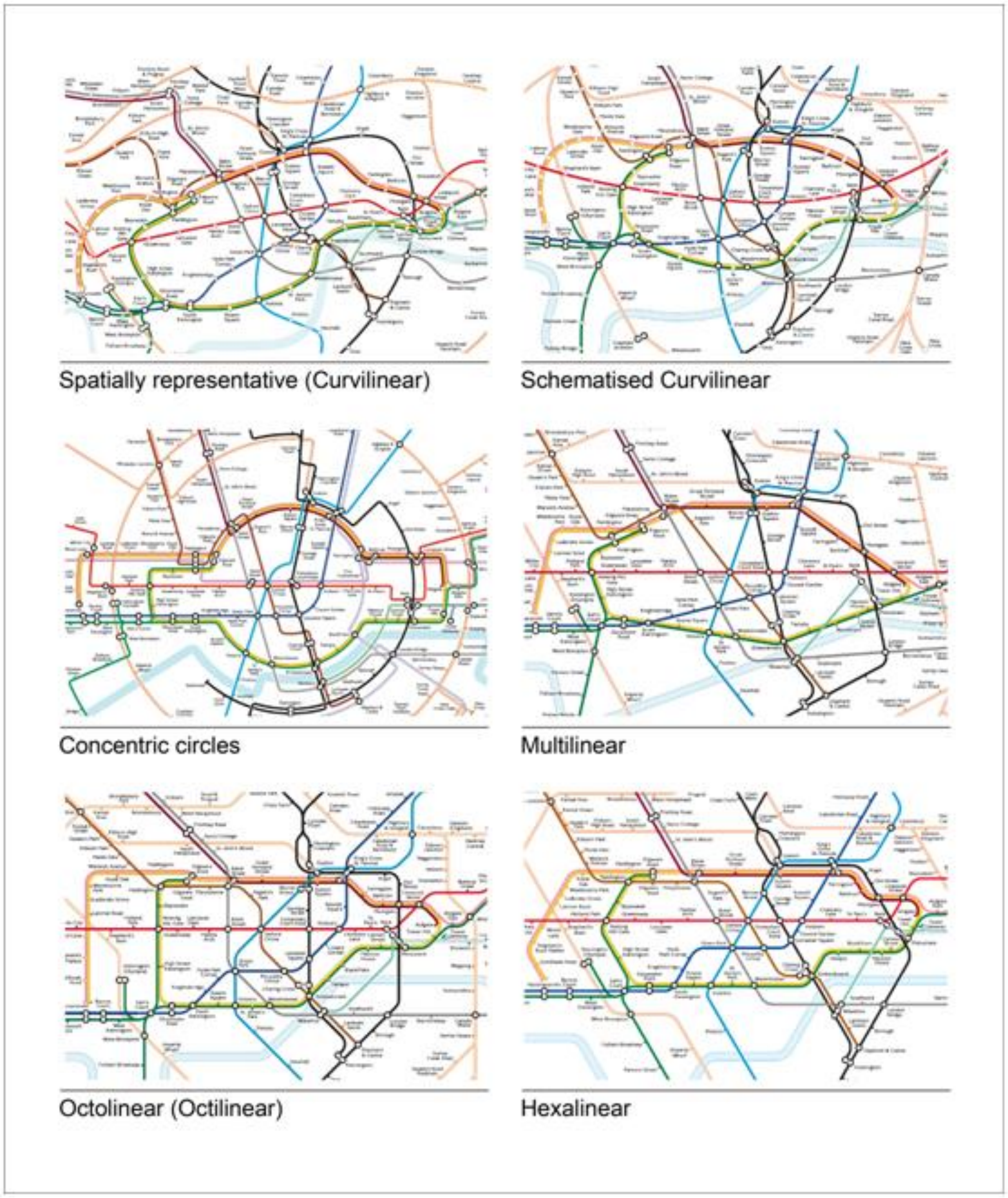


Figure 2.5: Six different transit line layout styles of London Underground (Roberts, 2012)

From Figure 2.5, linear layout, Curvilinear layout and Concentric layout are the three common layouts in transit map design; their characteristics can be summarised as follows (Wu et al., 2020):

Linear layout: Each connection is represented as a polyline whose segments are parallel to some orientation from a specified set of orientations. There are three main design cases octolinear, hexalinear and tetralinear layouts.

Curvilinear layout: Each connection is represented by a smooth curve, Bezier curves and circular arcs are commonly used in curvilinear layout transit maps.

Concentric layout: Each connection runs along an ortho-radial grid that consists of a set of concentric circles and rays emanating from the centre of the circles.

Establishing a transit network is a time-consuming process; designers need skills and intuition to make the design result informative and easy to understand (Garland, 1994). In the past 20 years, many experts from different areas investigated the transit line layout include graphic designers, geographers, computer scientists even psychologists (Roberts, 2012). Normally, there are four important stages when creating a transit map (Figure 2.6); the first step is to sketch the main topographic and transportation elements of the area, then locate the specific locations of stations and lines (Step 2), in this step, some geographic features like forests or rivers can be marked. In Step 3, the transit lines need to be adjusted to a more transparent scheme, then distribute stations evenly. In the last step, instructional information such as titles, map legends, texts and images are added to make the map more informative.

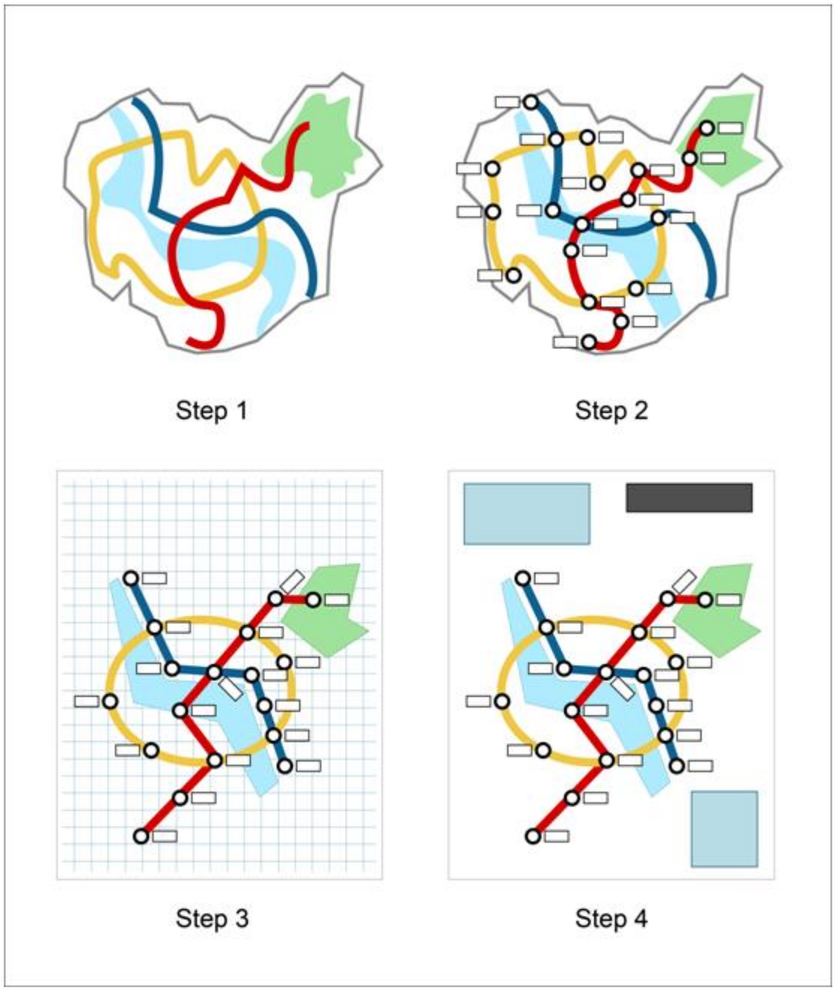


Figure 2.6: Four main steps for transit map creation

At the early stage of transit map design, the complex geographical layouts were normally simplified by smoother lines that show minor topographical details (Figure 6.4); these **curvilinear** layouts helped users better understand the complicated transportation network, and find easier to locate their positions on the map. This design style was popular during the 1920s-1930s (Garland, 1994; Roberts, 2012). Later, the concentric circle layout was created; it was an improved plan of the curvilinear style, lines and stations are displayed by ortho-radial layouts. But this plan was soon replaced by straight-line layouts for further simplification considerations; since then, the irregularly shaped geographical accurate lines are straightened to enhance the readability. There are four main styles for straightened transit line layout. The **multilinear** layout provides the most flexible plan that transit lines can be displayed at any angle (Roberts, Gray and Lesnik, 2017), multilinearity is difficult to implement in design because the designer has to consider the balance of every angle on the map. Still, the multilinear design may suit the network with strongly radial lines (Roberts, 2012). The **linearity** settings have more strict rules on angles, such as octolinear, hexalinear, and tetralinear layouts, etc., they are commonly used in modern transit maps (Figure 2.7). Plans that include more angles such as decalinear, dodecalinear and tetradecalinear layouts also belong to linearity, but they are rarely used because the layout consists of too many angles is difficult to simplify the line trajectories and create geometric harmony, unless the layout is particularly well-suited to the network (Roberts, 2012). Compared with octolinearity, the hexalinearity design contains three angles at 60° rotations, leading to simpler line trajectories, i.e., fewer direction changes (Roberts, Gray and Lesnik, 2017). The purpose that reduces the number of unnecessary changes in the transit lines' directions is to avoid disruption when users are tracking stations and lines. In addition, try to avoid overlapping the transit lines, the overlap of three or four lines are generally be demonstrated satisfactorily and can be accepted by users; although it is almost not possible to display all the lines side by side, there should be a maximum number of overlaps depends on the complicity of the transit system, too many overlaps in certain areas may reduce the legibility of the map. A practical method to solve this problem is to distort the shapes or directions of the lines that can make more space to avoid overlapping (Avelar and Hurni, 2006).

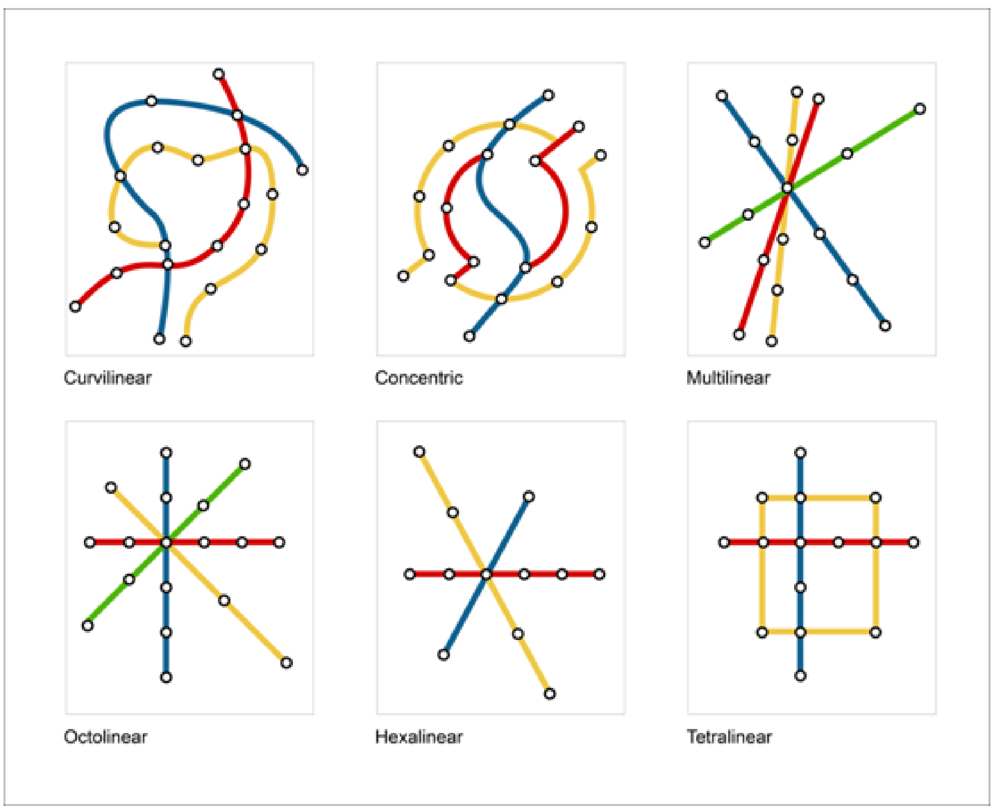


Figure 2.7: Six layout styles of transit lines

Nowadays, the **octolinear layout** has become a commonly used standard; the Berlin S-Bahn network had first adopted it in 1931, and then became popular in 1933 that Henry Beck created the first London Underground map. Nowadays, more than half of transit maps worldwide adopted Beck's octolinear layout (Ovenden, 2003). When designing a Beck style octolinear layout transit map, there are four equally spaced angles allowed for the alignment of lines: horizontal (0°), vertical (90°), and two diagonals (45° and 135°); Beck also tried 60° diagonal angles, but the outcome was not satisfactory and less famous. In fact, the 60° diagonal angles can reduce the horizontal pressure on the map and make more space for station names, it can also create a more dynamic impression than 45°, but it may not be suitable for all transit networks (Roberts, 2010; Roberts, 2012; Wu et al., 2020). In Experiment III (*Chapter 5*), the effectiveness of both 45° and 60° octolinear layouts were compared in usability tests. Overall, the octolinearity made it possible to demonstrate transit lines with fewer bends, and led to a schematical and tidy network that consumes less space on the map (Nollenburg and Wolff, 2011).

2.2.3. Stations and typographic considerations

Nodes (e.g., dots, squares, short lines, etc.) are used to represent stations; they can be adjusted by size, shape or outline width to show differences or importance levels; some stations may be represented with numbers, letters or short lines (Sort, 2006). Specially designed nodes can clearly demonstrate interchange points and terminals, discriminating such particular points apart from ordinary stations (Avelar and Hurni, 2006). Stations on the lines need to be allocated appropriately according to their relative positions, trying not to reserve their direction relationship, such as using arrows to show the west-east direction (Roberts, 2014). Sometimes, distorting the shapes of lines is helpful to allocate the stations more schematised. Still, users may have a mental model of the stations presented on the map; relative station positions are better preserved unless the benefits of schematisation overweight this (Roberts, 2019).

Different stations must be displayed in different locations; this rule applies to all transit maps that preventing stations from overlapping each other (Wu et al., 2020). In addition, it is often recommended that distances between stations on the lines are equal; this criterion can lead to a better-organised grid alignment, which also fits different distorted line layouts when some areas need to be enlarged or compressed (Roberts, 2012). The even spacing of stations is also considered as a good choice for aesthetics that applies to all Beck-style transit maps (Degani, 2013; Lloyd, 2017). In addition, the proximity of place was determined by typographic (as opposed to geographic) concerns; that is, the representation of the distance between stations had to do with the layout of text and graphics rather than the actual geographic relationship between places (Guo, 2011).

Moreover, although the sizes of stations in real are all different from each other, but on the transit map, size distinctions between stations are not the key information. Beck used the same size dot to represent each station on the map no matter how big or small the actual station is; this called “standardisation” to keep visual clarity and balance. Sometimes, the main interchange stations can be represented by other notations such as diamonds to make them visually outstanding (Guo, 2011).

In addition, the design and layout of text and labels can influence the legibility of a transit map; a label is a text, a symbol or an image that represents a station or a place, which is significantly affected by the positions and directions of the stations (Cheng, 2014; Nollenburg and Wolff, 2011). There are some design principles that can be followed:

Consistency: when using a node with the corresponding name to display a station, there are three main ways (see Figure 2.8), allocating the characters inside the nodes, beside the nodes or using leader lines to connect the nodes and their names. A consistent design style, typeface, direction and size of stations belong to the same service is preferable in design. Station names are better to be placed on the same side of a line; the inconsistent placements may cause reading difficulties (Ovenden, 2015).

Figure 2.8: Three main ways to layout the stations

Shorter label distances: it is necessary to minimise the distances between each other when placing labels on the lines, the perception of proximity helps to enhance the information searching efficiency, far distances between stations are not recommended (Roberts, 2019).

Avoiding overlap layout: It is necessary to make sure that the labels of stations are not overlapped, the overlapped stations can lead to poor legibility. Sufficient labelling spaces for stations are required, especially for dense areas that multiple stations may be located in a narrow margin (Yoeli, 1972; Imhof, 1975).

Spacing horizontally: the horizontal layout applies to people's reading behaviour, but orientations can be switched to other directions if they conflict with other station names (Ovenden, 2003; Ovenden, 2015; Roberts, 2019). However, there is almost no empirical research to investigate whether the non-horizontal text layout may affect the legibility of a map; this question needs to be further investigated in the next stage.

Typographic considerations: typography has a substantial influence on legibility for all reading materials. In transit map design, a compromise between typefaces and transit lines is required, condensed typefaces are preferable or break the long station names into multiple lines, but it has to be done according to the correct linguistic form (Mijksenaar and Vroman, 1983; Roberts, 2014; Roberts, 2019).

Figure 2.9 shows some correct and incorrect design examples of label displays, it also shows some practical layout methods on special occasions, such as the station located at the cross point of multiple lines.

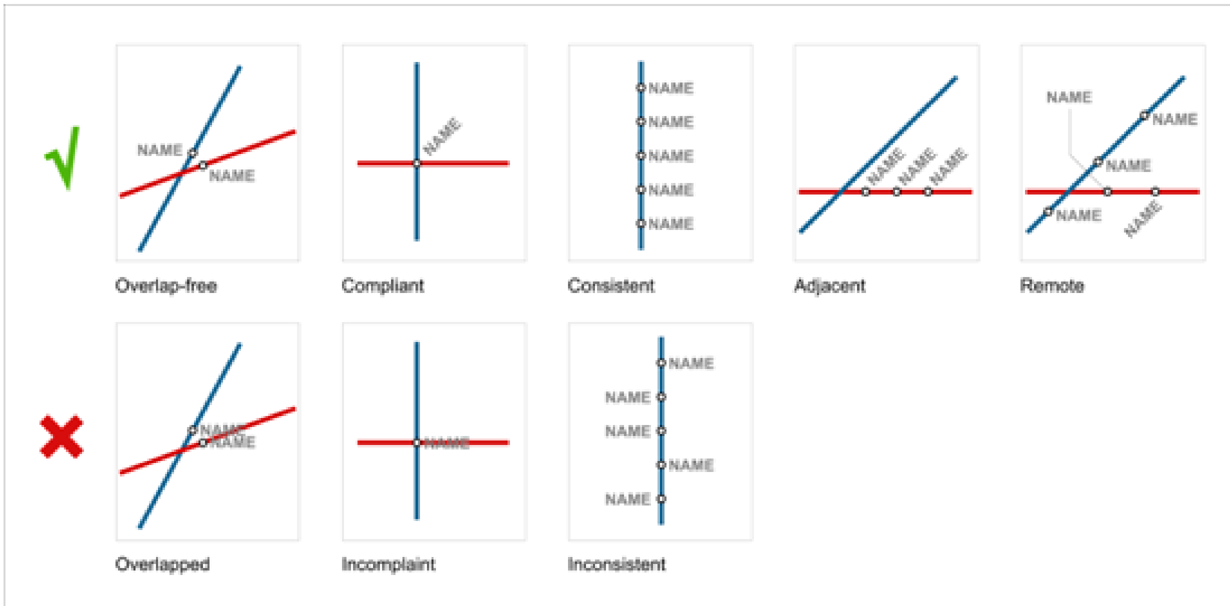


Figure 2.9: Label display examples

Moreover, the typography of texts can also affect the legibility of a map, suitable sizes and typefaces can make all texts more legible, sometimes the typefaces can be used to differentiate the different categories of information or show the different importance levels of the information, e.g., the bold font may indicate that the information is necessary (Mijksenaar and Vroman, 1983; Roberts, 2014).

Typography plays an important role in information design, it affects the effectiveness and legibility of information design materials. In transit map design, texts are mainly used to display station names, line names and corresponding numbers, or explain necessary service information (Mijksenaar and Vroman, 1983).

The writing style is the main reason that makes a text difficult to read rather than grammar, spelling and syntax (Lipton, 2007; Pettersson, 1989; Pettersson, 2016), the writing style that contains complex and long sentences, abstract words, acronyms, jargon, passive constructions and stilted language needs users to have more cognitive capacity to process. Short, direct and straightforward sentences are always recommended; they can enhance people's reading and understanding efficiency, which provide readers with "visual comfort" of the text (Mackiewicz, 2004; Petros et al., 1990).

Choosing suitable typefaces is the crucial step when establishing the typographic system in design. Appropriate typefaces make the readers feel pleased and willing to read (Dyson, 2011). Different typefaces have their own characteristics; according to Henestrosa et al. (2017), typefaces are mainly classified into three main categories: serif fonts, sans-serif fonts and display fonts. Serif fonts have strokes attached to the main part of the letters, and they are widely used in traditional design because of their classic appearance (Henestrosa et al., 2017). Serif fonts are slightly more legible than sans-serif fonts on paper (Arditi and Cho, 2015), because the strokes help readers to read faster and avoid fatigue (Velasco et al., 2015). Serif fonts are popular in printed publications as well, like posters, newspapers and magazines. Sans-serif fonts do not have strokes; they look more modern, fresh, and clean than serif fonts. Sans-serif fonts are widely used in software design because they are more legible than serif fonts on digital design screens (Henestrosa et al., 2017). In addition, serif typefaces have more expansive inter-letter space than sans-serif typefaces; this indicates that the exact text using serif fonts is more extended than using sans-serif fonts (Gump, 2001). Based on this, most transit map design examples used sans-serif fonts to capacitate more characters in the limited space than the serif fonts. Display fonts come in numerous styles, and their strong decorative characteristics make them suitable only for short text, like titles or headers, which will make the text look more ‘artistic’ (Henestrosa et al., 2017). Display fonts are not commonly used in transit map design, because they may occupy too much space on the map and interfere with users’ attention. Some map titles chose the display fonts to enhance the attractiveness of the map, which are common in earlier maps.

Building up a well-organised hierarchy and corresponding sizes for texts is important; if all words are in the same typeface and same size, it will be tough for readers to get the key information on the map (Hartley J. and Burnhill, 1977). Map designers should avoid unusual typefaces and fonts that are too small or too large (Lipton, 2007; Williams and Tollet, 1998). Headings are usually larger, sub-headings are medium-sized, and body text is smaller (Wang, 2016). According to Brychtova and Coltekin (2016), throughout reading tests using different fonts, participants had lower scan path speeds when searching for the answer on stimuli with font size 11pt, indicating participants viewed fewer pixels per second. Participants can also read efficiently between stimuli from font sizes 8pt (Mdn5417.3 px/s) to 14pt (Mdn5425.9 px/s); no significant differences in scan path were found. The results showed that the 11pt font size is more effective in information searching compared with other font sizes on the screen, because a lower scan path speed reflects that participants found information effectively without searching as many texts as possible to target needed information (Brychtova and Coltekin, 2016; Bartz, 1970). In the test, the author used a screen resolution of 1920 x 1280 pixels; this setting is the same as the screens used in China's railway stations to display maps.

Moreover, changing font size is not the only way to make text hierarchical; designers can also try to change the typefaces, colours, space, style and weight, using italics, underlines or adding visual signs are also effective methods to provide emphasis (Benson, 1985; Dwyer, 1978; Hartley et al., 1980; Hyndman, 2015). In addition, designers can try to combine complementary fonts to enhance the text's hierarchy, e.g., serif fonts with sans-serif fonts, tall fonts with short fonts, or decorative fonts with simple style fonts; this design solution is common to see in many transit maps globally (Hyndman, 2015).

Taking the Paris Underground transit map as an example (Figure 2.10), different sizes of sans-serif texts are used to display lines, stations and interchange points; the mainline names are bolded to make them easier to be found on the map.

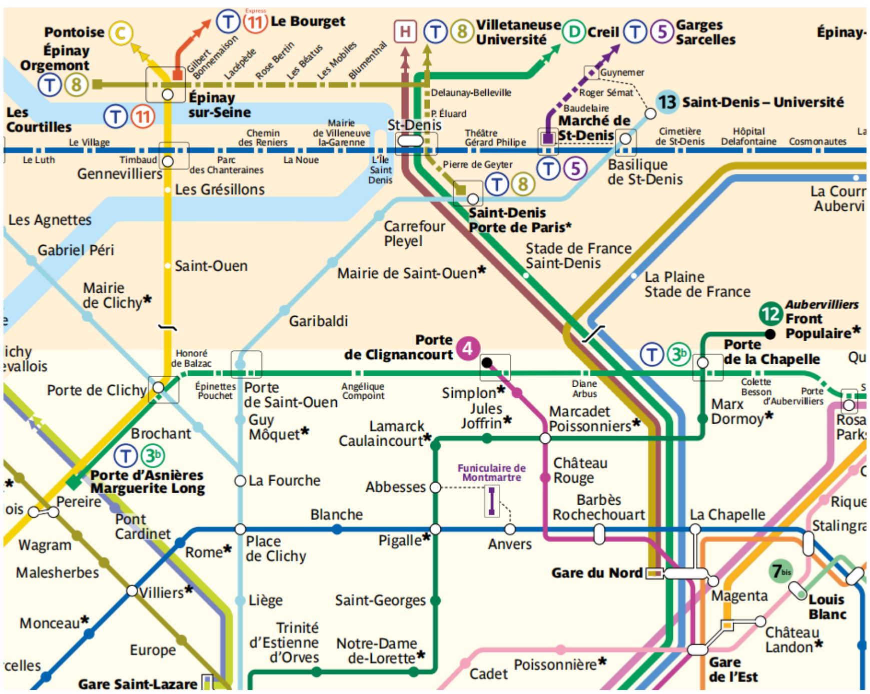


Figure 2.10: the Paris Underground transit map (partial)

Appropriate line length and inter-line space should be applied when writing longer sentences on the map, such as the long explanation of certain services. When the text line length is too long or too short, it will cause inefficient reading as readers tend to spend more time to continue a new line and may easily get lost in the text (Crisp, Temple and Davis, 2012). Moreover, text with no inter-line space or very short inter-line space will make the layout too crowded and affect the reading efficiency (Lonsdale, 2016). Leaving margins is an excellent choice to avoid the text being crowded; margins are also very functional and allow the readers to make some notes, punch and clip copies without damaging the text (Lonsdale, 2016). In map design, the labels of stations should strictly avoid overlapping and try to keep the horizontal direction, as the horizontal layout applies to most people's daily reading habits (Ovenden, 2015).

2.2.4. Interchange system

Interchanges are very common in public transportation systems, especially for a more extensive multimodal network; passengers usually need to transfer between multiple interchange points and services to reach their destinations (Hadlaw, 2003). Taking the transportation system in London as an example, about 68% of underground trips and 35% of bus trips contain at least one transfer (Transport for London, 2020). In New York City, around 82% of commuter rail trips and 33% of bus trips contain at least one transfer (NYMTC, 2019). In Shanghai, about 65% of underground trips and 40% of bus trips have at least one transfer (Shanghai Metro, 2019). The data showed how common the transfer is for passengers. It also emphasised the importance of a clear interchange system with well-designed visual signs to guide passengers travelling between transferrable lines.

In the early 1930s, the visual design of transfers or interchange was discussed and explored in successive versions of the London underground map by Beck. In 1946, a "white-line connecter" notation (Figure 2.12) was designed for transfers and received unexpected positive feedback from the public. This design has soon become a well-recognised transfer sign all over the world and has been widely used on many transit maps, because it successfully pointed out where passengers can transfer between multiple lines and linked them with a simple notation (Bain, 2011).

It is difficult to find a study that focused on interchange system visual design; three main reasons probably cause this: firstly, the positions and categories of interchange points or services are not decided by map designers; they were constructed before the map design. Secondly, a transit map in use includes the proper transfer signs that may not be possible containing errors in the interchange system. The last reason is the lack of analytical tools to understand transfer behaviour and evaluate transfer signs (Hadlaw, 2003). In Experiment I (*Chapter 3*) and Experiment III (*Chapter 5*), the design quality of the interchange system was analysed based on users' map using behaviour observed via eye-movement data, which filled the gap from the users' perspective.

Codification of the interchange points is a critical work when presenting connections on a transit map; there are various methods to represent the transfers (Figure 2.11), such as overlapped stations (the most common design, taking Shanghai Underground map as an example), semi-overlapped stations (Kiev), separate stations connected by a link (Tokyo), or a single line with no connections at all (Madrid).

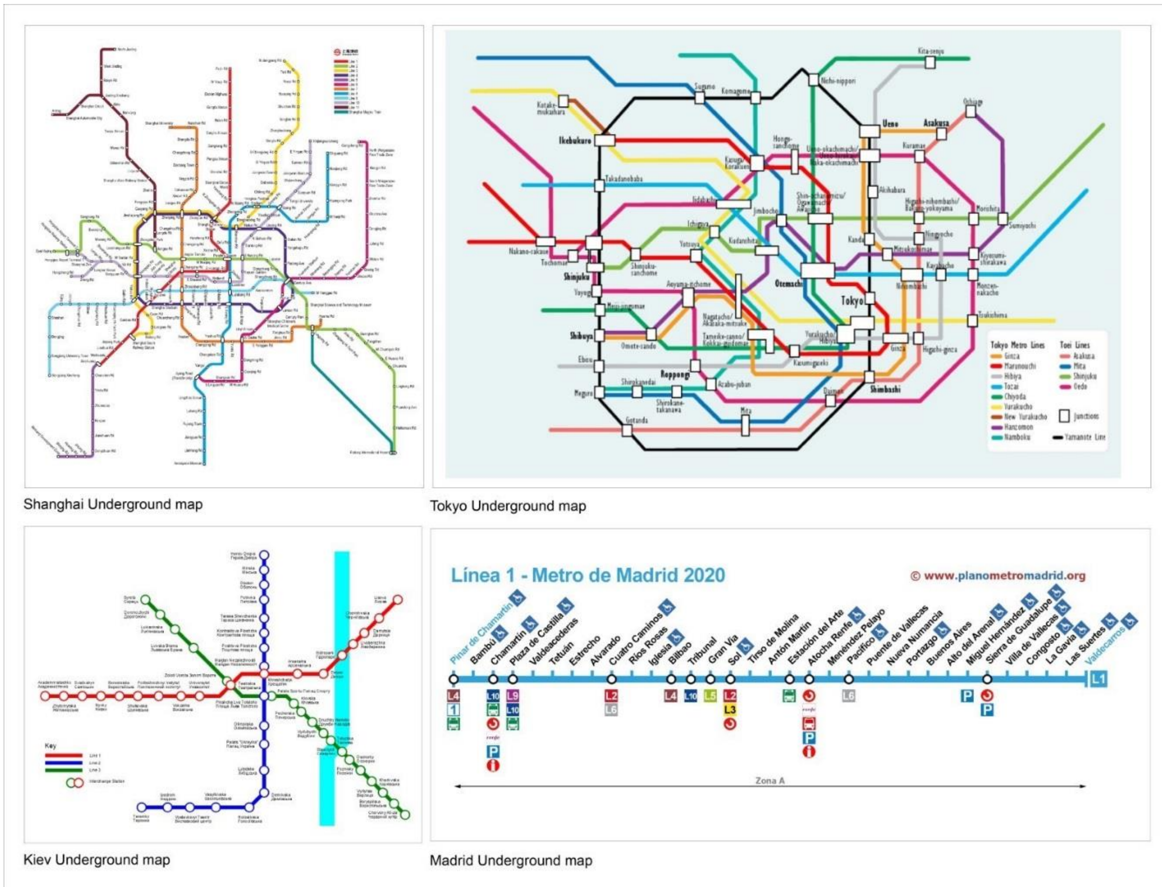


Figure 2.11: Different ways to represent transfers

There are many different interchange point design examples on the different counties' or cities' transportation system map; some representative designs are showing in Figure 2.12. The white "Bone" shape white-line connecter transfer sign of London underground map is prevalent among the contemporary transit map design; some other similar designs were derived from the London underground transfer sign, such as the Amsterdam underground map used a white block transfer sign that includes the dots with the corresponding lines' colours. The transfer sign of the underground transit map of New York is simply a white block linked to both transfer stations. The underground transit map of Moscow used a similar white “bone” shape transfer sign and added the number of the corresponding lines.

Tokyo underground map shows a design example (Figure 2.12) that two paralleled white dots without additional signs to represent the transfer relationship; current China’s High-speed Railway Map also used the same design method. The Washington DC. Metro map used a white dot that simply overlapped two lines to show the transfer point; this may be an extreme example in transfer sign simplification. The railway transit map of Denmark used the short black lines at the same position to demonstrate the transfer points. Finally, the transfer point of the railway transit map of the Japanese Kansai area is exceptional, except for the white blocks (stations), there is a grey zone to represent the transfer point; some zones could include more than two stations.

Overall, the function of an interchange sign is to show the exchanges between two or multiple stations clearly, and it is always suitable to use simple shapes, the complicated or decorated designs are not recommended, the interchange signs on a transit map should be consistent in design style, size and colour (Roberts, 2014).

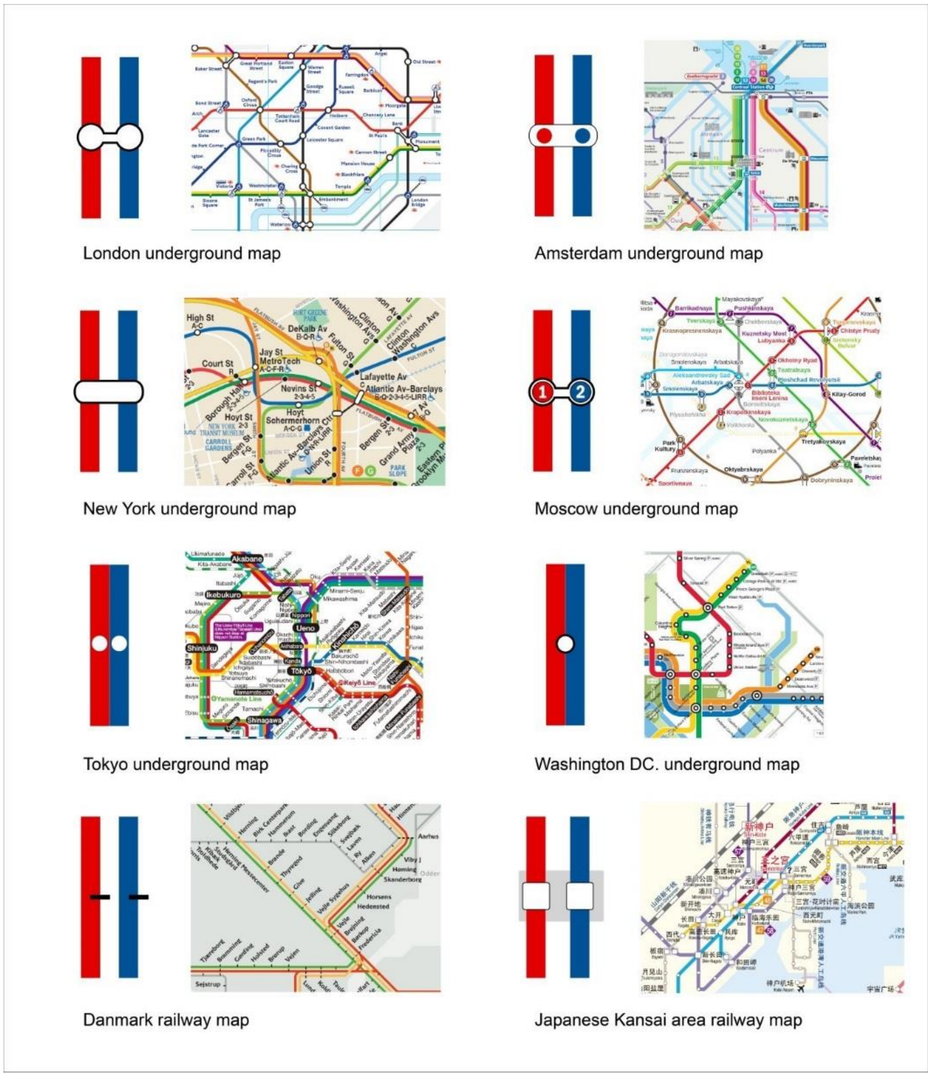


Figure 2.12: Representative interchange point design examples

2.2.5. Colour system

Colour is the most multi-dimensional and complex graphic variable in design; as a dominant visual variable, colour operates in a preponderant way in readability problems (Stigmar, 2010). Research showed that when people look at an object for the first time, around 80% of vision focuses on colours, attention to colours reduces to 60% after 2 minutes, but still more than shapes. This explains how influential colour is in visual perception (Liu and Lin, 2009). Colours are regularly used in informative reading materials, not only in illustrations, but also in the text and icons, etc. Colours can clarify the structure of the text or visual elements to make the reading process easier for readers (Petterson, 2019). The black text has a strong contrast to most light colour backgrounds; keeping a strong contrast of the text and the background is beneficial for achieving higher legibility (Petterson, 2016). Colours enhance the attention and perception of a visual element; research showed that people always prefer the coloured plan rather than black and white in visuals (Moriarty, 1991).

A colour contains three essential elements: hue, value and saturation (Mollerup, 2015). Hue is generally understood as colour; hue is the colour dimension associated with different dominant wavelengths (Robinson et al., 1995), all hues can be found on a colour wheel. Value can be understood as brightness; it stands for the amount of black or white added to the hue found on the colour circle. Saturation is defined as its absence of white and black; it is also called "chroma" in some theories. Itten, the master of architecture design at Bauhaus, mentioned that all visual perceptions come from seven forms of colour contrasts: the contrast of value, saturation, hue, extension, warm/cold, complements and simultaneous contrast (Norman, 1990).

Colours are widely used in information design; they can make the message clear and emphasise the key information in reading materials (Horton, 1994). Colours can help attract and direct the user's attention in the reading process and even guide the users to places the designer hopes to highlight. According to Horton (1994), "colour-coding" is the most effective tool to make a target more outstanding than any other technique, such as shape coding. Colours can always assist users in figuring out target information effectively in a disordered and complicated display environment.

Colours are beneficial to make small icons or patterns stand out. Icons with expected, familiar colours are more likely to be identified and easier to understand than icons displayed by black and white (Horton, 1994). According to the result of Guo's (2016) experiments, users prefer negative-display-polarity icons. Blue, green, and red were the more preferred icon colours, and purple, orange, and yellow were the less preferred icon colours.

It is proved by Netzel et al. (2016) that coloured transit maps are more legible than grey-scale transit maps; colours help users to enhance the trip plan accuracy, with less frustration, less confusion and more confidence. According to Harrie and Stigmar (2009), two main factors may affect the legibility of a map: first, the complexity of the map (i.e. quantity and distribution of the information included on the map display), second, the visualisation design quality of cartographic symbols. In addition, in visual design, colour takes almost half of the six basic visual variables: size, colour value, colour hue, texture, orientation and shape (Bertin, 2010).

Therefore, colour is a key visual variable that can strongly influence the legibility of a map. The stronger colour contrasts between visual elements on a map can make them easier to be identified (Stigmar, 2010). Research also shows that colours can affect users' attention, relevant to reading accuracy and speed when searching for information on a map (Brychtova and Coltekin, 2016).

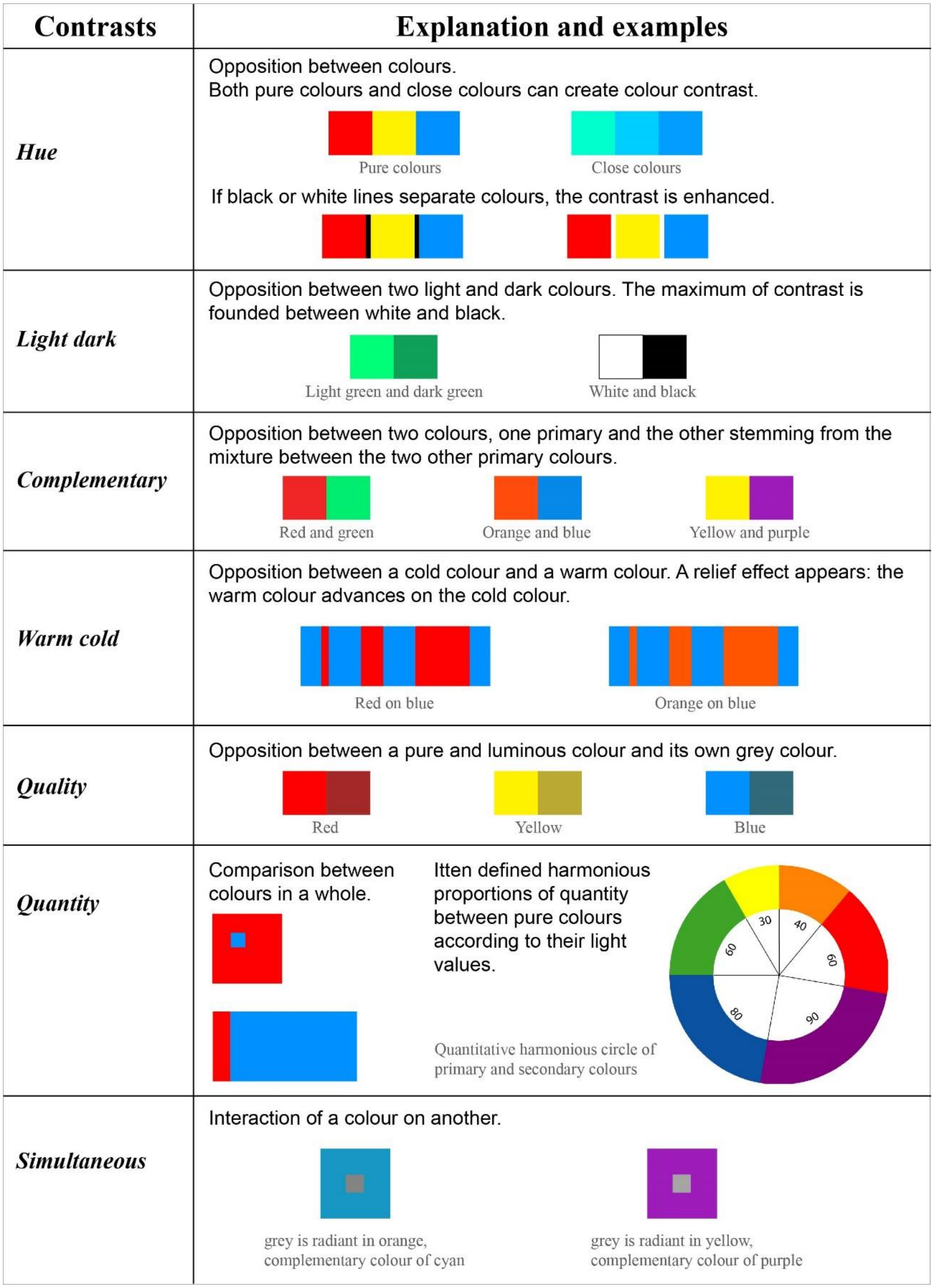
Compared with black & white maps, there are some advantages and suggestions of colours utilise on a map:

1. Colours can be used to describe data (e.g., difference services) on a map without weakening map understanding, colours are selective and flexible in various plans (Chesneau, 2005).
2. In most cases, nominal data (e.g., different transit lines) on a map can be represented by different hues of colours and ordinal data can be displayed by different values of the same colour (Adams and Stone, 2017).
3. Colour is a very useful tool to control other visual variables on a map, e.g., different levels of transparency can be combined with colours to show the background below the figures according to certain needs (Best, 2017).
4. Colours can help users to understand symbols on a map better, such as light blue refers to rivers and light green refers to forests. However, some users may have a different understanding of colour symbolisms due to the different cultural backgrounds or educational levels (Mcdowell, 2008).
5. Colours can affect people's emotions, in some map design examples, designers used red colour to stimulate users' attention (Wang et al., 2008), but the red colour is often used to warn people of danger, it is not always wise to highlight the important information on a map in red (Lee, 2015).
6. Colours are unplaceable in the aesthetic aspect of map design, it can strongly decorate visual elements on a map and make them more memorable for users (Pridmore, 2011; Saliha and Menekse, 2015).

Robinson (1952) conducted many studies focusing on the relationship between map readability and text colours; the author investigated different combination sets of background colour and map information colours. According to the results, the best combination is black letters on a white background; the worst combinations are black on purple, red on green and orange on white background.

There are many common problems of colour in map design; colour overlapping is one of the riskiest design limitations (Buard and Ruas, 2012). Colour overlapping refers to different hues overlapped with each other without clear gaps, this problem can cause confusions in reading even make some information be hidden, e.g., when the colour of an object has low contrast with its surrounding objects, users would ignore this object. This indicates that information on the map can be partially lost due to the unsuitable colour use; it is necessary to keep stronger contrasts among neighbour colours. Buard and Ruas's (2012) research improved the colour plan of a map by figuring out the colours have weak contrasts of hue and value with surrounding colours and replacing them with new colours in strong contrasts, users' information searching accuracy of the map enhanced afterwards. This research showed that colours could help display information clearer and improve the identification of objects on a map. However, although the colour system on a map is helpful to enhance its legibility, but in Netzel et.al's (2016) research, when the complexity of way-finding tasks increased, the difference of response time and accuracy between coloured and grey-scale maps became smaller, which indicated that the advantages of colours may not very useful when the complexity reached a certain level.

It is recommended to create a stronger contrast among surrounding colours in map design, Bauhaus School has emphasised this in the 1920s. According to Kandinsky (1910), the lecturer in Bauhaus School, the purpose of establishing contrasts between colours is to create sensible differences or intervals between visual elements. Itten (1985) further defined the colour contrast into seven possibilities: the contrast of hue, the light-dark contrast, the warm-cold contrast, the complementary contrast, the simultaneous contrast, the contrast of quality and the contrast of quantity (Chesneau, 2005). More details are showing in Figure 2.13:



Contrasts	Explanation and examples
Hue	Opposition between colours. Both pure colours and close colours can create colour contrast. Pure colours — Close colours If black or white lines separate colours, the contrast is enhanced.
Light dark	Opposition between two light and dark colours. The maximum of contrast is founded between white and black. Light green and dark green — White and black
Complementary	Opposition between two colours, one primary and the other stemming from the mixture between the two other primary colours. Red and green — Orange and blue — Yellow and purple
Warm cold	Opposition between a cold colour and a warm colour. A relief effect appears: the warm colour advances on the cold colour. Red on blue — Orange on blue
Quality	Opposition between a pure and luminous colour and its own grey colour. Red — Yellow — Blue
Quantity	Comparison between colours in a whole. Itten defined harmonious proportions of quantity between pure colours according to their light values. Quantitative harmonious circle of primary and secondary colours 30, 40, 60, 60, 80, 90
Simultaneous	Interaction of a colour on another. grey is radiant in orange, complementary colour of cyan — grey is radiant in yellow, complementary colour of purple

Figure 2.13: Seven contrasts defined by Itten Johannes

2.3. Relevant user performance studies

Research showed that the quantity and design quality of the transportation information presented on a transit map might affect user performance and decision making in two main ways. First, it influences the number of available opportunities and travel options perceived by travellers regarding destination, mode, or path choices. Second, it affects the perceived attributes of these opportunities and travel options, such as the desirability of a place and travel time and cost (Chorus et al., 2007). Affected decisions include location, mode, and path choices (Guo, 2011).

Some researchers investigated how to understand and evaluate the design of transit maps from the users' view, including how users find out information on the map and plan their trips, or how users interpret and perceive transit maps. Research in the human perspective can help to understand and evaluate the effects of design on usability and identify potential problems; some specific solutions can be implemented to make the design more efficient (Rosenholtz, 2011). Researchers can extrapolate from user behaviour findings to evaluate the transit map design quality, it may not specific enough to provide effective design solutions, but user behaviour findings can provide evidence to critique existing design examples, it is helpful for researchers to validate their evaluations via existing empirical findings from the actual transit map usability tests (Roberts, 2017).

In most cases, obtaining data from the use of actual transit maps is a more objective and direct way to analyse user behaviour; researchers can investigate users' real route choices using regression analyses with respect to the map design features (Guo, 2011). Alternatively, map design examples can be tested in laboratories; researchers can measure user performance from qualitative or quantitative aspects when participants accomplish different tasks. Design limitations and better design solutions may be identified and conducted after evaluating user performance (Netzel et al., 2016). Based on this, the user performance test such as eye-tracking tests and map information searching tests were conducted in this research (Experiment I) to identify design limitations and user needs; some other quality test methods were used at the same time to collect detailed feedback from the users. Conducting usability tests is an effective way to evaluate novel designs. However, the feedback from users may not be strongly relevant to objective measures, but still provide valuable insights or suggestions (Roberts, Newton and Canals, 2016); more details about different usability test methods are discussed in *Section 2.3.1*.

User performance is also affected by the number of distractors and users' knowledge or familiarity of the transit system; the information searching process would be very efficient if the user is familiar with the map or has rich knowledge about the area displayed on the map (Beck et al., 2012; Wolfe, 1994). This indicates that when recruiting participants in the transit map usability test, it is important to make sure that participants never used the testing map and had no knowledge about the area displaying on the testing map; this standard was insisted in all the empirical tests in this study, which helps to enhance the objectivity of test results.

Moreover, the difficulty levels of the tasks can affect the user performance test result as well. Grison et al. (2016) found a surprising result that users showed better accuracy in tougher route plans (include at least two transfers) than the simplest route plans (direct route without transfers). This may be due to the reason that simple routes include substantial detours, but routes that contain transfers may be less curved, or the distance between transfer stations are short; a route contains multiple transfers can be understood as a combination of multiple short direct lines, which probably easier than a long direct route when users track the lines. However, individual differences between different transit networks are significant, and the users' reading behaviour could be entirely different when using other maps (Grison et al., 2016). In this research, tasks with varying levels of difficulty were set up in all tests (Chapter 3, Chapter 4, Chapter 5) to reduce the interference of some potential factors such as participants' knowledge differences or other accidental factors in the test, which is helpful to strengthen the objectivity of the experimental results.

2.3.1. User habits

Analysing user habit when reading a transit map can help researchers to find out more details about how users find out the needed information and what design limitations caused reading problems in this process; based on this, some information or visual design can be improved to enhance users' reading accuracy and comfort. If the map's design is not applying to users' habits, they may give up using the map and make decisions based on their own experience (Avineriand Prashker, 2006).

Before making any decisions about the trip, users need to know the places where they are locating; this needs an accurate display of all stations and services that users can locate their positions on the map quickly (Avineriand Prashker, 2006). According to Burch (2018), the central area of the map seems to be visually attended much more frequently than peripheral stations; this effect increased with the increase in task complexity (Grison et al., 2016). The potential reason is that busy transportation regions are located in the central area. More importantly, due to the reason that designers commonly enlarge central areas to contain more lines and stations, this may imply to the users that this area is more important than others, this trend can be observed in almost all maps in many eye-tracking tests (Burch et al., 2014; Netzel et al., 2016). Another explanation is that the stations allowing for transfers are typically in the central part of the map; users prefer to pay more attention to where containing as many transfer stations as possible; this may explore their choices of route plan in travel (Grison et al., 2016).

In the empirical tests, another user habit was observed is that participants paid more attention to the **map legend** than other components on the map, which seems to indicate that the map legend is the most concerned and vital part of a transit map (Netzel et al., 2019; Wang, Lonsdale and Cheung, 2021). Some research explained why users visually attended the map legend and destination of the lines frequently, this behaviour may drive by the tasks set by researchers that participants required to solve the route-finding tasks correctly (Krejtz, Duchowski and Coltecin, 2014; Burch et al., 2014). Due to this, the visual behaviour in the laboratories may differ to map reading in daily life, and some conclusions may not be objective if only depends on users' behaviour during the lab experiments.

When planning the direct route with multiple transfers, participants spent more time looking at transfer stations. If the routes are complex, participants focus more on connection stations than origin and destination stations to avoid any potential mistakes that may cause the route unconnected (Grison et al., 2016). In addition, no matter how complex the route is, destination stations always receive more attention than origin stations; this phenomenon may be due to the reason that is the direction-based strategy is a prominent planning strategy in user's wayfinding behaviour (Conroy Dalton, 2003; Golledge, 1995; Holscher, Tenbrink and Wiener, 2011).

Apart from the frequent review of the map legends, central areas and destinations, there is another interesting finding in Burch's (2018) research that users frequently looked at rivers or water areas such as the Thames River in London. This finding shows that users still pay attention to topographic information when reading a transit map; preserving some topographic visual design can provide users with some wanted information such as the border of land and water. Not only topographic information, some other graphic elements such as airports signs, underground signs or long labels also attracted people’s attention (Burch et al., 2014). Moreover, for colour-coded maps, red colour lines were more visually attended than other colour-coded lines. It is also surprising that there were not many differences in users’ visual attention between colour-coded maps and grey-scale maps (Buard and Ruas, 2009; Burch, 2018).

There is an old belief that travellers always try to find out the shortest route when planning trips, a large number of studies and experiments were conducted and analysed based on this assumption; this belief significantly influenced the research in transit map user habit study (Grison, 2019). But some research questioned this assumption; they found that when users use a dense network map such as the London underground map, other factors such as travel cost and numbers of transfers are also considered when planning routes (Guo, 2011). Moreover, the network topography can also affect the user’s route planning process (Raveau, Guo and Wilson, 2014; Raveau, Munoz and Grange, 2011). Results also indicated that a trip is composed of different slices of time, includes waiting time, walking time, in-vehicle time, etc.; these time slots are evaluated differently by users when making their route choices. In fact, users care about the waiting time and walking time more than the in-vehicle time (Raveau, Guo and Wilson, 2014). Some other factors, such as the uncertainty of the trip, potential loss of control, and spatial complexity may strongly affect users’ route choice. This explains why travellers prefer the direct routes without transfers or routes with as few transfers as possible, because the number of transfers is a key factor that users consider when choosing the routes (Grison, Gyselinck and Burkhardt, 2016; Hine and Scott, 2000). This result showed that it is not objective to design performance tests that assume passengers prefer the shortest route in the distance (Grison, 2019) because this assumption does not follow the actual user habit. Some studies focused on users’ gaze movement and discussed the possibility of using the number of transfers as a criterion of route selection user behaviour study, because the number of interchanges is a key factor when users making decisions in route planning (Grison, Burkhardt and Wiener, 2016; Netzel et al., 2016). In this research, the relationship between the number of interchanges and users’ route choices was investigated in Experiment III (Chapter 5), the result was analysed in Section 5.6.3.

The research found that the topological factors in transit map design can affect user’s route planning process (Grison, 2019). A study investigated a route between the “Metro centre” station and the “Pentagon” station of the Washington Subway to see how design affected user’s route plans (Guo et al., 2017). There are two options to join both stations, the first one is a direct route with no transfers, and the second one is a route with a transfer. It was clear that the first route is more preferred by users, which caused serious congestion on this route. In order to solve this problem, the authors lengthened 20% of the first route's line on the map; this increased the number of people who chose the second route from 2% to 6%, when the authors lengthened 40% of the first route's line, the number of people who chose the second route increased 10%. Then the authors shortened the second route's line on the map; this increased around 2.6% of readers selected the second route. This shows that users' route planning behaviour can be affected by topographic design (Grison, 2019), or in other words, by changing the layout of routes, the runner of the transportation system can modify users' route choice to solve some existing traffic problems. However, the authors found that this method only worked on users who were not familiar with the system much more than the frequent users (Guo et al., 2017). Morgagni and Grison (2019) conducted an experiment on the Lle-de-France schematic map; the studied problem was similar to the one investigated by Guo et al. (2017). There are two route choices between "Juvisy" and "Corbeil-Essonnes" stations; the western one is direct with no transfers includes four stops, and the eastern route has one transfer and three stops. The authors used the same method to modify the routes to prevent congestion on the western route. However, different to Guo et al.'s (2017) result, when the length of the western route be lengthened 20%, more people chose the eastern route, but when it extended 40%, it did not bring any additional increase of people who chose the eastern route. This result showed that modification in topography might not be effective when it reached a certain level.

In relevant studies, researchers also found that participants tended to treat the layout of a schematic map as the actual layout. Vertesi (2008) found that users' mental models of the structure of roads, landmarks, green areas and rivers in London were distorted in a very similar way as the London Underground Map's spatial layout. Berend, Rauh and Barkowsky (1997) provided participants with a railway transit map of an unfamiliar city and its topographical map; participants were asked to predict a railway station that was beyond the topographic map's shown area, most participants used the exact spatial relationship of the railway transit map to predict the station. The finding from both tests indicated that designers should maintain the topographic correctness as much as possible because most users prefer to predict the actual topography based on transit maps.

As previously mentioned, users prefer to choose the routes with fewer bends; even the route is not the shortest in the distance, this is called the "least-angle" principle in route-finding behaviour (Roberts et al., 2013). This may be because straighter routes look easier to reach the destination than the zigzag routes (Guo, 2011). In addition, users prefer to choose the routes that pointed towards the destination; this habit was observed in many studies, which may cause inefficient route choices (Raveau, Guo and Munoz, 2011). Moreover, users prefer to choose a route with a later interchange rather than an earlier one; this habit can lead to inefficient route plans as well (Roberts and Rose, 2016).

2.3.2. User preference and potential biases

Users' map acceptability and desirability are critical considerations for designers; otherwise, users may give up using maps, turning to other relevant trip plan applications or simply choosing routes based on their own experience. This may become a risk for the running of the transportation system. It is why understanding users' preference is necessary. This can help to enhance users' acceptability and desirability by taking design solutions. Although both factors are important for new designs, only a few studies have solicited users' opinions and preferences.

Roberts (2017) found that users have a strong preference for octolinear layout (horizontal, vertical and two 45°diagonal angle lines), maps using octolinear layout tend to have higher acceptability and usability than multilinear and curvilinear maps, this may be because of the inertial trust of traditional Beck's London Underground Map layout, users get used to this design style for almost a century that led to a higher familiarity than any other layouts. This trend is global; Wu et al.'s (2020) study showed that there were no distinct differences in preferences for octolinear layout among participants from Britain, America and Germany. Wu et al.'s (2020) research also support this finding that participants' rates of usability and attractiveness are dissociated; octolinearity was the most preferred for both criteria, multilinearity was rated more usable than curvilinearity and curvilinearity was rated more attractive than multilinearity. Grison's (2019) research found that users' preferred map did not influence on user's route planning time result in his tests, which indicated that there might be no correlation between the subjective preference and the objective result; this hypothesis was further investigated in Experiment III (*Chapter 5*). In Grison's (2019) study, German participants rated curvilinear maps better than American and Canadian participants; this showed that users' preferences might differ in different regions. In addition, a simplicity preference of users has been found that maps with more straightforward line trajectories tend to be more preferred than those with the same design rules but more complicated in trajectories design. Although many studies focused on people's user habits and preferences between octolinear and curvilinear maps, very few investigated users' different route planning behaviour when using both layout schemes. The study investigated this topic; some interesting findings were observed through users' route choices in both Experiment I (*Chapter 3*) and Experiment III (*Chapter 5*).

As previously mentioned, users prefer the route with a longer initial straight segment or point directly to the destination (Bailenson, Shum and Uttal, 1998, 2000). Another interesting finding shows that users prefer the southern route when asked to choose between a southern route and a more northern route; participants showed a reliable preference for the southern route (Brunye et al., 2010). This preference has been replicated in various countries; this may be because of the misconception of increased elevation to the north. Most people may assume that the northern routes are more uphill (Brunye et al., 2012).

Roberts's (2017) research showed that no matter layout structure or trajectory simplicity, users' preference rates were sometimes mutually exclusive to actual using efficiency, which indicates that the design of transit maps preferred by users may not be the most effective plan and the individual differences in map evaluations are substantial, users' judgments of familiarity or attractiveness may have no direct relationship to the actual usability, this phenomenon has been called the usability gap (Roberts, 2019). A similar result was proved by Grison (2019). The preferred maps declared by participants did not influence planning time results. The author did not find any potential correlation between the subjective preference and the objective result, which indicates that the attractiveness of a map is not equal to its usability. In addition, it is meaningless to ask users which particular map they think is easy for route planning; people can only guess and make meaningless choices; the usability of a map should be objectively tested based on time, accuracy and route quality (Roberts, 2012).

Moreover, an interesting finding shows that people with relevant expertise background (design or transportation) responses in tests are very similar to those who do not have such experiences. But Grison (2019) mentioned that people familiar with map design issues rated transit maps more attractive and usable than non-familiar users. This finding indicates that assessment of transit map usability by people with relevant expertise may not be distinguishable from the public; the individual difference of user's professional background in map usability evaluation is not significant (Wu et al., 2020). In addition, Grison (2019) found that feedback about transit map design received from female participants is more attractive, detailed and valuable than male users. There are continual debates about whether the prescriptions for design should be modified depending on suggestions from experts or ordinary users. Still, it has been proved, as previously mentioned, that there are no significant differences in the feedback from both experts and users with no relevant backgrounds; it is wiser to collect evaluations from users despite their backgrounds, this idea was applied to all empirical tests in the research, more than one hundred participants from different backgrounds were recruited, they provided numerous valuable feedbacks and suggestions in the tests, which helped to improve the map design enrich the knowledge in both information and cartographic design.

2.3.3. Relevant usability test methods

The most commonly researched micro layout topics in transit maps are mainly about the identification of visual elements (Guo, 2011), categorisation of information ((Lloyd, Rodgers and Roberts, 2018) and the usability of different functions on maps (Guo et al.,2017; Xu, 2017), as well as the relevant consequences of design limitations, normally focused on route choices. Colour-coding is also a frequently investigated topic, but most researchers only made comparisons or figured out problems without providing practical colour-coding modules or solutions; this gap was filled by the detailed colour evaluation, redesign and tests in this research. Lloyd, Rodgers and Roberts (2018) investigated the effects of individual routes' colours and routes on a trunk using identical colours; this research focused on colour-coding effects on different route categories, which is considered as a breaking study about colours on transit maps. In addition, other questions such as interchange symbols and interchange layout are barely researched; this study investigated visual symbols and layout issues of interchange points, which are discussed in Experiment III (*Chapter 5*).

Some researchers investigated the macro layout of transit maps; many different transit layout rules are tested, such as the comparison between octolinear and curvilinear (Bronzaft and Dobrow, 1984; Roberts et al., 2013, Roberts, 2016), effects between octolinear, curvilinear and multilinear (Roberts, Gray and Lesnik, 2017). Roberts, Newton and Canals (2016) investigated the impact of octolinear versus concentric circles and spokes. However, although different layout rules may be proved effective in some research, it is not easy to define which layout rule is the most effective plan in general or a specific transit network. Few studies investigated individual geographic differences in transit networks in different cities or countries (Bronzaft and Dobrow, 1984; Roberts, Gray and Lesnik, 2017; Xu, 2017). Raveau, Guo and Munoz (2012) investigated route choice differences of underground networks between London and Santiago; it shows individual differences of networks' topography can make differences in user performance. The research about the effect of supplementary details on route planning performance is rare, such as additional information on the map about services and facilities (Wu et al., 2020).

When testing the usability of a transit map, three measures are frequently researched: route choice (how do users make decisions of travel plan), route planning time (the time consumed when identifying a route between two specified stations), and route efficiency (based on time/number of transfers/inconveniences estimates for chosen routes). These measures can be collected directly from tests, and they are valuable evidence of the map's route panning efficiency (Roberts, Newton and Canals, 2016). In most cases, studies of micro layout tend to investigate route choice, whereas studies of macro layout tend to analyse route planning time (Wu et al., 2020). The measures of route planning performance are closely relevant to negative consequences of poor designs, and users' route planning errors. In recent years, more methodologies have been developed to study the influence of transit map design on user's route planning performances, not only the common studies in the labs or online demonstration, but also studies collecting user's eye-moving behaviour (Wu et al., 2020), such as the eye-tracking test (Experiment I, Chapter 3) in the study, various design limitations of the map were identified through users' eye-movement data.

However, some measures are difficult to collect or may have fewer effects on the research, sometimes may have limitations when leading to the conclusion. The first is the topographical route mistakes; it is not likely to happen if all transit routes on the map are displayed according to actual lines, e.g., a non-existed interchange point (Lloyd, Rodgers and Roberts, 2018). In addition, the investigation of users' gaze direction or duration may be difficult to define its meaning, e.g., it is difficult to distinguish whether the user was interested in the place or felt confused if looked at a certain area for a longer time, this frequently happened in eye-tracking tests (Netzel et al., 2016). Because of this, some additional research methods can implement together to enhance the objectivity of the gaze direction or duration. Moreover, station finding is not very meaningful in usability tests. It has a considerable chance factor; the time or accuracy of station finding tasks is not objective enough to support a specific conclusion (Wu et al., 2020).

Some researchers investigated multiple other valuable measures. The direct route verification tasks asked users to determine whether there is a direct route between one station and another; the researchers (Lloyd, Rodgers and Roberts, 2018; Roberts and Rose, 2016) found that user behaviour is far different between simple networks and complex networks. Vertesi (2008) investigated users' mental models for city structure by asking them to choose and add the missing information on the map; similar research was conducted by Berend, Rauh and Barkowsky (1997) to find out people's mental models of a transit map's topographic information. Some studies investigated users' choice of design examples that followed some specific map usability criteria; this may be helpful to analyse users' opinions or expectations about different map design examples.

Some researchers complaint that almost all transit map usability tests were conducted in laboratories without investigating real journeys; they argued that participants planned routes on the map which they did not actually need to implement, this may lead to artificial test results and may not be representative enough in actual practice (Wu et al., 2020). Some researchers (Lloyd, Rodgers, Roberts, 2018, Roberts et al., 2013) replied to this argument that usability tests could effectively compare different map design examples and identify users' route plan errors when tracking routes on maps. In addition, users' route planning time even eye-movement paths can be recorded to evaluate the legibility of a map. These measures can figure out the design limitations which may cause reading difficulties; it is reasonable to believe that the design example caused various route plan errors or showed low legibility in laboratory tests can also lead to problems in reality (Lloyd, Rodgers, Roberts, 2018, Roberts et al., 2013; Wu et al., 2020). Moreover, route choice, route verification errors and route planning time have been proved to be valuable and straightforward variables to measure in usability tests. It may be harder to measure users' learning process when using a transit map. Still, some qualitative data can be collected to get some insights from users; this may be helpful to evaluate a map's design quality from the view of users (Roberts, Gray and Lesnik, 2017).

However, for some route planning tests under the laboratory settings, the inappropriate or wrong plan of the routes may not appear in the context of real settings, because inefficient routes have actual-time cost consequences, some mistakes that users made in the laboratory may not be made in real as well (Wu et al., 2020). But conducting usability tests is still an effective way to identify potential inefficient routes caused by design limitations, which is helpful for designers to improve design examples that reduce the possibilities of inefficient route plans or mistakes that happen in real journeys (Guo, 2011). Just like Grison (2019) mentioned, the *excess of methodological rigour and the simplification of protocols may lead to test situations disconnected from the real situations travellers encounter in their daily lives*. Based on this, Wu et al. (2020) suggested that it is wise to be more cautious in interpreting laboratory tests; the test results can be analysed as valuable but not conclusive findings.

Although conducting usability tests is a reliable way to identify the most and least designs from a series of map design examples, it may be difficult to formulate a generalised design principle based on a specific design (Roberts and Rose, 2016). Taking the comparison between the existing octolinear Paris Underground Map and its curvilinear design as an example, although the curvilinear design has the better efficiency in route plan, it is not appropriate to conclude that curvilinearity is superior to octolinearity in transit map design, even for the Paris Underground Map itself (Roberts et al., 2013; Roberts, Gray and Lesnik, 2017). In addition, other factors apart from the route planning efficiency need to be considered; individual differences between topographies cannot be ignored. The design of a transit map is affected by its design priority and design rules; some maps need to keep the topographical correctness as possible, but simplifying the line trajectories may be the priority for some other maps (Wu et al., 2020). Hence, researchers may need to be more careful when making conclusions from the usability test findings.

2.4. Summary

This chapter shows how information design knowledge affects the principles in transit map design; the main design elements of information design contained infographics, data visualisations, visual symbols and typography are reviewed and analysed. The knowledge regarding information design in transit maps is emphasised, mainly focusing on information structure, information quality and quantity, visual design, and typographic considerations.

The **information structure** of a transit map mainly contains both topographic information and transportation service information; the typographic information aims to demonstrate the basic knowledge of the geographic space displayed on the map, such as the spatial projection and scale (Avelar, 2006; Meirelles, 2013; Robinson et al., 1995). The transportation service information aims to show lines, stations, interchange points and other travel information such as travel distance and travel time (Guo, 2011; Wu et al., 2020). Based on this, the information presented on the map should always focus on passengers' travel information needs and strictly relate to their travel purposes; the information that can instruct users to plan and finish the trips need to be well-organised, such as detailed instructions of the transit line networks (Bain, 2010). The irrelevant information should be eliminated to avoid information pollution, such as the latitude or the area's temperature; these types of information may be helpful on a topographic map, but not closely relevant to the transit network (Meirelles, 2013).

In order to visually display the information clearly and effectively, various signs are needed on a transit map, such as transit line signs, transfer signs and direction signs, etc., the excellent design quality of **visual elements** on a transit map can effectively speed up users' information searching and understanding process, symbols and patterns should be carefully chosen to convey the information accurately (Ware, 2008). Thus, the visual element design principles summarised in this chapter provided an initial standard for visual designs in the later map redesign work. In addition, the colour system is a critical topic in transit map's visual design; it strongly affects the legibility of a transit map; some design principles regard to colour design are mentioned in this chapter, more details focused on colour harmony and colour-coding schemes are furtherly discussed in *Chapter 4*. The typography in transit map design is more complicated than everyday reading materials, because there are various text categories, such as station labels, city labels, service numbers & labels, and other necessary explanations (Wu et al., 2020). The fundamental typographic design principles discussed in this chapter helped evaluate and improve the typographic limitations of the testing map in *Chapter 3* and *Section 5.3.4*. Overall, the information design principles in the chapter macroscopically constructed theoretical design guidance for the transit map design in terms of two main parts: information structure and visual design. More details about the application of information design knowledge in cartographic transportation design are investigated and discussed in the following empirical tests.

3. Experiment I: An eye-tracking test examining information search in the transit map

After a thorough review of the information design and transit map design principles, in this chapter, a study investigated the legibility of China's high-speed railway map through eye-tracking measurement was conducted. The study was practised in two steps, firstly, a scoping user performance test was conducted to target the main design limitations of the map, and the findings were beneficial to the design of the later eye-tracking test. In a deeper stage, an eye-tracking test was practised to find out information and visual design limitations of the map that caused reading difficulties, which provided strong evidence to support the future map improvement work.

3.1. Introduction

As mentioned in Chapter 2, the high-speed railway is the most popular transportation system among international tourists who visited China in recent years, its popularity emphasised how important a well-designed network is to support people's trip plan.

The aim of the study is to evaluate the design quality of China's high-speed railway map based on transit map design principles and information design theories, to figure out its potential design limitation in information design structure and visual elements, then explore the practical design solutions to improve the legibility of the map, trying to investigate the optimum design of a transit map. Three main research objectives were set as follows:

1. To evaluate the legibility of the existing map in terms of information structure and visual design.
2. To find out information design limitations that affected users' reading speed or information design accuracy.
3. To observe participants' map reading behaviour and find out useful evidence that explains user needs and information searching habits when using a transit map.

In addition, the following research questions were investigated in the test:

a. How do users find out the target information they need from a transit map? What areas on the map do people pay more attention?
b. What design limitations can be identified from users' information searching behaviour?
c. How the information structure and visual design of a transit map affects the information searching behaviour?
d. What design solutions could be implemented in the next stage to improve the design limitations identified from the existing map?

In order to achieve the objectives and answer the research questions, an eye-tracker was used to record users' eye-movements in the test, which is a very effective way to evaluate the legibility of the map and observe users' information searching performance. More details about why the eye-tracking test is selected as the research method in the study are introduced in the next section.

3.2. Research method

In the test, an eye-tracker is selected as the main equipment to record each participant's eye-movement path, fixation points and fixation duration, then demonstrated people's reading process in gaze plots and heatmaps (Kang et al., 2016). In this section, the advantage of the eye-tracking test and what user behaviour and habit can be analysed from the eye-movement data is discussed.

There are three main factors that researchers pay more attention to when using an eye-tracker:

- **Hotspot**: to show the overall fixations of the tested reading material, normally the areas that users visually attended the most are emphasised by warmer colours, less concerned areas are in yellow or green on a heatmap (Kang et al., 2016). Longer gaze duration in the certain area reflects user's interest (Dwyer, 2018) or confusion (Wiliam, 2018). The heatmap can transform to a gaze plots map, which helps to show the fixation order and demonstrate readers' eye scan path (Just and Carpenter, 1980).
- **Scan path**: to show people's eye-movement paths through the whole reading process, the gaze diameter change is recorded to show people's reading habit and reading speed (Just and Carpenter, 1980).
- **Area of interest (AOI)**: to show areas that are frequently reviewed by people, AOI is very important in eye-tracking data analysis because it provides evidence of regions

where potentially attracted users (Kurzhals and Weiskopf, 2017). AOI is also the most popular topics investigated by researchers in many legibility studies.

These data can help to demonstrate and investigate each user's reading process, habit and preference, which is very helpful to review their reading performance, to analyse their perception and underlying cognitive process (Holmqvist et al., 2011). With the development in eye-tracking technology, conducting the eye-tracking test is currently became a practical way to evaluate the legibility of reading materials or web pages (Kang et al., 2016).

Ehmke and Wilson (2017) provided a suggestion of the eye-tracking data and the possible corresponding interpretations, which summarised from their empirical experience in eye-tracking tests:

Eye movement	**Possible interpretations**
Long fixations.	Users may have interest or confusions when reading the certain place.
Back-track saccade.	Feel confused.
Not looking at any elements.	Users may not have interest or get distracted.
Not reading in order, such as from left to right.	Users may not understand what target information they need to find, or possibly get lost in the design.
Back and forth between two objects.	Users are possibly making comparisons between objectives or finding it difficult to make a choice.
First fixation.	The element that draws people's attention the most.
Last place the user looks.	Less attractive or difficult to find.
When making a choice, fixations back to one item.	An intrusive design that makes people hesitate.
Reading headings or subheadings, but no more.	The title may not be attractive or the topic makes users feel bored.

Table 3.1: eye-tracking data and possible interpretations

The suggestions provide insights when analysing users' eye-movement data. In addition, there are some common reading behaviours that can be observed by an eye-tracker that may provide evidence regards to the design quality of the reading material (Bojko, 2006).

Exhaustive review: when users frequently review certain areas, it may indicate that the areas are not well-designed or crowded. This behaviour is known as exhaustive review, which is one of the least constructive reading performance in eye-tracking research, it can lead to considerable waste in reading time (Grison et al., 2016; Nielsen and Pernice, 2010).

Desired exploration: it shows people extend their eye-movement and explore their review range, this may indicate that people have an interest in the reading material and take pleasure in it. Both desired exploration and necessary review may lead to repeated reading of certain areas, but different from the desired exploration, the necessary focus on specific target information (Nielsen and Pernice, 2010).

Necessary review: users may not enjoy the reading but still productive, such as review the price when doing online shopping, this necessary review is not relevant to the design, but depends on how important the information is (Nielsen and Pernice, 2010; Ooms et al., 2015).

Repeated review: this indicates that people look at the same specific element many times, different to exhaustive review, exhaustive review refers to reading many different areas multiple times, it contains numerous repeated reviews during the process (Krejtz, Duchowski and Coltecin, 2014; Nielsen and Pernice, 2010). Repeated reviews can show various refixation points when analysing, a refixation refers to the reader's fixation move back to the place which has been read before (Mannion and Leader, 2014). Normally, the high frequency of refixations happened in the key information area (de Smet, Leijten and Van Waes, 2018).

Selective disregard: people may ignore somethings on the reading material with confidence, because they do not need them at the moment, in most cases, users may only pay attention to the things that important to them (Grison et al., 2016; Nielsen and Pernice, 2010).

These behaviours recorded by the eye-tracker can tell detailed stories of people's reading process, and show the potential design issues that may affect the readability. Although the eye-tracking test is not the end-all usability test method, but it is a very effective tool to observe people's looking behaviour, more importantly, understanding people's underlying cognitive process based on the eye-mind hypothesis, which is helpful to evaluate the usability of the products (Coltecin, 2010; Kang et al., 2016; Kiefer et al., 2014; Nielsen and Pernice, 2010).

There are examples of studies using eye-tracking tests to evaluate the design quality of transit maps. Most studies investigated users' reading speed, AOIs (Areas of interest) or reading strategies, the research topics were mainly focused on people's attention when reading certain materials. Such as investigating changes in people's information strategy on the map when the task difficulty levels gradually increased (Netzel et al., 2016). Brychtova and Coltekin (2016) conducted eye-tracking tests to investigate how font sizes and colours affect people's reading speed based on fixation durations. Their studies showed that the eye-tracker is a useful tool to evaluate the visual designs on a map, which provide some valuable insights and experience. However, there are few studies focused on how the design limitations of a transportation map might affect user reading speed and accuracy based on user information searching behaviour and how to improve these problems following a user-centred approach.

3.3. Eye-tracking user performance test

3.3.1. Scoping test

Before the eye-tracking test, a scoping test among 20 participants (average age of 20.6) was conducted, each participant had to finish a series of information searching and route planning tasks with different difficulty levels, some questions were asked based on their user experience. This scoping test helped to understand users' opinion of the map and initially address the potential design problems, results are shown in Figure 3.1.

	N	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1: Is the map easy to use?	20	20%	25%	25%	20%	10%
		45%			30%	
Q2: Are the information and instructions clear?	20	5%	15%	20%	35%	25%
		20%			60%	
Q3: Are the visual designs easy to understand?	20	20%	25%	25%	20%	10%
		45%			30%	

Q4: What make you feel that the information and instrucions are clear/unclear?

Good aspects	*Potential limitations*
Clear and understandable instructional description.	The map legend is inadequate and not well-organised.
Necessary travel information has been provided.	The description in the map legend is too long.
Different services are clearly demonstrated.	Other information such as travel time is not included.
Transit lines are easy to find.	Disordered numbers between stops are confused.
	The cities and stations are easily get confused.

Q5: What make you feel that the visual designs are easy/difficult to understand?

Good aspects	*Potential limitations*
Transit lines are basically displayed clearly.	Similar colours of the lines caused confusions.
Stations are evenly spaced.	Some transit lines are overlapped with each other.
The important stations are easy to identify.	Some interchanges are confused.
The colours are basically clear to distinguish the lines.	Some areas of the transit network are crowded.
	Acute angles may easily recognised as stops.

Figure 3.1: participants' feedback (scoping test)

The scoping test showed some design limitations of the map in information structure and visual design, most design problems that caused reading difficulties are mainly related to the layout of the transit lines, interchanges, colours and map legend design. The result helped to initially understand the design limitations of the map and focus on specific design problems when setting tasks for the coming eye-tracking test.

3.3.2. Participant recruitment

The participants' recruitment for the eye-tracking test is stricter than the scoping test, all participants were non-Chinese citizens, nor had knowledge of Chinese geography. They needed to pass an Ishihara colour deficiency test (Ishihara, 2018) before the study, this helped to make sure that all participants had a normal colour vision.

There were thirty participants came from more than 11 courtiers attended the test. Although the gender difference in map using is not the key research question in the study, but still recruited the same number of male and female participants (15 for each), which allows deeper analysis of the research findings. The average age of the participants was 26.1 years old, which applied to the largest age group (20-30 years old) of international travellers who visited China in 2019 (31.4%), the data of that in 2020 and 2021 is not representative due to the reason of the global pandemic.

3.3.3. Test environment, materials and task settings

The test was taking place in a lighting laboratory user a "Daylight" setting, this was to simulate the lights in the railway station. Participants used a computer with a screen resolution of 1920 x 1280 pixels to finish the tasks, the same size screens are used in China's high-speed railway stations to display the maps and other travel information. Each participant sat in front of the screen at a distance of 80 centimetres. During the whole testing process, a Tobii Pro 2C eye tracker was used to record participants' eye-movement data, participants may be asked questions after each task accomplished.

In this study, the eye-tracking software Tobii Studio (Version 3.01) was used to analyse the eye-tracking data via gaze plots and heatmaps, as well as the eye-movement videos and time consumption. In addition, SPSS calculation system was used to make the analysis more accurate and reliable, such as making paired sample *t*-tests to make comparisons between different variates.

There are totally four tasks that needed participants to finish, the task details and corresponding research aims are listed in Table 3.2.

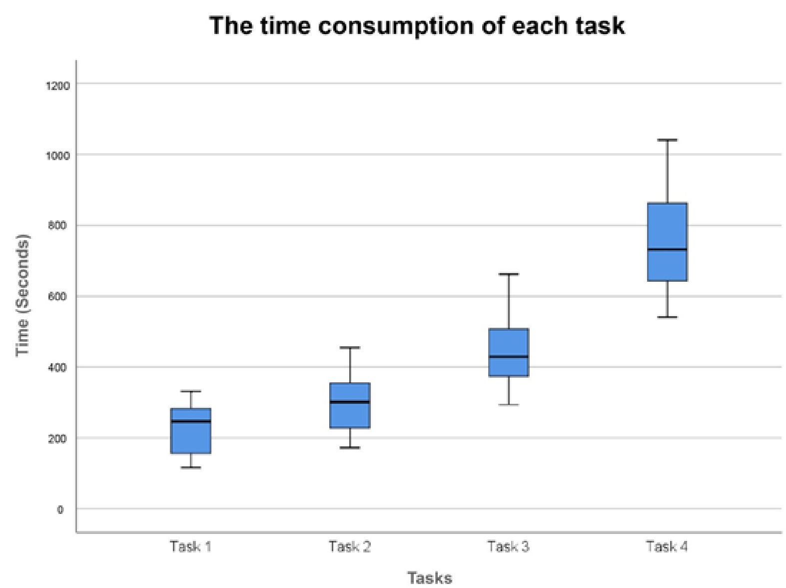
Tasks	Task details	Research aim
Task 1	Find the transit line: Huning PDL.	To test the efficiency of the colour coding used for the transit lines, and observe how people locate a specific transit line on the map.
Task 2	Find out the distance between Jinanxi and Zhangqiu after reading the map legend.	To test the legibility of the map legend, especially the layout structure and visual design of the key information.
Task 3	Plan a route between two stations: Beijing and Shijiazhuang.	To assess participant reading strategy when planning a simple route, and to investigate the potential layout problems of the cities and/or transit lines.
Task 4	Plan a route between two stations: Nanjing and Ningbo.	To assess participant reading strategy when planning a complicated route that contained more than three interchange points. This task focused on the transfer system and transfer signs of the map.

Table 3.2: Task details and corresponding research aims

These tasks were set according to the potential design limitations identified from the scoping test, the layout of the lines, the colour system, the map legend and the interchanges were furtherly tested and discussed. During the test, participants would be asked some questions regard to their user experience, this helped to understand users' reading behaviour better and increase the objectivity of the result. For example, in the eye-movement gaze plot map, the intensive refixation points showed on a certain area indicates that users frequently watched the area for multiple times. There could be two main reasons to explain this. First, the information in the certain area was important or well-designed that attracted users to read it more (Dwyer, 2018). Second, the information in the area is confused that caused users to read it for multiple times (William, 2018). Both explanations are contradictory to each other, in this case, some other methods such as doing interview can effectively supplement more information about user behaviour before a conclusion is made.

3.3.4. Results and analysis

The average time that participants finished the tasks was 1715 seconds, from 1367s (the fastest) to 2126s (the slowest). As Figure 3.2 shows, participants' time consumption gradually increased with the task difficulty levels increased. Most participants spent a longer time in route planning tasks (Task 3 & 4) than the information searching tasks (Task 1 & 2).



Tasks	N	Mean	Std. Deviation	Std. Error
Task 1	30	228.47	70.434	12.859
Task 2	30	293.50	78.917	14.408
Task 3	30	437.43	95.384	17.415
Task 4	30	755.20	141.565	25.846

Figure 3.2: Participants' time consumption in each task

3.3.4.1. Result of Task 1

Task 1 needed participants to find out a transit line (Huning PDL) from the network, this task aimed to observe how people locate the target lines and investigated whether the colour system of the network is effective.

There were 17 participants (approx. 57%) who found the target line correctly for the first time, the most common mistake in this task was that ten participants (approx. 57%) confused with another line (Jingguang HSR), its colour looks similar to the target line (Huning PDL) and easily mislead the users, the similar problem also existed in other transit lines. This result showed that the current colour system did not show transit lines distinctively, which needs further study to improve or redesign, a detailed research focused on the colour system is introduced in the next chapter.

How did participants locate a transit line when using the map? How did the design limitations in the colour system affect users' information searching accuracy? In order to answer both questions, a participant's gaze plots map is selected as an example (Figure 3.3), which is also a representative reading behaviour among half participants.

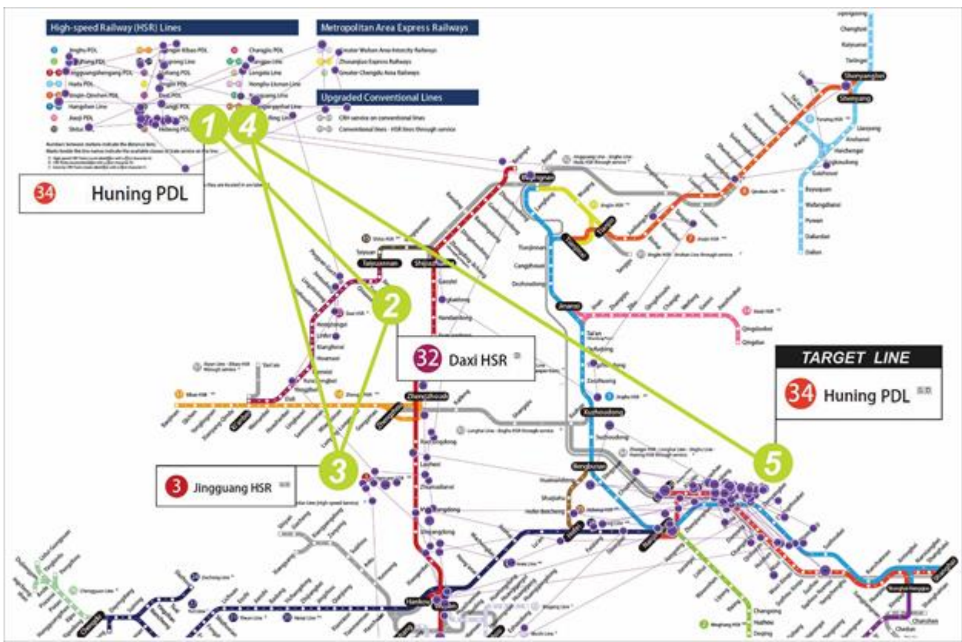


Figure 3.3: The representative reading behaviour in Task 1

The whole reading process can be demonstrated in five steps, which can be observed from the gaze plots (Figure 3.3） and information collected in the interview:

Step 1: The participant started from the map legend and found the corresponding instruction of the target line.

Step 2 & Step 3: Then looked into the railway network and reviewed the lines with similar colours (Daxi HSR and Jingguang HSR). Especially the Jingguang HSR, the massive fixation points showed that the participants tried to double-check the selection was correct.

Step 4: The participant looked back to the map legend and double-checked the target line information.

Step 5: The target line (Huning PDL) was found, but the participant looked back to the map legend (repeated Step 4) multiple times in order to double-check the target line information, the refixation path on Figure 3.3 showed this process.

This reading behaviour showed how the lines which have similar colours with the target line misled users, and the frequent re-reading wasted their information searching time. In eye-tracking data analysis, the refixations focused on a certain area indicates that users are not confident with their findings, this can cause information searching errors (De Smet, Leijten, & Van Waes, 2018).

Another finding observed from the task is that participants relied on the colour of the target line rather than its name. Table 3.3 shows the fixation count paired sample test of the target line's name and its colour on both map legend and network. The first comparison group between V1 and V3 showed a significant difference ($p < .01$), which indicates that the colour of the target line (M=3.27, SD=2.53) was reviewed for many more times than its name (M=1.1, SD=1.24) when people reading the map legend. Similar to this, in the second comparison group, the significant difference ($p < .05$) between V2 and V4 showed that the colour of the target line (M=3.4, SD=4.18) received more fixations than its name (M=1.5, SD=2.33) when people reading the map legend. The result showed that participants looked at the target line's colour much more than its name on both the map legend and the network when looking for a transit line.

Fixation Count Paired Samples Test

		Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
Pair 1	V1 - V3	-2.167	2.890	.528	-4.107	29	.000
Pair 2	V2 - V4	-1.933	4.675	.854	-2.265	29	.031

Fixation counts (n):

V1 - Fixation counts of the target line's ***name*** on map legend.

V2 - Fixation counts of the target line's ***name*** on network.

V3 - Fixation counts of the target line's ***colour*** on map legend.

V4 - Fixation counts of the target line's ***colour*** on network.

Table 3.3: Fixation count paired sample test of the target line's name and its colour on both map legend and network

Another fixation duration paired sample test was made (Table 3.4) to investigate the watching time of the target line's name and its colour on both map legend and network. From the result, participants looked at the colour (V7, *M*=1.15, *SD*=1.02) of the target line much longer ($p < .01$) than its name (V5, *M*=0.38, *SD*=0.56) when reading the map legend. Similarly, the colour (V8, *M*=1.15, *SD*=1.51) of the target line on the network received significantly ($p < .05$) longer duration than its name (V6, *M*=0.42, *SD*=0.27). This result reinsured the fact that participants relied on the colour of the target line rather than its name when searching for a transit line, on both the map legend and the network.

Fixation Duration Paired Samples Test

		Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
Pair 1	V5 - V7	-.77345	1.10397	.20500	-3.773	28	.001
Pair 2	V6 - V8	-.59133	1.53587	.28041	-2.109	29	.044

Fixation duration (Sec.):

V5 - Fixation duration of the target line's ***name*** on map legend.

V6 - Fixation duration of the target line's ***name*** on network.

V7 - Fixation duration of the target line's ***colour*** on map legend.

V8 - Fixation duration of the target line's ***colour*** on network.

Table 3.4: Fixation duration paired sample test of the target line's name and its colour on both map legend and network

3.3.4.2. Result of Task 2

Participants were asked to answer the distance between Jinanxi and Zhangqiu after reading the map legend, this task aimed to test whether the information design of the map legend is effective. The correct answer of the task should be 69km (the sum of the two target distances: 20km plus 49 km), there were only 37% (approx.) of the participants (11 out of 30) answered correctly, and the most common incorrect answer was 49km, there were 16 participants (approx. 53%) made the same mistake. This showed that there could be some design limitations regard to the information design on the map legend that caused confusions in understanding.

Taking a participant’s gaze plots as an example (Figure 3.4), this representative reading behaviour demonstrated more than half of participants’ reading process. Firstly, the participant made an exhaustive review of the whole map legend, tried to find any useful information regards to the distance between stations. After a long time reading, the participant finally found the key information (Figure 3.4, Part a), which can be observed from the dense fixation points around the area. Then the participant looked at the target stations on the Jiaoji HSR line (Figure 3.4, Part b). The participant was unsure of the answer and frequently looked back to the map legend to read the sentences, the refixation paths showed this process. However, the participant still provided the incorrect answer after such a long time reading and thinking, he mentioned that he did not understand the description on the map legend and suggested adding visual examples.

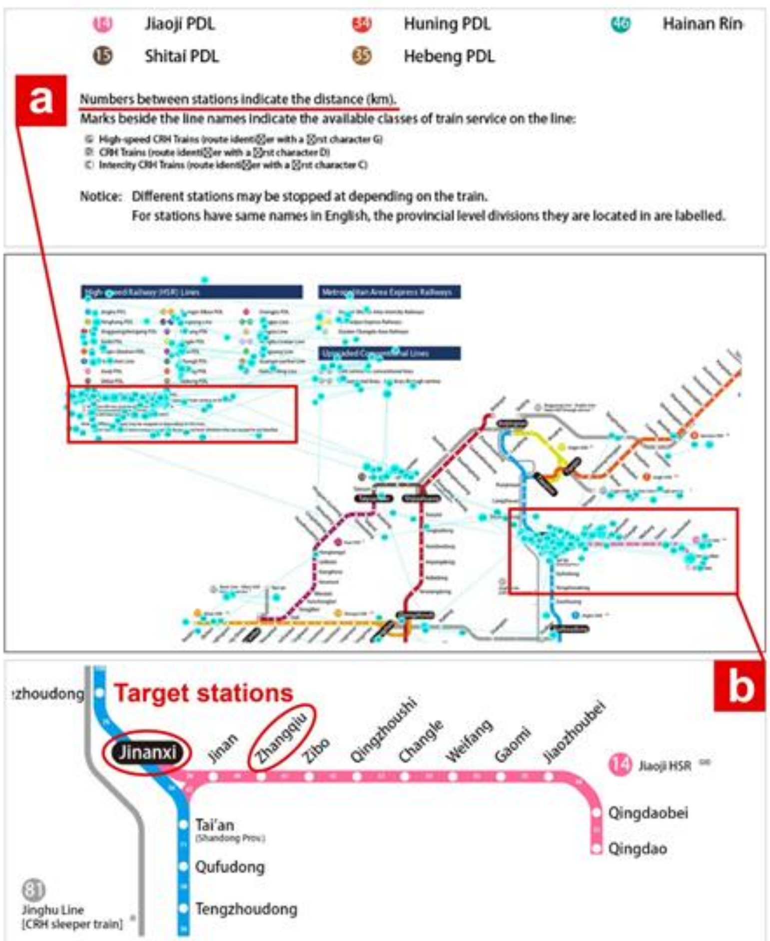


Figure 3.4: A representative reading behaviour in Task 2

The reading behaviour showed that the information design structure of the map legend was not clear that participants could not target the needed information quickly. In addition, the long sentences were not easy to understand and led to low accuracy in this task, they may need to be simplified and visualised in the next stage, as many participants suggested.

3.3.4.3. Result of Task 3

Task 3 required participants to plan a route between two stations: Beijing and Shijiazhuang. This task aimed to observe users' route planning habit and to test whether the stations are well-organised. Like previous tasks, most participants started from the map legend, but the information regards to target stations is not included on the map legend. This reading behaviour showed that participants relied more on the map legend rather than other parts of the transit map, but also supported the design problem of the map legend's information structure identified in Task 2, participants were not clear about what information is including on the map legend after two tasks.

The route planning accuracy of this task was satisfactory, there were 24 (80%) participants planned the route correctly. But in this task, another problem is found that some stations in certain areas may not be well-organised, which cause confusions and waste users' time. Figure 3.5 shows one of the target stations: Beijing station and its neighbour stations: Beijingxi and Beijingnan. In fact, three of them are different stations in Beijing City. Beijingnan was the most misleading station in the test, this important transportation centre was emphasised by the black box and located very close to Beijing station on the map, it attracted most participants' attention and made users confused because of its position and its similar name to Beijing.

Figure 3.5: A representative reading behaviour in Task 2

By analysing participants' gaze plots and fixation durations, the design limitation of the station layout is further investigated in Table 3.5. The fixation points on Beijingnan (*M*=35, *SD*=9.04) are much more than ($p < .01$) both target stations: Beijing (*M*=8, *SD*=3.7) and Shijiazhuang (*M*=8.37, *SD*=3.42). In addition, the time people looked at Beijingnan (*M*=14.37, *SD*=4.4) was much longer than ($p < .01$) both Beijing (*M*=2.8, *SD*=1.27) and Shijiazhuang (*M*=2.95, *SD*=1.29) as well. This result showed how the misleading target (Beijingnan) wasted user' time and led to information searching mistakes due to the layout limitation of stations in the area.

Paired Samples Test (Task 3)

		Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
Pair 1	V1 - V3	-27.433	9.339	1.705	-16.089	29	.000
Pair 2	V2 - V3	-27.067	10.329	1.886	-14.353	29	.000
Pair 3	V4 - V6	-11.57333	4.25593	.77702	-14.894	29	.000
Pair 4	V5 - V6	-11.42133	4.56201	.83291	-13.713	29	.000

Fixation counts (n):
V1 - Fixation Count (Beijing).
V2 - Fixation Count (Shijiazhuang).
V3 - Fixation Count (Beijingnan).

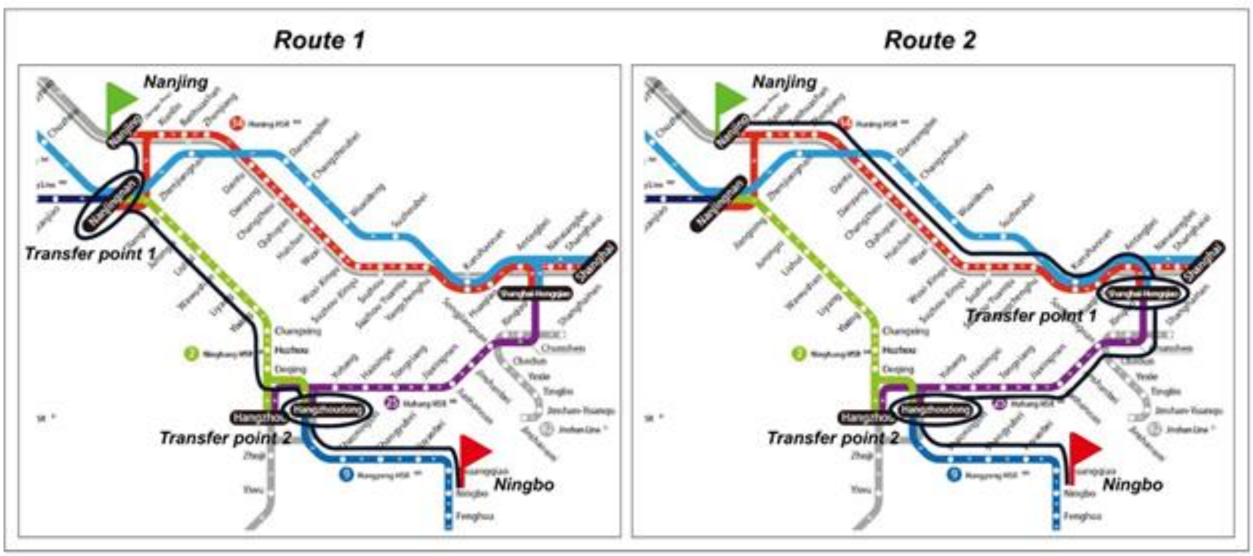
Fixation duration (Sec.):
V4 - Fixation Duration (Beijing).
V5 - Fixation Duration (Shijiazhuang).
V6 - Fixation Duration (Beijingnan).

Table 3.5: Comparison of the fixation counts and durations between the three stations

3.3.4.4. Result of Task 4

Similar to Task 3, participants needed to plan a route between two stations: Nanjing and Ningbo. But it involved more interchanging points and longer distance, this task focused on the design quality of the transit line layout and interchange points. There were two main route choices that linked both stations in the task (Figure 3.6), each route includes at least two interchange points.

Two main routes between the target stations: Nanjing & Ningbo



Route 1 is to take Huning HSR from Nanjing (green flag) to Nanjingnan, **transfer** Ninghang HSR to Hangzhoudong, and then **transfer** Hangyong HSR to the final destination – Ningbo (red flag).

Route 2 is to take Huning HSR from Nanjing (green flag) to Shanghai-Hongqiao, **transfer** Huhang HSR to Hangzhoudong, and then **transfer** Hangyong HSR to the final destination – Ningbo (red flag).

Both main routes contained 2 transfer points.

Figure 3.6: Two main route choices in Task 4

The accuracy of this task was 63.3% (approx.), which is lower than Task 3 after the difficulty level increased. The reason caused this are various, but mainly showed the design problems in interchange points and transit line layout. There were 7 participants (23.3%) transferred to impossible routes in the same area, as the red circle showed in Figure 3.7. Both Ninghang HSR (green line) and Huhang HSR (purple line) overlapped each other, the intersected angles made participants thought as an interchange point and transferred from the place directly, which is not possible in the actual trip. From the gaze plots (Figure 3.7), it is obvious that the overlapped point of the lines received more fixation points than the correct interchange point (Hangzhoudong station), there were a large amount of refixation paths between both points as well, this indicated that participants were not sure about route choice and spent longer time to double-check both places (Mannion & Leader, 2014). Apart from the misleading overlapped angles, the lack of interchange guidance on the map could also be another reason that users were not confident with the route choice.

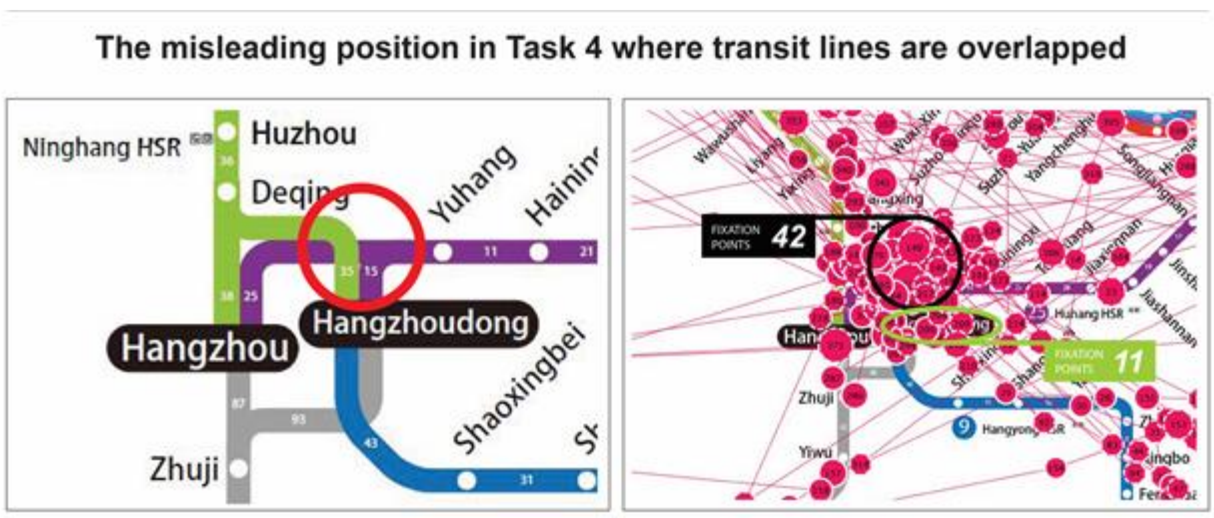


Figure 3.7: The misleading overlapped angles and the gaze plots around the area

3.4. Discussion of results

To ascertain the legibility of China's high-speed railway map, user performance was measured in terms of reading time and reading accuracy through different tasks. The eye-tracker was also used to 1) identify the design limitations in more detail; 2) analyse user information searching behaviour, which provides further insight into problems related to information structure and visual elements. In addition, many suggestions provided by participants may bring valuable insights for map improvement work in the next stage. In this section, the design limitations identified from the test regarding information structure and visual designs are further discussed.

Findings of users' information searching behaviours are analysed with more details, which may help to improve the design based on user habits.

3.4.1. Information design

The design quality of the **map legend** can influence the effectiveness of a map, the map legend involves all necessary information and instructions of the service information, and guide users to understand all the functions on the map (Meirelles, 2013). The current map provided basic travel information to users, and all the participants were able to use it without additional help. However, participants kept reporting that the crowded layout of information and a lack of necessary visual instructions in the map legend caused difficulties in almost all the map reading tasks. Such as, in Task 2, participants found that the **long sentences** that explained the travel distance was difficult to understand, this caused a very low reading accuracy in this task (approx. 36.6%). Most participants made the same mistake because they did not understand that the distances between different stations should be added up. Participants suggested that using visualised examples to demonstrate such a long-written instruction could be much easier to understand . MacEacgren (2008) thought that visual encoding could simplify the flat and complicated information with visual design elements; this can help users understand the information quickly because the unfamiliarity with professional terminology can be an obstacle for information understanding. People prefer visual designs rather than written words in reading, because visualised information tends to be easier to get access to and may also enhance people's reading confidence (Pettersson, 2019).

Another information design problem of the railway network observed in Task 2 is the line distance numbers. Participants found the disordered numbers are difficult to understand, the main reason was the lack of instructions in the map legend. Some participants questioned the necessity of the line distance, they mentioned that travel time between stations could be more useful when planning trips rather than travel distance. According to Guo (2011), the main design purpose of a transit map is to display the locations, directions, connections of stations and lines of an area clearly, other services information like travel time or crowding is not included on a transit map. Hadlaw (2003) argued that a transit map is a way of imagining not only geography, but more importantly, social space and (ultimately) time that people wish to explore. A relevant study showed that travel time can help users to make decisions quicker when planning trips, the feeling that taking control of travel time could make users feel more confident with their route choices (Avineri and Prashker, 2006). Based on this, the distances between lines should be remained, so that passengers can estimate the travel time based on the distance divided by the train speed. In this task, some participants advised to adjust the length between stations to show the longer or shorter distances between stations. But in most cases, the stations are equally displayed to keep a better-organised grid alignment (Degani, 2013; Harvey, 1989; Lloyd, 2017), this design principle should be kept in the future map improvement work as well.

In Task 3 and Task 4, although there was no needed information in the **map legend**, most participants still spent plenty of time searching information from the legend, because they assumed or expected that there could be useful information on the map legend. This reading behaviour was explained by Nielsen and Pernice (2010) as the desired exploration in eye-tracking test, which also showed that the **information structure** of the map legend is not well-organised. Participants did not familiar with the information structure of the map legend after using it in previous tasks, the frequent refixation between the map legend and the network resulted in low reading efficiency, this could waste users' time in the actual trip plan. Meirelles (2013) suggested following the grouping principle when designing the map legend; the information belonging to different categories should be grouped together and displayed hierarchically according to the importance levels. This can avoid forcing users to search for information through exhaustive reading when using the map legend.

The transit system is the primary source of information that can guide passengers to plan their trips accurately in unfamiliar places (Dziekan, 2008), but the unsatisfied information design of the railway network of China's high-speed railway map caused various information searching errors and wasted user's time. In Task 3, the crowded layout of the stations with confusing names made participants hesitated whether their route choice was correct, this can be observed from the massive re-fixation points around Beijing station. The layout of stations is very crowded, and the relationship between them is not clearly shown, which is a very common problem in transit network design (Grison et al., 2016). If the stations are not linked or have any other service connection, they should be displayed separately with observable gaps in between to show their separateness (Stott et al., 2011). If there are multiple stations in a popular tourist city, participants suggested linking them together by using symbols, or establishing a visual zone for the stations in the same city, just like the British national railway map that grouped stations in each popular tourist city by using a grey block.

In current China's railway map, ordinary **stations** are represented by white dots. When seeing two paralleled stations on two different lines, participants thought that passengers could transfer from one station to the other. According to Jones (2015), individuals prefer to judge the information based on intuition or personal experience, but these judgements could be biased and cause misleading or wrong decisions. Therefore, designers should avoid any potential confusion by testing the design first, rather than assume the users will use an untested design solution accurately (Brasseur, 2003). For example, as participants suggested, it is important to always make sure that the unconnected stations are located separately without being paralleled.

3.4.2. Visual design

The visual design quality of China's railway map has been tested in the eye-tracking test, participants' eye-tracking data provided evidence to explain how the visual designs on a transit map affected people's reading speed and information searching accuracy. Overall, the visual designs of the map did not show excellent performance in both information searching tasks and route planning tasks, various problems were targeted, especially in the colour system and the transit line layout. In addition, participants also suggested some potential design solutions that may improve the visual design of the map.

In Task 1, the confusing **colour system** caused many mistakes in route finding. Garland et al. (1979) provided evidence for the importance of colours in transit map in their tests. The colour-coding of transit lines can largely affect people's information searching accuracy, especially for maps with complicated railway networks, a well-design colour system can make users feel more confident in route planning and avoid many potential confusions (Garland et al., 1979; Netzel et al., 2016). In task 1, users were confused by other lines that represented by similar red colours to the target line, this indicated that the differences between are not clear enough to differentiate the lines, this is a common problem in transit map design, most of them caused by the insufficient contrast between values or hues (Buard & Ruas, 2012). The colour system is an important topic in transit map design, which has been further investigated and improved in Chapter 4.

Almost all the participants mentioned that the layout of **transit lines** are too crowded and disordered, some of them are overlapped with each other, which led to various information searching errors in the test. The overlapping problem refers to the crossing of routes running on different places that do not actually overlap, this problem was identified in many transit map design examples (Sadahiro et al., 2015). The acute bend is another issue identified in Task 4, the massive fixation points and longer fixation duration in certain areas showed that the acute bend clutters the straight routes with sharp angles; this can make the lines look unconnected and disordered (Agrawala and Stolte 2001). According to the interview with an officer who is currently working in the Chinese Transportation Department, the current map was designed according to the actual topography, which means that the lines and stations on the map are basically geographically accurate, this is the main reason that the transit line's layout in some areas looks disordered. Is it an effective method that organises the transit lines based on their actual topography? Hochmair (2019) and Marcus (2016) thought that the transit lines is an independent system apart from the actual geographic environment, different to geography maps, the topographic accuracy is not a key factor when organising the railway network of a transit map, designers should make more efforts to simplify the lines and organise them schematically, which helps users to locate and plan routes quickly and accurately. The London Underground map designed by Beck shows a good example that organised the underground network by using straight lines with fixed angles (straight angle, right angle and 45-degree angle), this design is called octolinear layout, which is widely used in transit map design globally (Mollerup, 2015; Roberts and Rose, 2016). Therefore, the topographic accuracy is not a key factor in the transit line layout, the layout of the transit network was improved according to the schematical design principles and has been tested in Chapter 5.

In Task 3 and Task 4, participants felt confused if they can transfer to other lines at some **interchange points**, this mainly caused by the lack of interchange instructions on the map legend, participants were hesitating when planning a route with multiple transfers. Interchange points linked the transferrable lines, but they are often not well represented and can therefore be interpreted incorrectly in transit map design (Grison et al., 2016). The interchange signs of the current map are basically understandable, except for some interchanges located in crowded areas that are not well-presented. In addition, the lack of interchange instructions also led to the errors that users assumed the acute angles as interchange points. Based on this, participants advised the researcher to demonstrate the transfer signs clearly in the map legend by using visual examples. Guo (2011) supported this advice that map designers need to understand different ways to represent transfers and visualise them with symbolised elements. The overlapped interchange signs are commonly used, while there are semi-overlapped interchange signs, or using a simple link to connect the transferrable stations, more examples are introduced in Chapter 2 and Chapter 5. In addition, the unconnected lines should be displayed separately with sufficient gaps in between, if they are located too close to each other, it may easily mislead users to make the wrong route planning, this problem is clearly identified in Task 3 and Task 4.

3.4.3. Findings of users' information searching behaviour

In Task 1, participants preferred to see the colour of the target line first and read its name when double-checked the answer. This behaviour showed by the gaze plots that the target line received more fixation points than its name. Although the colour could help the participants to find out the target lines easily, almost all participants double-checked the target station/line names to ensure their choices are correct. This behaviour indicates that users may still trust the text more than colours when making a decision in route plan. Many participants mentioned that the written sentences made them feel more confident, the text seems to be more trustworthy than any other visual elements. This finding also applies to the design guidance that users prefer to trust certain words (Ovenden, 2015; Roberts, 2014), which means some important information cannot be completely replaced by visual symbolisation.

Another interesting user behaviour is that participants preferred to see the central area of the map first when they started searching for information. This process lasted for more than 2 seconds. Therefore, the location of the first fixation reflects the reader's first area of interest, even if that was not the area where the information for the required task was. This behaviour challenged Nielsen and Pernice's (2010) opinion, which found that readers prefer to start from the top and review the information following an F shape eye-moving path on screen. This provides evidence that readers have a different reading behaviour when using a transit map compared with other reading materials.

Moreover, the accuracy of Task 4 (route plan includes 2-3 transfers) is even better than Task 3 (route plan with no transfer). This surprising result was caused by the unsuitable route design. A similar finding has been mentioned in Conroy's research (2003), caused by confused curves in transit line system. In Task 3, although one line directly connected two target stations, some curved shapes and acute bend caused more reading difficulties, and the overlapped lines also mislead some users to the wrong directions.

In Task 4, a user habit is observed that participants paid more attention to the destination rather than the starting point, similar reading behaviour was also noticed by Holscher et al. (2011) that users prefer to plan their trips based on the direction-based strategy. This can also explain why 70% of the participants (21) chose Route 1 (Figure 3.6) because the route points to the direction of the destination (Ningbo). From the heatmap of the task (Figure 3.8), this trend is more obvious that Rout 1 (downside direction from Nanjing) has been reviewed much more than

Route 2 (right-side direction from Nanjing), and the destination (Ningbo) showed darker red colour, which indicated that it was the most review target area in this task. Although there is no sufficient evidence to support that this reading behaviour may cause ineffective route choices in trip plan, but this strategy may increase the probability that the more effective routes are ignored by users.

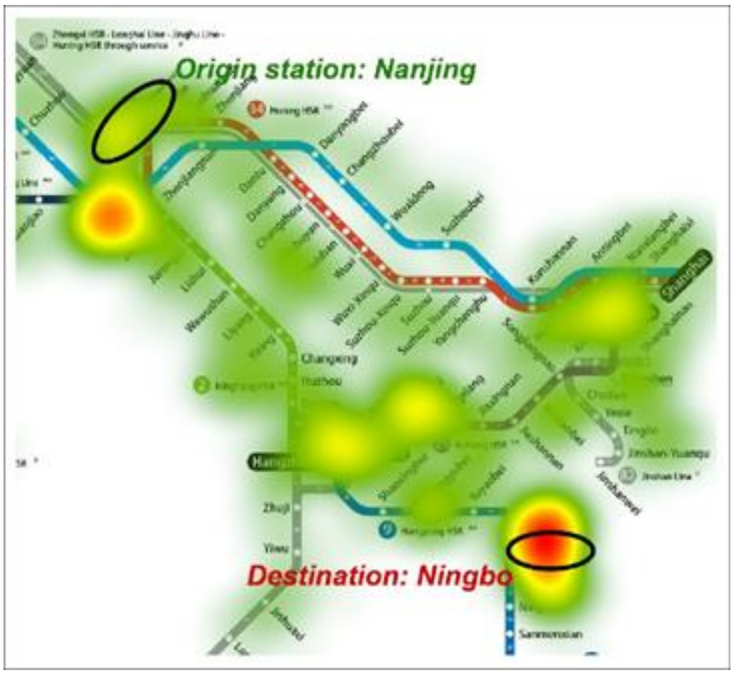


Figure 3.8: Heatmap of Task 4

In addition, participants preferred to spend a long time searching for information in the map legend, even if there was no relevant information in Task 3 and Task 4. This behaviour indicates that users prefer to trust and rely on the map legend when they access the rail transit map. Participants expected that the information they needed could be found directly in the map legend rather than exploring the transit line system. This user behaviour emphasised the importance of a well-designed legend for a transit map, all the instructions and functions of the map should be demonstrated with examples clearly, because the design quality of the map legend can affect the legibility of the whole map (Buard and Ruas, 2009).

3.5. Conclusion

Overall, the study thoroughly evaluated the legibility of China's high-speed railway map by conducting eye-tracking tests and doing interviews. The eye-tracker showed its advantage that recorded users' eye-movement paths, which showed various design limitations of the map and users' information searching behaviours. This helped to provide reliable evidence to explain how the design limitations of the map affected users' reading speed and information searching accuracy; suggestions provided by users also bring valuable insights for future map improvement work.

There are various design limitations regard to the information design and visual design elements identified in the study. The major information design issue is the lack of consistency and relevance among the vast amount of transit information. From the results in all tasks, the poor information structure isolated the train line systems, number systems and train stations; they have been demonstrated separately without strong connections. Irrelevant number systems also confused the relationship between cities and station, the transfer accessibilities among stations are unclear, etc. As the focus of all the information and instructions of the whole map, the map legend did not provide sufficient support in trip planning. The long sentences with poor data visualisation wasted users' reading time and caused various misunderstandings. The result showed that it is necessary to improve the information structure and strengthen the map legend's information design in the next stage.

Numerous visual design problems were identified in the test, especially the colour system of the current rail transit map. Participants' eye movements in Task 1 showed that confused colours can mislead users to the wrong routes. As participants suggested, the colour system needs to be redesigned, especially the contrast between hues and values should be further enhanced. In addition, the eye-moving path showed that the visual layout of transit lines largely influences user's route plan choices, efficiency and accuracy. The overlapped line layout or acute bends can easily cause mistakes in the trip plan. Moreover, icons and other symbolisation are considered as useful elements to emphasise certain functions, such as the transfer availability between stations.

The study showed that the eye-tracking test can demonstrate user's information searching behaviour, and provided valuable evidence for the researcher to improve the design based on user's habits and preferences. The gaze plot detailly showed how users finished the tasks and the progress they made based on the previous experience; this can help the researcher better understand the user's confusion and expectation. This indicated that conducting the eye-tracking test is a very effective method to evaluate the design quality of a transit map, but the study also showed that eye-tracking data could not be used as the only evidence when analysing user behaviour; it is better to analyse complemented by other qualitative data, such as participants’ interview recordings; this can help understand users' reading process accurately and avoid potential bias in the analysis.

Overall, this study identified numerous information design and visual design limitations of current China's high-speed railway map, which clarified that the research direction of the next stage is to focus on the design improvement work of the map colour system, map legend and transit line layout. With the help of users' suggestions, an initial information design structure of the transit map is built up. The test highlights the importance of information structure and visual design to the legibility of a transit map, and more specific design problems will be investigated and improved in future studies in Experiment II and Experiment III.

4. Experiment II: A colour coding study examining colour effects in the transit map

4.1. Introduction

In the previous research, the legibility of China's High-speed railway map has been tested by using eye-tracking technology among 30 participants. There are various visual design problems identified from the test result, especially a particular design limitation that needs further investigation, the colour system of the map, which is also a key factor of all information and cartographic design materials. (Wang, Lonsdale and Cheung, 2021).

In the transit line finding task, there were 11 participants (approx. 37%) made the same mistake that selected another line which has a **similar** red colour to the target line. In other tasks, some other colour design problems have been found, such as similar colours **overlapped** on each other, it caused route-finding errors when participants planning trips. In addition, the users' eye-movement data shows that people preferred to locate the target line according to its **colour** at the first place rather than its name, which means users have a strong dependence on the **colour system** when locating a line. There were 14 participants (approx. 47%) mentioned that they met difficulties or felt confused when searching for information on the map due to the reason of colour design problems, they suggested to improve the colour system of transit lines.

Based on these colour design problems and the feedback from participants, in this research stage, the author did a thorough research of map colour design principles and evaluated the colour system of the map, then a new re-designed colour system based on findings and colour theory has been established for further test.

The aim of this study is to investigate such limitation thoroughly and to suggest and revise colour design to resolve it. Three research questions in this stage are:

1. What colour design principles and colour theories are applicable to map design?
2. Is the existing China's high-speed railway map designed according to map colour-design principles and colour theories?
3. What design solutions can be implemented in the map's colour design to enhance design quality, specifically users' speed and accuracy when they search for information?

4.2. Colour design principles

4.2.1. Colour harmony

In map design, it is not only necessary to keep strong contrasts among neighbour colours, but also important to create colour harmony. Goldstein (1965) tried to build a colour harmonious coding scheme for composing transit maps, Liu and Lin (2009) also emphasised the importance of colour harmony principles in transit map design. A map with a harmonious colour system can attract users to explore more information on the map, research also showed that harmonious colours are also helpful to enhance the legibility of the map (Goldstein, 1965; Liu and Lin, 2009). Judd and Wyszecki (1975) mentioned that colour harmony is that more than two or more colours in neighbour areas that create a pleasing effect. This indicates the combination of colours may be effective to fulfil some specific design purpose, that may make users feel comfortable. Many researchers investigated this in different views.

Ostwald summarised colour harmony in the following four different situations (Westland et al., 2012)

1. Colours are located at the equal white and equal circle in the solid.
2. Colours have equal white content.
3. Colours have equal black content.
4. Colours have equal hue content.

Munsell is a master in colour communication and his Munsell system is popular in colour research， Red, yellow, green, blue and purple are the five basic hues in the Munsell system. According to Munsell's theory, colours are harmonious when located on a specific path in the Munsell colour space, there are 5 conditions that fulfil the Munsell colour harmony:

1. Colours on the greyscale.
2. Colours have the same Munsell hue and saturation.
3. Complementary colours have the same value and saturation.
4. The brightness and saturation of the colours are in descending order.
5. Colours located on an elliptical path in the Munsell system.

In addition, a small area with high colour strength can balance a bigger area with low colour strength, as a result, a strong colour should always occupy a smaller area to balance a weak colour.

Itten and Birren (1997) mentioned that the colour circle is the fundamental base of all colour theory, which can classify all colours. All complementary pairs, three-colour combinations (forming equilateral or isosceles triangles on Itten's colour circle) and four-colour combinations (forming square or rectangle on Itten's colour circle) are harmonious.

It has been widely recognised that complementary colours create colour harmony. The following four modes are the most common colour harmonious examples between complementary colours:

a. Monochromatic colour harmony (the hue of chosen colours is same or close)

b. Complementary colour harmony (opposite colours located on a hue circle)

c. Analogous harmony (colours are chosen with similar hues)

d. Split-complementary harmony (three chosen colours, two of them are either side of the complement of the third in the hue circle).

Figure 4.1 shows more details about the corresponding four colour harmonious examples:

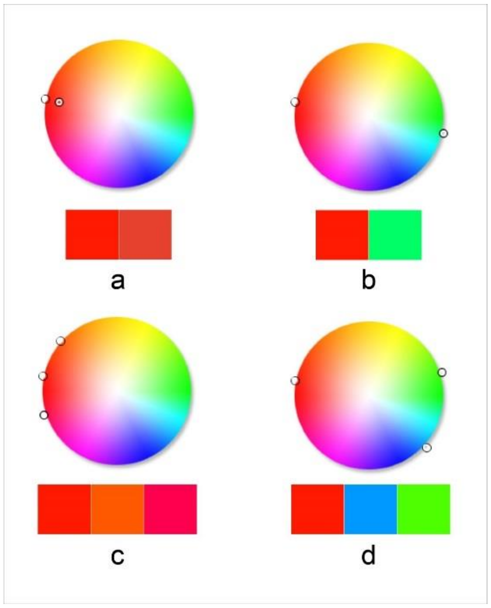


Figure 4.1: Monochromatic (a), complementary (b), analogous (c) and split-complementary (d) colour harmonious examples

Excepting the hues of colours, the **brightness** and **saturation** are also influential in colour harmony (Feisner, 2006), sometimes depends on the rhythm, balance, proportion and scale. According to Ou et.al (2010), two colours are harmonious when only different in brightness, but when differences of brightness get smaller, the harmony of the pair may weaker.

Although colour harmony is a key standard when select colours for reading materials or products, it can help users to find out the target information easier. But it is not wise to separate colours from design, because the user's preference and the trend of fashion are also key factors in colour selection (Granville, 1987). Based on this, it is hard to establish a fixed rule or a universal standard for creating harmonious colours, users' colour preference can be affected by their age, gender, cultural background and educational level, etc (Wong, 1986). According to Harrower and Brewer (2003), some colour schemes may satisfy the colour harmonious requirements in colour space, but not apply to user's colour preference or have negative feedback on the identification of visual elements. In other words, colour harmony is the combination of colours that make people feel pleasant, it changes over time and between cultures, it is also affected by specific applications (Holtzschue, 2017).

Moreover, although there are many differences between colour harmony theories, but some principles are widely recognised and commonly used, such as complementary colours, colours have equal hue, colours have equal chroma and colours have equal brightness, more details can be summarised as follows (Ou, 2016):

1. Equal hue: colours have the same or similar hue tends to create harmony.
2. Equal chroma: colours that have the same or similar chroma tends to create harmony.
3. Unequal brightness values: when the brightness difference between colours gets smaller, the harmony of the combination get weaker.
4. High brightness: The higher brightness value of colours in a combination, the more colour harmony will appear.
5. Hue preference: In most cases, blue is the hue that most likely to create harmony and red is the least.

4.2.2. Colour design principles in transit map design

The colour use of a map is always an important topic in cartographic design, designers must choose the colours carefully, as the users may read a map in a time-critical situation. In transit map design, colour is one of the most effective tools to discriminate different transit lines, Netzel (2017) and Burch's (2018) eye-tracking tests demonstrated how colours facilitate visual interpretation of transit maps, Roberts (2012) mentioned that colour-coding in transit map design is the same important as transit line layout.

A well-designed colour system can greatly assist users to find out the target information on the map without searching back to the map legend (Bertin, 1981). Colours should be selected and organised carefully, too many colours arbitrarily displaying the transit lines may destruct the design, in dense areas, transit lines should be displayed with no more than six colours (Roberts, 2012). According to Brychtova and Coltekin (2016), larger colour distance can always enhance readers' response time in map reading.

Lloyd, Rodgers and Roberts (2018) compared three different colour plans based on New York's schematic metro map (Figure 4.2): line coloured by route (routes coloured as separate lines), trunk (the trunk is coloured as one line) or shaded (same colour but different shade for the routes). The authors compared users' information searching speed and accuracy, the result showed that colouring by routes is the best colour plan for users. In contemporary transit maps, the colour systems are mainly based on the principle that displays individual routes in distinct colours, this helps users to distinguish lines easier (Lloyd and Ovenden, 2012; Roberts, 2012).

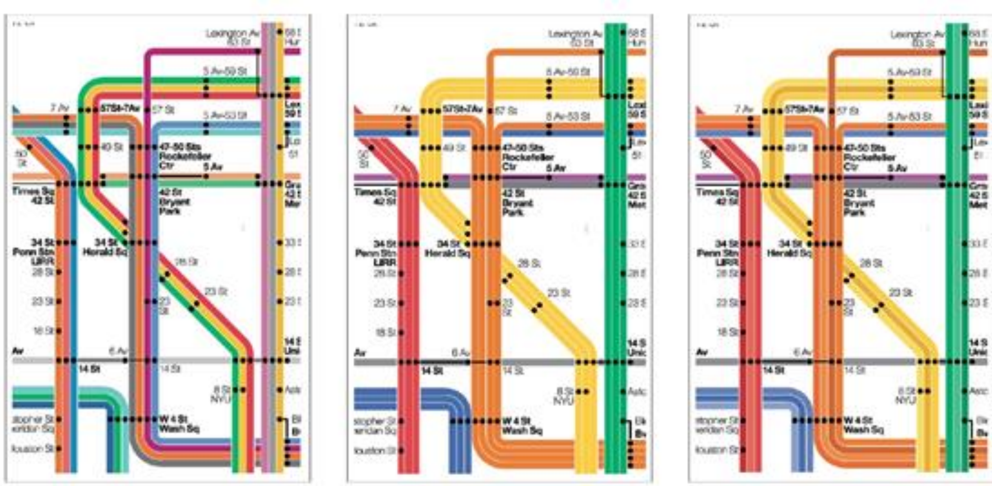


Figure 4.2: lines coloured by routes, trunks and shaded

In map design, there are some colour schemes guidelines that can be followed, in Brewer's (1994) research, the author summarised some detailed colour combination plans based on different data needs. Such as one-variable data colour schemes, two-variable data colour schemes and duplicate-variable data colour schemes, etc. But in transit map design, almost all information belongs to one-variable data, such as different names of the cities.

When using colours to display one-variable data on a map, there are four basic colours schemes (Table 4.1), more examples of the four schemes are showing in Figure 4.3.

One-variable data colour schemes		
Data type	**Hue**	**Brightness**
Qualitative	Different hues (not ordered)	Similar in brightness
Binary	Neutrals, one hue or one hue step	Different brightness steps
Sequential	Neutrals, one hue or hue transition	Single sequence of brightness steps
Diverging	Two hues, one hue and neutrals or two hue transitions	Two diverging sequences of brightness steps

Table 4.1: One-variable data colour schemes

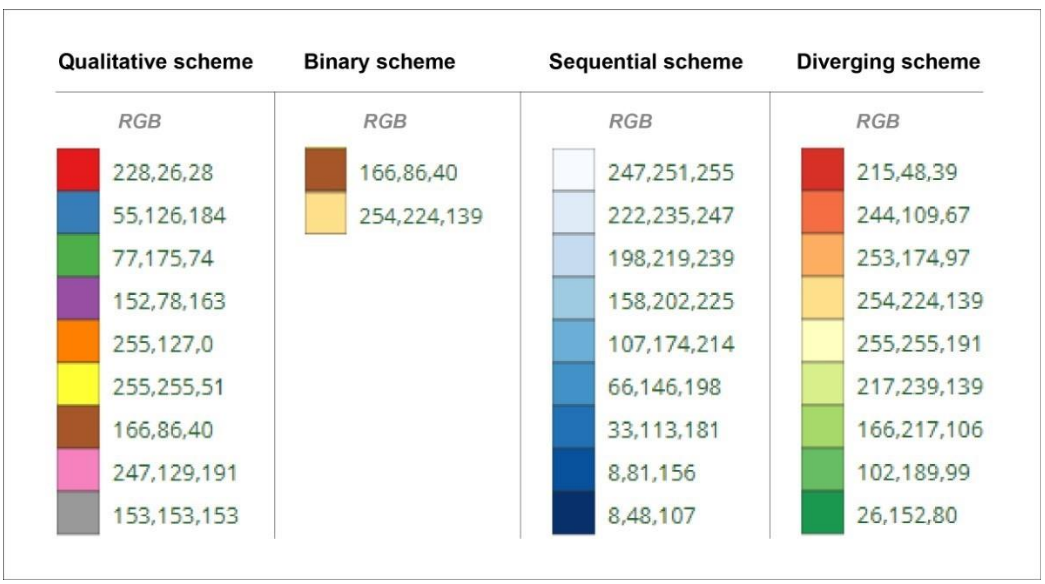


Figure 4.3: Examples of qualitative, binary, sequential and diverging colour schemes

The brightness of hues used for **qualitative** data should be similar, but not necessarily to be equal. Small brightness differences between hues are helpful to differentiate colours, and make area shapes and hue boundaries easy to be identified, especially when coloured areas are not bounded by lines on the map (Livingstone and Hubel, 1988). But the rule changes when dealing with various qualitative categories, such as numerous transit lines on railway map, it may be necessary to use large differences in brightness within hues to differentiate different categories of information. Key information on the map can be highlighted by lightest, darkest and most saturated colours to emphasise its importance, while less important information can be represented by medium brightness and less saturated colours. Some small areas on the map such as narrow streams can be displayed by greater lighter or greater saturated colours, otherwise, they may be difficult to be observed on a colour map.

Ordinal relationship data can be grouped within qualitative date colour schemes, such as demonstrating how busy the routes are on the map, using different brightness steps of the same or similar hues is a good idea to show the different busy levels, e.g., lighter and darker reds. Although a map is considered to be qualitative and most colours differences on a map are hue differences, but using brightness differences is appropriate when making comparisons between data among the same category (Brewer, 1994). In addition, categories of great similarity are suitable to be represented by colours that closer to each other on the colour wheel. For example, red and orange are neighbour hues, but red and cyan are complementary or opposite hues, they can create a stronger contrast to represent significantly different or unrelated categories on a map (Westland et al., 2012).

Binary data colour schemes are special cases of qualitative data colour schemes, binary variables are differences that only divided into two categories, such as correct & incorrect. Using different brightness steps to display the two categories of a binary scheme is a common method, which is different from using hue steps for multi-valued qualitative variables (Brewer, 1994). The brightness steps chosen for a binary variable normally be distinct, no hue, one hue or two hues can be used, such as light grey & dark grey, light green & dark green and light blue & dark green. The most important is to show differences in brightness steps. In addition, it is wise to show the more important information of the two data categories with a darker brightness step.

Logically, **sequential** data classes are arranged from high to low, the categories of sequential data should be represented by sequential brightness steps, normally follows a no less than 10% increase/decrease in brightness. In most cases, the high data categories are represented by dark colours and low data categories are represented by light colours. While the association can be reversed when the overall area is dark on the map, the light colours can represent high data categories to create strong contrast on the map (McGranaghan, 1989). The simplest sequential scheme can be displayed from dark to light grey, or even from black to white if needs to show a greater difference among categories. However, it is not wise to select a fully saturated hue in the lightest and lowest data category, a saturated hue is not likely to be a light colour, it may limit the contrast range of the rest categories. Selecting more than one hue can be used in a sequential data colour scheme, but the hue differences are subordinate to brightness differences between categories, the brightness steps from light to dark accompanying with a transition in hues can enhance the contrast between categories (Brewer, 1994)..

Data that suitable to be represented by **diverging** colour schemes on a map are deviations above and below a mean, such as data represents travel time longer or shorter than the average time (Brewer, 1994). For example, using a hue for time categories below average and anther hue for time categories above average, and then darken both hues sequentially. Or in other words, a diverging colour scheme can be understood as a combination of two sequential colour schemes, but diverging colour scheme has more freedom in colour selection. Normally, classes similar in value above and below the critical value should keep the same or similar brightness and saturation steps, which is helpful to create colour harmony (Westland et al., 2012).

4.2.3. Considerations regards to colour-deficient users

According to Atchison and Pedersen (2003), colour-deficient people have longer reaction times and make more mistakes when reading coloured objects comparing with people with normal colour-vision. Congenital red-green colour-vision defects are the most common colour deficiency among people (Pugliesi and Decanini, 2012). From the dichromats population, 1% is made up of red-deficient (protanopes) and 1.1% of green-deficient (deuteranopes), about 25% of the people with red-green colour vision defects are dichromats. Considering about anomalous trichromats, 1% is made up of red-insensitive (protanomolous) and 4.9% green-insensitive (deuteranomolous). Blue-deficient men are represented by only 0.002% (tritanopes). In addition, due to the reason that genes which affect colour-vision are part of the X-chromosome, men with colour-deficiency are much more than women, 0.003% of men are totally colour-deficient (achromatic vision). Research also showed that there are approximately 3 million colour blind people globally (about 4.5% of the entire population), around 8% of the Caucasian men and 0.4% of the Caucasian women have different degrees of colour-deficiency (Birch, 1997, Mcdowell, 2008; Pokorny et al. 1979), as Caucasian participants are the major group in the following colour test.

In Olson and Brewer's (1997) research, people with red-deficient and green-deficient used maps more effectively after the authors adjusted the colour on the map, but the new colour plan was not friendly enough for normal colour-vision users, this is a paradox in map colour design. But it is good to see that there are many colour-deficiency colour options in many design software such as Adobe Photoshop to help designers understanding what a visual material looks like for colour-deficient people.

The contrast is used to make a distinction between visual elements by differentiating them in terms of colours, lightness steps, shapes and scale (Dondis, 2003). The contrast is also the most important design element in thematic mapping and visual communication, it can intensify the result and simplify the information (Dent et al., 2009). Value is the key factor that strengthens the contrasts between colours (Arditi 2002). But it is necessary to remember that people with colour deficiency may see weaker contrast than normal colour-vision users (MacEachren 1995; Hess 2000; Dent et al. 2009). In Pugliesi and Decanini's (2012) research, the colour-deficient users' information searching accuracy on the route map enhanced after increased the colour contrast between lines and symbols, it shows how effective the contrast is for colour-deficient users.

4.3. Evaluation of the existing map’s colour system

In China's high-speed railway map, there are totally 27 colours representing 67 transit lines in map legend and railway line system. In order to evaluate the colour system, the 27 colours presented on the map have been divided into six categories according to their hues (Figure 4.4), their corresponding RGB values, saturation and brightness have been listed as well. They are red category (from dark red to light pink), orange/yellow category (from dark brown to light yellow), green category (from dark green to light yellow green), blue category (from dark blue to light blue), purple category (from neutral purple to light purple) and grey category (from neutral grey to light grey), black and white are not included.

Research showed that strong contrast between colours can make objects look more distinct on a map (Brychtova & Coltekin, 2016). In the previous eye-tracking test, participants mentioned that most colours can clearly distinguish the lines, but weaker contrast between lines, such as No. 34 (Huning PDL) and No. 7–8 (Jinqin-Qinshen PDL), No. 9–13 (Hangshen Line) and No. 1 (Jinghu PDL) caused the most errors in information-searching in the test (Wang, Lonsdale and Cheung, 2021). This indicates that the weaker colour contrast between lines may affect the accuracy of searching for information on a transit map.

Figure 4.4: Six hue categories of colours on China's high-speed railway map (numbers in coloured blocks represent railway line numbers)

4.3.1. Colour harmony evaluation

According to Figure 4.4, the saturation steps (*M*=0.71, *SD*=0.32) and brightness steps (*M*=0.75, *SD*=0.19) are different between all 27 colours. Among all six categories of hues, none of them has the same or similar saturation, nor follows Munsell's colour harmonious rule that brightness and saturation of the colours are in descending order (Westland et al., 2012).

Are the colours following complementary colour harmonious rules? Taking the most common red-green, orange-blue and yellow-purple complementary pairs as examples to see more details on a colour wheel. There are many colour schemes such as Pantone colour palette, but in this stage, I selected RGB colour wheel for designers in Adobe Photoshop to display the line colours, the white dot represents each line colour's corresponding locations on the colour wheel. Figure 4.5 shows five colours in the red colour category and their corresponding complementary colours (colour dots) on a colour wheel, all the complementary colour dots are located in green-blue hue areas. In addition, seven colours in the green category are displayed on the colour wheel, none of them overlapped with the red colours' complementary colour dots, most of them located far away from the complementary colours' area of red colours. This indicates that red colours on the map are not complementarily harmonious with green colours.

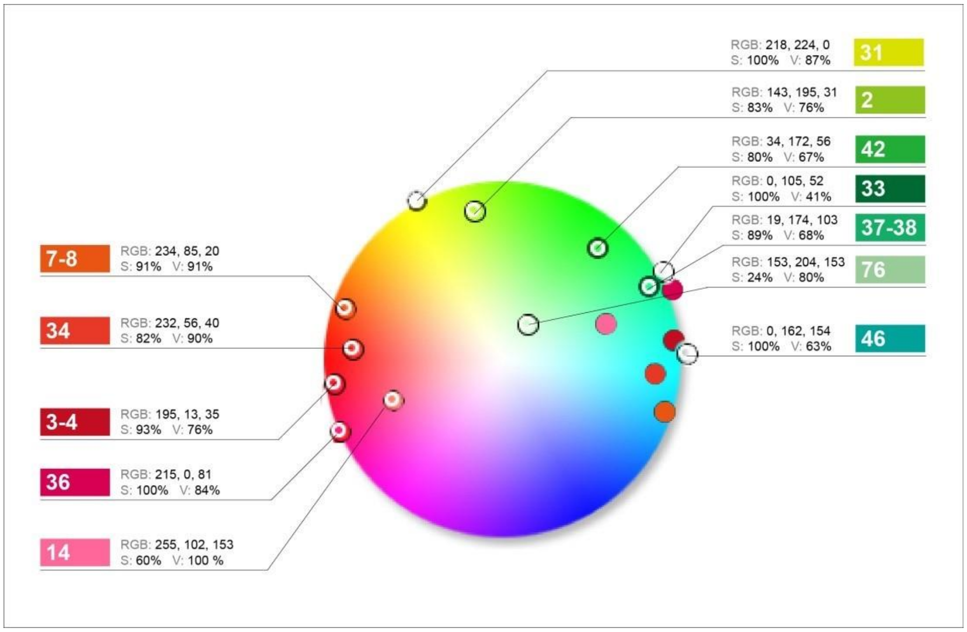


Figure 4.5: Colours in red category and their corresponding complementary colours compare with colours in green category (numbers in coloured blocks represent railway line numbers which represented by the corresponding colour)

In addition, according to Figure 4.6, six colours in orange/yellow colour category and their corresponding complementary colours (colour dots) are showing on the colour wheel, all the complementary colour dots are located at blue and purple hue areas. Additionally, four colours in blue category and three colours in purple category are displayed on the colour wheel, none of them overlapped with the orange/yellow colours' complementary colour dots. This shows that orange/yellow colours on the map are not complementarily harmonious with blue and purple colours.

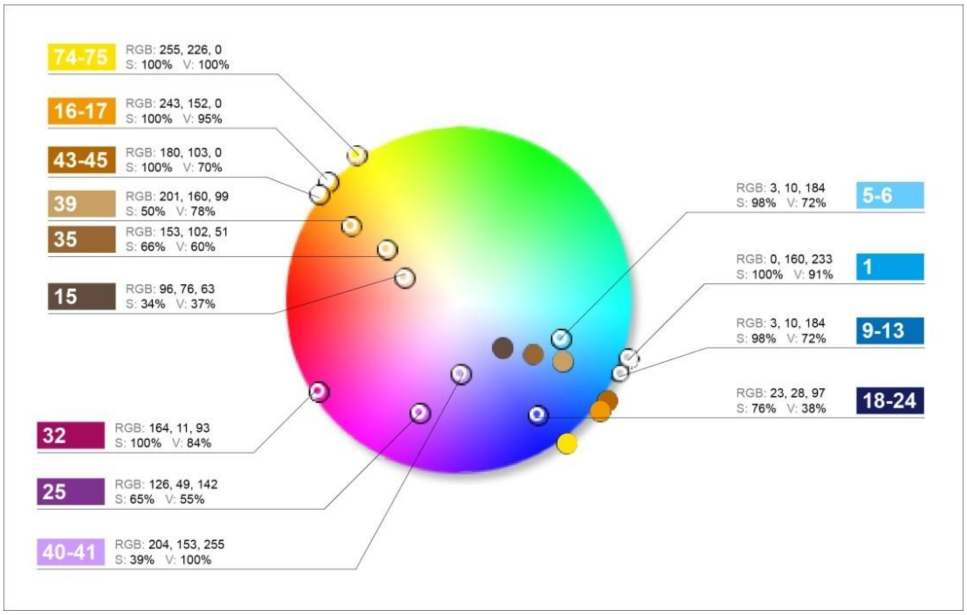


Figure 4.6: Colours in orange and yellow categories and their corresponding complementary colours compare with colours in blue and purple categories (numbers in coloured blocks represent railway line numbers which represented by the corresponding colour)

The result shows that the colours on the map are different in saturation steps and brightness steps, the different levels in saturation might weaken the colour harmony, but the differences in brightness levels may strengthen the contrasts between colours. The comparisons between important complementary colour groups such as red & green, orange & blue, yellow & purple indicate that the colours are not following complementary colour harmony principle. According to Figure 4.7, if displayed all 27 colours on a colour wheel, it is easy to observe that colours are irregularly located on the wheel, some of them are very closed in the area, which means they are similar in either saturation or brightness, or both. This problem may cause identification problems in reading, just like the previous eye-tracking evaluation test showed.

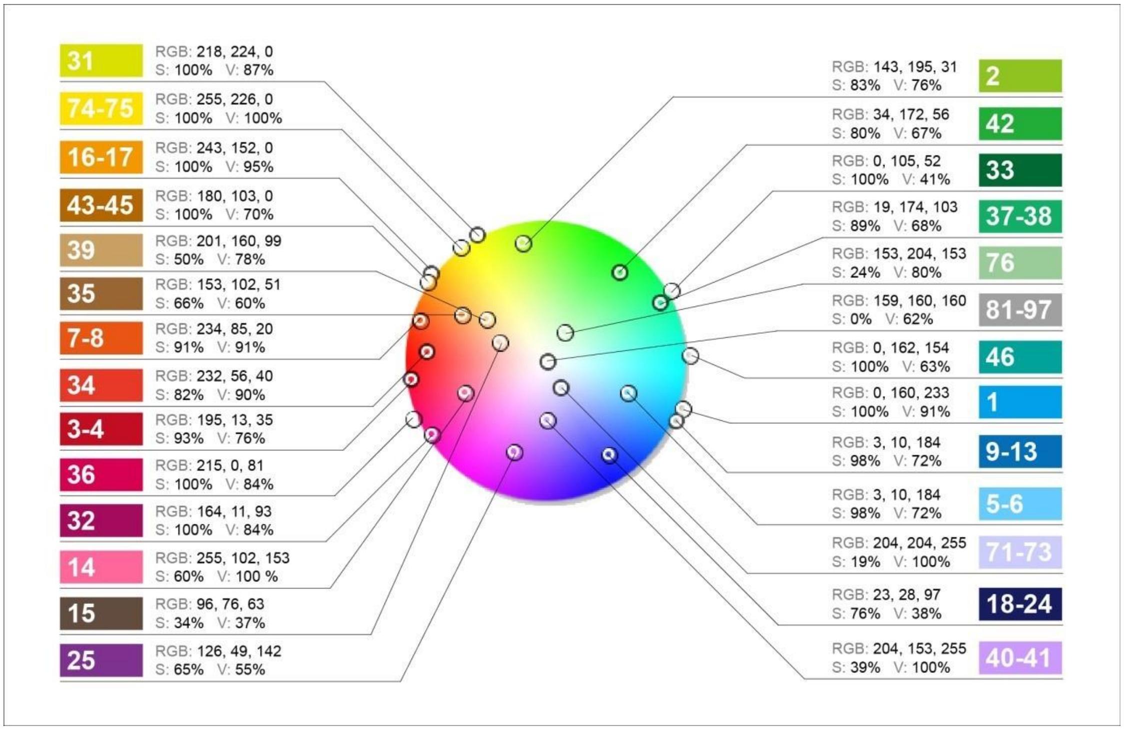


Figure 4.7: All 27 colours on the transit map (information includes RGB value, Saturation and brightness)

Overall, the colours on China's high-speed railway map are randomly selected, they are not designed based on colour harmony theories, which may weaken the colour harmonious of the transit lines, but the different levels in brightness might be helpful to enhance the contrast between colours.

4.3.2. Examination based on colour design principles

As mentioned previously, there are four main colour schemes in map design when **one-variable data** needs to be presented, such as transit lines, the different line's names are the only variable in this case.

A **Qualitative colour scheme** allows differences in hues, but the brightness steps of colours need to be the same or similar (Brewer, 1994). According to Figure 4, the brightness steps among colours are not the same or similar, they are more likely to belong to the ordinal relationship colour scheme, which is a special category of qualitative colour schemes. Ordinal relationship colour schemes emphasise different levels of brightness, but it requires regularly neighbour hues on the colour wheel or complementary colour groups. As mentioned previously, the colours of China's high-speed railway map located irregularly on the wheel, not following the neighbour colour selection or complementary colour selection rules. Due to this, the colour system is not designed according to qualitative colour scheme discipline.

The **binary colour scheme** is a special case of qualitative colour schemes, it only contains two hues to make comparisons between two categories (Brewer, 1994). The colour system of China's high-speed railway map contains more than six main categories of hues, which indicates that it is not designed according to binary colour scheme discipline.

The **sequential colour scheme** follows a rule that colours arranged according to sequential brightness steps, with a no less than 10% increase/decrease (McGranaghan, 1989). According to Figure 4.7, brightness steps among all the colour categories are not sequentially spaced, which means the colour system is not designed according to sequential colour scheme discipline.

The **diverging colour scheme** contains two main hues with transitions in brightness steps, but the colour system of China's high-speed railway map includes more than two colour groups, and the brightness steps were set irregularly. As a result, it is not designed according to diverging colour scheme discipline.

Overall, the colour system of China's high-speed railway map is not based on the map colour design principles, nor satisfied the colour harmony design theories, the design limitations in colours affected the legibility of the map, and caused potential information searching errors in previous tests (Wang, Lonsdale and Cheung, 2021). Due to this, a new colour system is built up based on colour harmony theories and map colour design principles in the next stage.

4.4. Re-constructing the colour system

In this section, the colour system of China's high-speed railway map is reselected and reorganised based on both colour harmony theories and map colour design principles introduced above, the newly designed colours are applied to the map and ready for the coming usability test.

4.4.1. An effective tool for selecting colour schemes: ColorBrewer

In order to establish a colour system for China's high-speed railway map based on map colour design principles, an effective colour selection tool for map designers: **ColorBrewer** is used in the study. ColorBrewer is an online tool that provides colour schemes for cartographic design, it is available at www.ColorBrewer.org. All colour schemes are described using Munsell hue, value and chroma specifications and following Munsell's colour harmony principle (Harrower and Brewer, 2003). Many transit map and geographic map design examples are designed based on this colour selecting tool, such as the newly designed urban railway map in New York (2015) and the updated underground map in Berlin (2017). These new design examples achieved better legibility and evaluation in the tests and proved the colour system is effective. In addition, it has been accepted and recommended by Cartography and Geographic Information Science association in the US since 2005. It is a very welcome and renowned colour selecting tool among cartographic designers, and it has been used in many colour system improvement projects and research (Lloyd, Rodgers & Roberts, 2018; Borland and Taylor, 2005; Brychtova and Coltekin, 2015). The software contains three main colour schemes: qualitative, sequential and diverging, which are introduced in the previous chapter. Here is a brief statement about the advantages of each colour scheme in the software:

Qualitative colour schemes have less brightness variation and a wider variation in hue than both sequential and diverging colour schemes. The most basic colours of qualitative schemes include red, green, blue, yellow, orange, purple, pink, brown, white, grey and black. Some mixed colours can be produced based on these colours and can be classified by brightness steps. Light and dark versions of each hue in the paired scheme can be used to represent related categories on a map, such as light green represents grass and dark green represents trees. The light, dark or highly saturated colours can be used to display small or important categories, which is helpful to emphasis the key information, e.g. using small and highly blue to represent a water station in a desert which represents by a large orange area. Brightness steps of colours in qualitative schemes can be different, the variation in brightness can strengthen contrasts to enhance identification of individual colours.

Sequential colour schemes based a series of basic colours on a saturated hue circle: red, pink (light desaturated red), orange, brown (dark desaturated orange), yellow, green, blue, purple, white, grey and black. The brightness steps transit from light to dark with a no less than 10%

rate. Most sequential schemes created in ColorBrewer also include slightly hue transitions, which is more advanced than single brightness sequences.

Diverging colour schemes contain a light midpoint and the brightness progressions extend out from that point toward two different hues. Most diverging colour schemes meet at a near-white grey midpoint, these neutral colours have no hues, which is not suitable to represent shapes with no borders on the map. In most cases, all the diverging colour schemes share the same form that colours from dark value/high chroma gradient to light value/low chroma (close to midpoint), and then back down to dark value/high chroma.

4.4.2. Colour re-selection

According to Figure 4.4, the original colour system contains six main groups in hue: red, orange/yellow, green/indigo, blue, purple and grey, they are totally 27 colours displayed in these groups. This combination showed a typical rainbow colour map, there are many research pointed out the potential limitations of the rainbow colour system on the map, the lack of perceptual order could make users feel confused, the random variation in value also obscures the data (Borland and Taylor, 2007). Rainbow colour system is a common default option in many visualisation software and applications, it may be due to users' inertia, and it is very common to see in modern information design, as well as the notion of "the more colour, the better".

An interesting experiment shows that people prefer to group the coloured cards in the order of red, orange, yellow, green, blue, indigo, violet, many of them believed that there is a potential order of the information on cards following the **rainbow colour order** (Borland and Taylor, 2007), this may cause misunderstandings in map use. Most maps using rainbow colours separated into bands of almost constant hue, with sharp transitions between hues. Users may perceive the sharp transitions in colour as sharp transitions in data, considered about people's colour ordering habit, this may bring more challenges for users.

It is a tough question that what is the best colour design choice for a transit map? There are many researchers investigated other colour plans. Healey (2007) mentioned that colours with **strong contrasts** are suitable to present nominal data, such as transit lines on a railway map, or political affiliations on a world map. Healey also investigated what colours are optimal to label different categories of data based on colour separability and distances in CIE LUV space.

Ware (2004) recommended the **six opponent-channel colours** (red, green, yellow, blue, black, white) followed by six other distinct colours (pink, cyan, grey, orange, brown, and purple) for this purpose. The **value** and **saturation variations** enable more colours can be selected in Ware's (2004) colour scheme than eight distinguishable colours found in the rainbow colours.

Due to the reason that binary colour scheme only contains two main hues, which is not suitable to be selected as the colour design standard for transit lines. Similarly, the diverging scheme only contains the transaction between two hues, which is undiversified and not able to show huge colour differences between transit lines. Based on that, both colour schemes will not be selected.

Currently, there are 27 colours in the existing map, single or paired colours will not be sufficient to differentiate the distinct lines, colour scheme with more colour options such as **qualitative scheme** is selected. Moreover, the **sequential scheme** provides stronger contrast options in every single hue, which is helpful to select more **neighbour colours**. In the current map, three Metropolitan Area Express Railway lines were displayed with three different colours, this caused time-wasting in the previous test (Wang, Lonsdale and Cheung, 2021). In the new design, they are demonstrated with one single colour, this can help to group them into the same service category and avoid potential confusions. Both Upgraded Conventional Lines are grouped into the same colour as well. This action reduced the needing colours from 27 in the current colour system to 25 in the newly designed system, they are 23 High-speed Railway Line colours and 2 special service colours.

By using ColorBrewer, in the **qualitative scheme**, there are eight colours selected by the software (Figure 4.8): red, blue, green, cyan, orange, yellow, brown and pink, which also follows Ware's (2004) colour selection advice when representing nominal data.

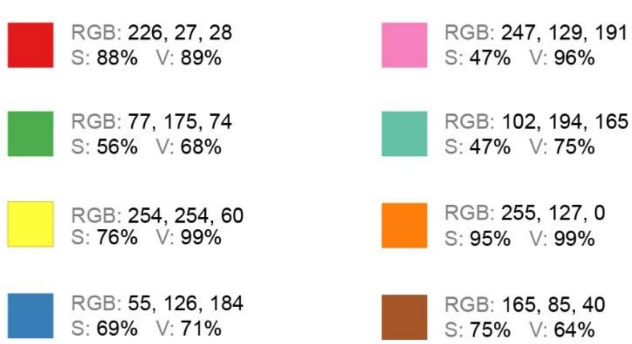


Figure 4.8: Colours selected by ColorBrewer

In Fang et al.'s (2017) research, the colour system of the London Underground has been improved by adjusting the hue, saturation and value, the authors adjusted the colours following the method of H: ±5%, and S, L: ±10%. The colour distances among lines have been enlarged, which improved the legibility in the test. Although research showed that 10% increase/decrease in lightness is sufficient to show colour differences on the maps (Fang et al., 2017; McGranaghan 1989), but people with impaired colour-vision may see less contrast than the normal colour-vision users. Based on this finding, the author made a method of H: ±5%, S±15% and L: ±20% of each selected colour to select other two neighbour colours, which means a stronger colour difference than Fang et al.'s (2017) research, more details are showing in Figure 4.9.

There are 16 more colours been selected based on the 8 ColorBrewer selected colours by using this method, some values increased less than 20% because it has reached 100%, as Ou (2016) mentioned that brighter colours are more likely to create colour harmony. Finally, the 23 colours are selected to display the 23 **ordinary high-speed railway lines**.

Figure 4.9: The newly selected colours

Then comes to the special service lines, blue is the hue that most likely to create harmony (Ou, 2016), and there is extremely low rate of blue-deficient among colour-deficiency population (Pugliesi and Decanini, 2012), then a lighter blue colour is selected based on the same method to represent the three **Metropolitan Area Express Railway lines**, this bright colour is also helpful to show this special service outstanding on the map. And a grey colour is selected to represent the two **Upgraded Conventional Lines**.

Overall, this newly designed colour system is a **combination** of the **qualitative scheme** and the **sequential scheme**, it provides both distinct hues and strong contrast transitions among each hue category. The colours are selected based on the colour harmonious theory and considered about the colour-deficiency users.

The last work is to use the newly selected colours to display all 28 transit lines (Figure 4.10). Each transit line is displayed sequentially by one colour from the colour groups, the order of colour selection follows: red – green – yellow – blue – pink – cyan – orange – brown, this order also breaks the **rainbow colour order** to avoid potential misunderstandings. Transit lines with **complementary colours** or **adjacent colours** are arranged close to each other on the map to create harmony, colours with similar hues are avoided locating closely on the map to prevent potential route tracing mistakes.

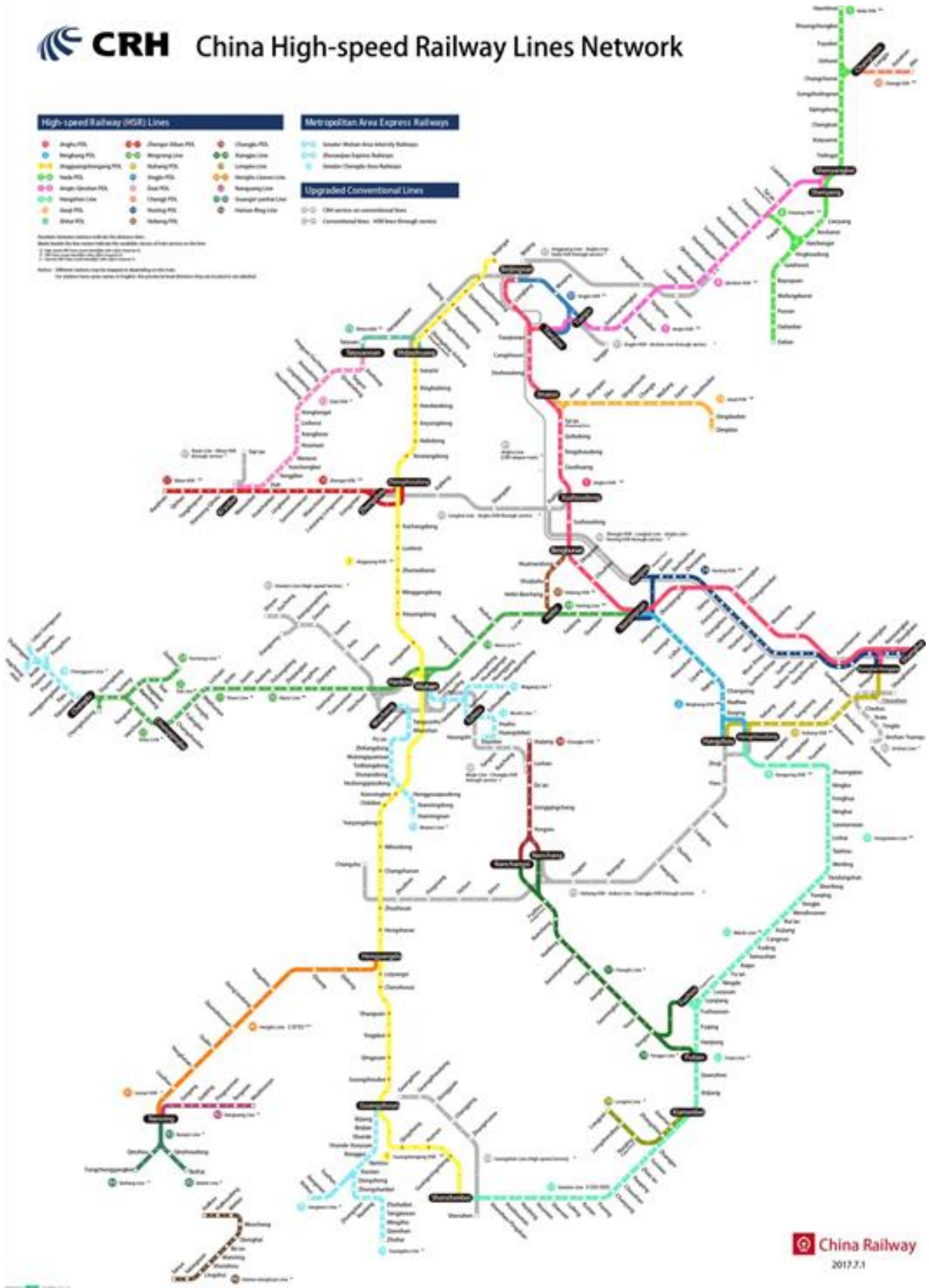


Figure 4.10: Newly colour-coded map

Moreover, when compare the colours on the colour wheel of both existing colour system and newly designed colour system (Figure 4.11), it is obviously that the newly selected colours are located regularly on the wheel compared with the random locations of the existing map colours. In addition, from Figure 4.11, the newly selected colours are overall less saturated than existing colours (very few colours located at the edge of the colour wheel), but more than half of the existing colours are fully saturated. As mentioned previously, a saturated hue is not likely to be a light colour, it may also limit the contrast range of the rest categories, which is not beneficial for creating strong contrasts between colours (McGranaghan, 1989). Moreover, the revised colours did not follow the rainbow colour order, more complementary pairs are selected.

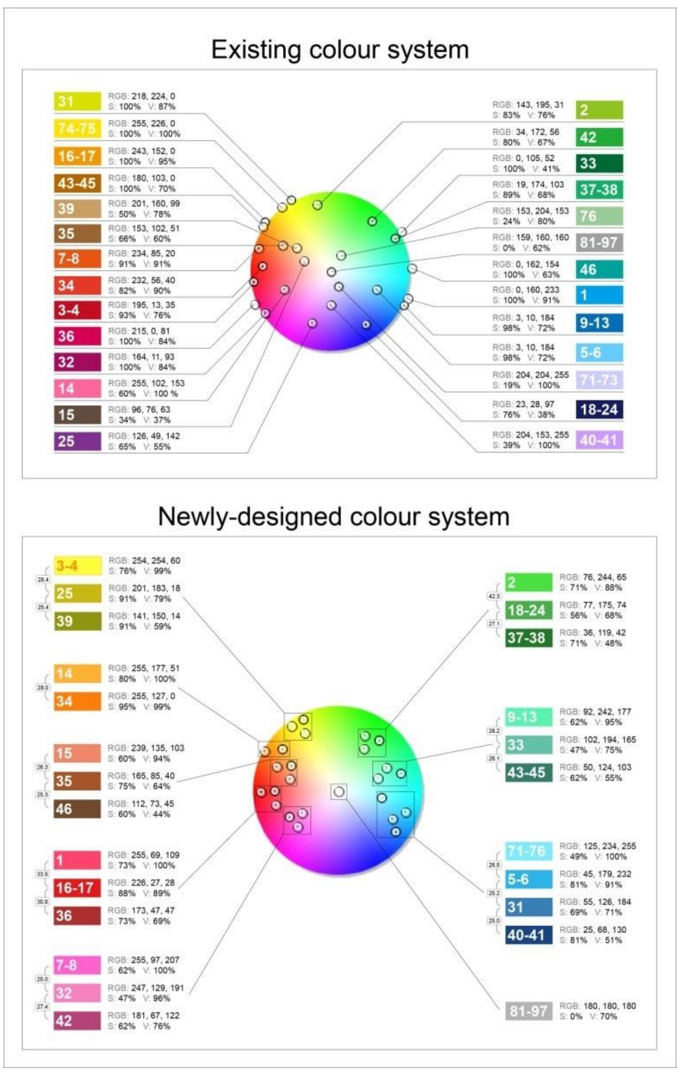


Figure 4.11: Colours on colour wheel (comparison between the existing colour system and the revised colour system)

Last but not least, the newly-design colour system shows more advantages in reading for colour deficient users than the existing colour system. Figure 4.12 shows the view of both coloured maps for red-deficient users, which is the most common colour-deficiency among the colour-deficient population. The existing map used grey, yellow and green to represent three lines (red blocks) in Metropolitan Area Express Railways (green block), this may cause confusions for colour-deficient users as there are three different colours in the same service, they may confuse with other lines with similar colours on their own view. The new-designed colour system used one blue colour to represent all three lines, which avoided this potential reading difficulty for colour-deficient users. In addition, colours of multiple lines of the existing map (black block) look almost the same (similar blue hues) for red-deficient users, this problem is due to the reason that multiple blue and purple colours are used in this area, but purple hues look very similar to blue hues for red-deficient users (Hess, 2000). In the same area of the newly designed coloured map, colours are distinct for red-deficient users, because similar hues are avoided to represent lines locate close to each other on the map, this design benefits both colour-deficient users and normal colour-vision users.

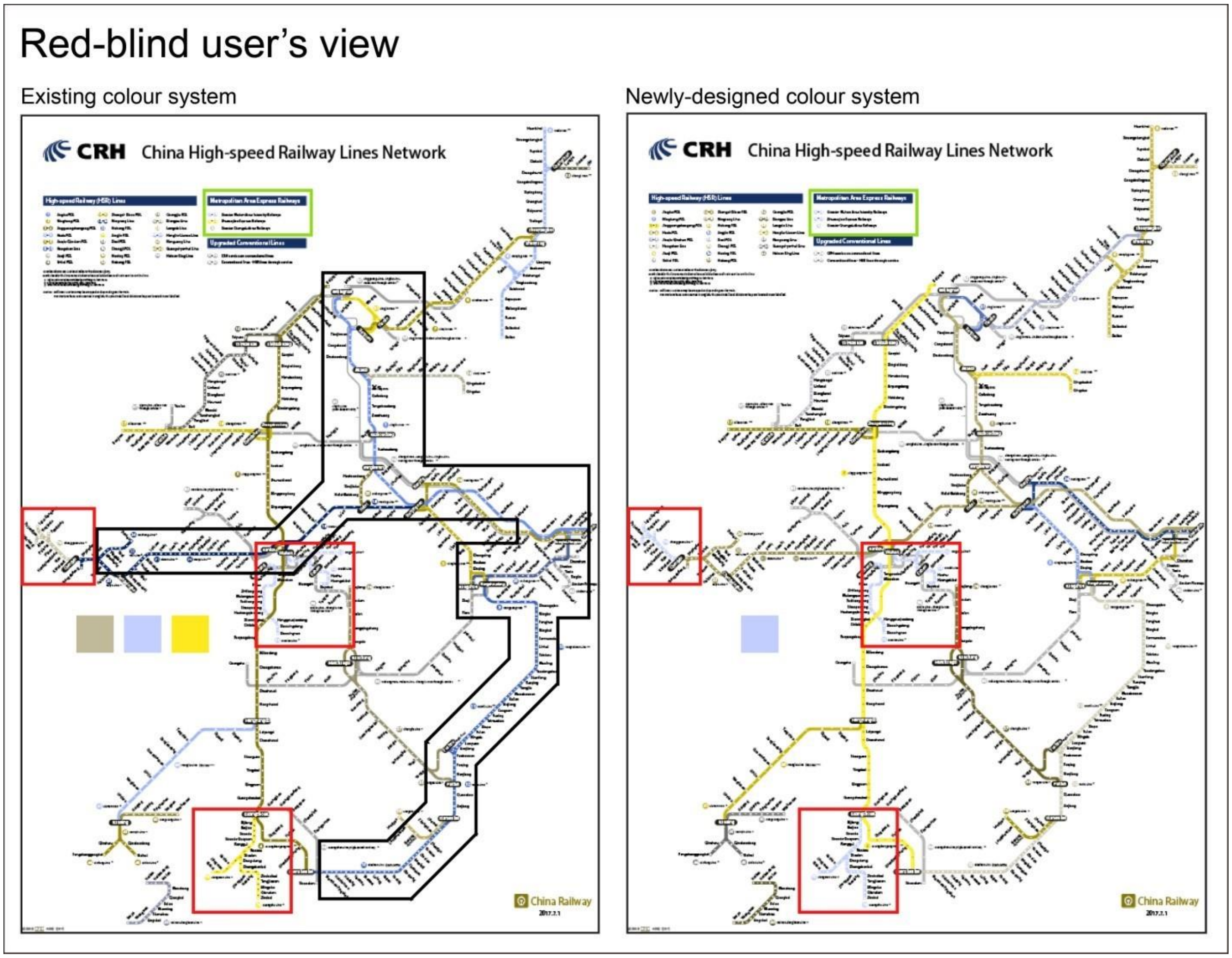


Figure 4.12: Red-deficient user's view of both existing map and newly colour-coded map)

4.5. Usability test of the new colour system

In order to investigate the effects of the newly designed colour system and make comparisons of reading speed and information-searching accuracy between the existing map and the revised map with the newly selected colours (Figure 4.13), a usability test was conducted among 40 participants. In this test, the layout of both maps is the same, and the two different colour systems are the only variants.

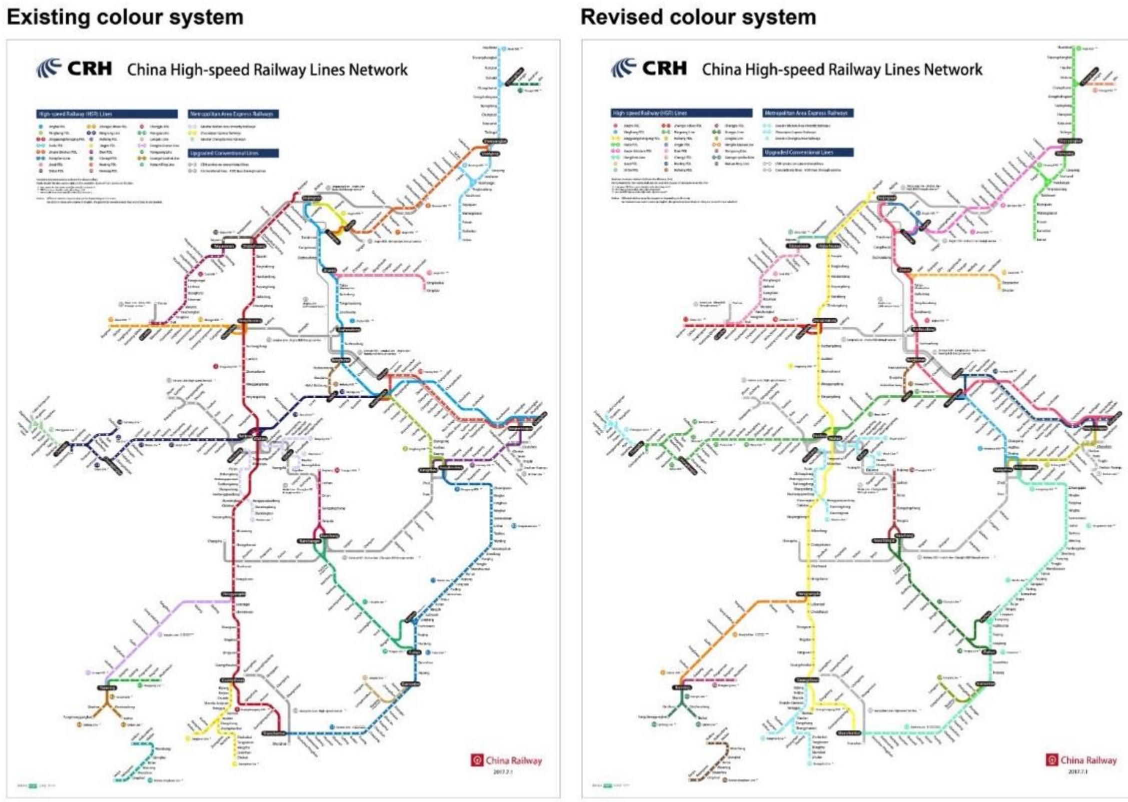


Figure 4.13: The existing colour design (left) and the revised colour design (right) of China's high-speed railway map

4.5.1. Participant recruitment

There are forty participants from different educational backgrounds and nations were recruited for this test. They were asked several questions to confirm they were non-Chinese citizens and had no knowledge of Chinese geography, e.g. Travelled in China or have Asian geography researching experience, this helped to enhance the objectivity of the results. Participants were mainly from the UK, the US, Australia, Canada, India, and Japan. Most of them were from the UK (28, 70.0%).

The numbers of male and female participants were kept the same (20 males and 20 females). The average age of the participants was 25.4, because tourists between 20 to 30 years old made up the largest population (34.4%) of people who visited China in 2019.

In addition, every participant took an Ishihara test (Ishihara, 2018) before the usability test, they were all deemed to have normal colour vision.

4.5.2. Test environment, procedure, and materials

The test was conducted in a dark room free from noise. Participants needed to complete a total of nine information-searching and route-planning tasks on a computer with a screen resolution of 1920 x 1280 pixels, this screen setting is the same as the screens used in China's railway stations to display maps and relevant travel information. Participants sat in front of the screen at about an 80 cm distance and used a mouse to point out target information. Participants' response time and information-searching accuracy for each task were recorded.

Other analysis methods, such as SPSS calculation, were used to increase the validity and reliability of the findings. In order to make sure that different groups of data were normally distributed, detailed data-distribution analysis, including histogram, was conducted. In order to make clear comparisons between variables, a paired sample t-test was used.

4.5.3. Test settings

To evaluate the redesigned colour system and compare the effects of the existing system to the new one, there were a total of nine information-searching (Type A) and route-planning tasks (Type B) in the test. Two different missions with the same difficulty level were set for both the existing and revised maps in each task.

Table 4.2 shows details of the task settings. Task A1 and Task A2 are transit-line identification tasks, both tasks aim to find out how different colour systems affect people's information-searching speed and accuracy. Task A2 aimed to find out if both variates changed after a long time using of the maps. Task B1 to Task B7 were seven trip-planning tasks. The difficulty of the tasks increased by containing more destinations and interchanges. This aimed to find out how the different colour systems affected users' trip-planning speed and accuracy, comparison of both variates (reading speed and accuracy) can evaluate the design quality of both colour systems. During the test, participants needed to point out every interchange point and target line correctly. Mistakes, such as transferring to the wrong place or planning an impossible route, lost them points.

Tasks	Instructions	Required targets	Difficulties
A1	Find 4 transit lines based on coloured instructions in the map legend	8	N/A
B1	Plan a trip that includes 2 destinations and 1 interchange	4	Easy
B2	Plan a trip that includes 2 destinations and 2 interchanges	6	↓
B3	Plan a trip that includes 2 destinations and 3 interchanges	8	
B4	Plan a trip that includes 3 destinations and 5 interchanges	13	Medium
B5	Plan a trip that includes 4 destinations and 7 interchanges	18	↓
B6	Plan a trip that includes 5 destinations and 12 interchanges	29	Difficult
B7	Plan a trip that includes 7 destinations and 18 interchanges	43	
A2	Find 4 transit lines based on coloured instructions in the map legend	8	N/A

Table 4.2: Nine tasks in the test and

Taking Task B4 for example (Figure 4.14), participants needed to plan a trip that included three destinations and five interchanges on each map, the order of both maps showing to participants is random in each task. Destinations were shown on the maps, as a station-finding task has a significant chance factor. The time or accuracy of station-finding tasks is not sufficiently objective to support a specific conclusion (Wu et al., 2020). Participants only needed to plan trips between target destinations without finding them out on the map.

The accuracy (showed in percentage: %) will be presented by counting the number of correct responses out of the total number of required targets for each task, and there was no time limitation on any task.

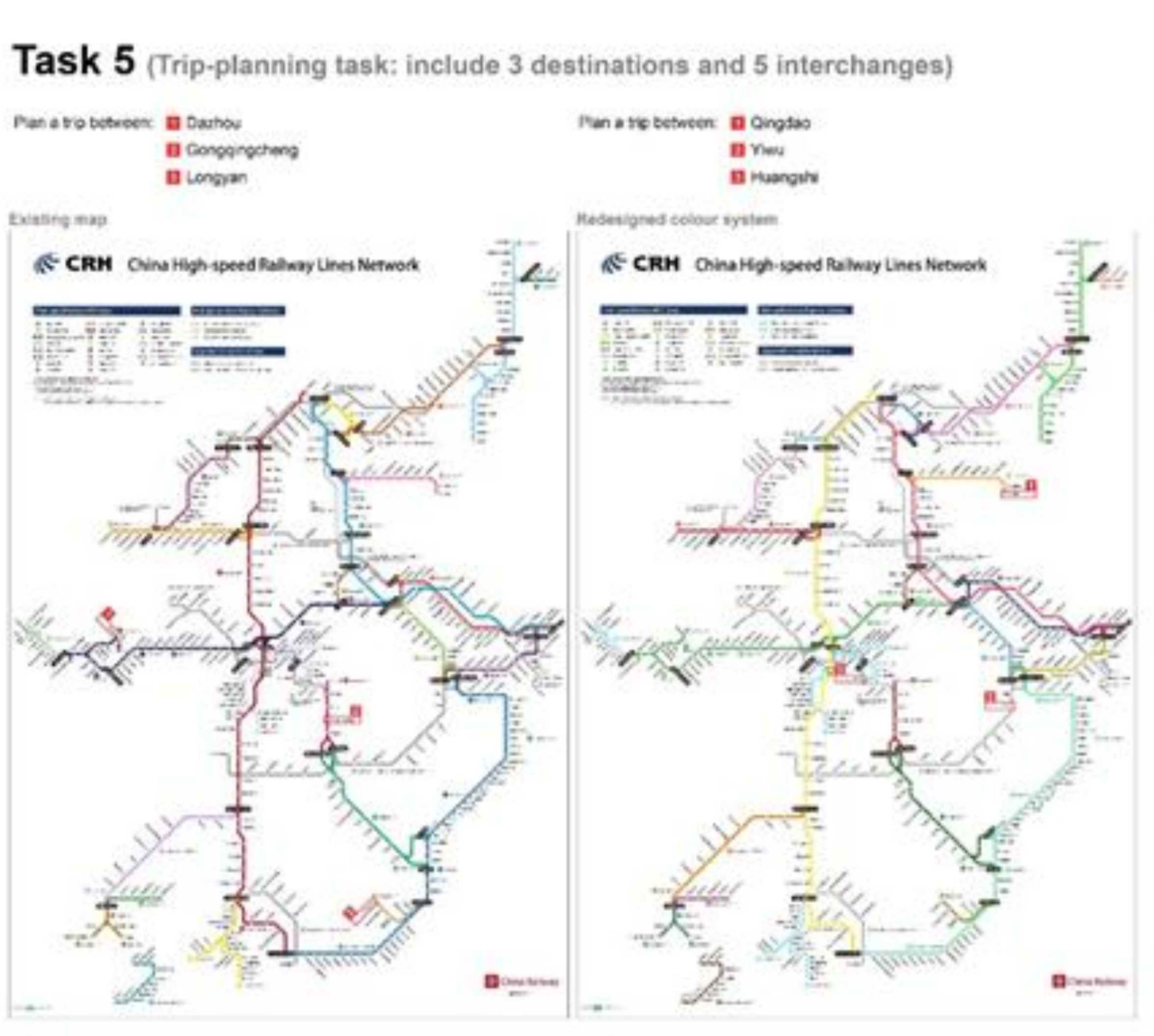


Figure 4.14: Task B4, trip-planning missions on both maps

4.5.4. Results and analysis

4.5.4.1. Comparison of reading speeds between existing and new colour system

Figure 4.15 shows the comparison of time consumption between the existing map (blue box) and redesigned colour-coded map (green box) in each task; the mean value of each column is emphasised. Overall, participants spent less time in all tasks when using the revised map rather than the existing map.

Both Task A1 and Task A2 were transit-line identification tasks. In both tasks, participants spent less time when using the revised map (*M*=120s in Task A1, *M*=102s in Task A2) than the existing map (*M*=165s in Task A1, *M*=135 in Task A2). Though the difficulty level of both tasks was the same, participants finished Task A2 slightly quicker than Task A1 after going through the previous eight tasks, and the revised map always showed a faster reading speed than the existing map in both tasks.

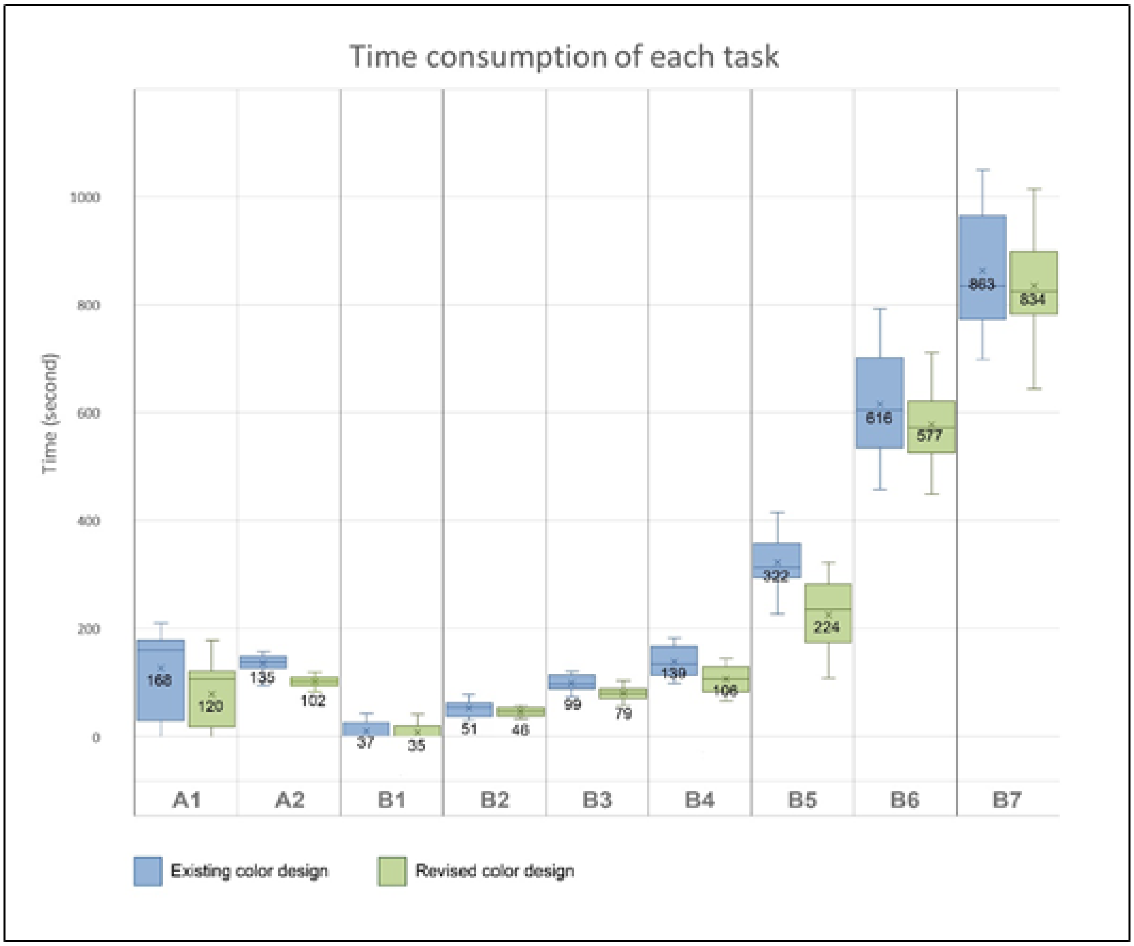


Figure 4.15: Time consumption of each task

Tasks B1 through B7 were route-planning tasks. The difficulty level of the tasks increased from a trip including two destinations and one interchange to a trip including seven destinations and more than fifteen interchanges. Overall, the reading speed for the revised map was faster than the existing map.

With the increase in difficulty, participants' time consumption in the tasks consistently increased. In the most difficult trip-planning task (Task B7), the average time used on both maps was beyond 800 seconds, the longest among all tasks. When comparing participants' time consumption on both maps, the average time participants spent on the revised map in Task B1 (M^{nB1}=35s) was only two seconds faster than the existing map (M^{eB1}=35s). Then, the differences between both values gradually increased in line with the increasing difficulty from Task B2 (M^{nB2}=46s, M^{eB2}=51s). The biggest gap in the test was reached in both values in Task B5 (M^{nB5}=224s, M^{B5}=322s), when the participants were an average of 98 seconds faster using the revised map than the existing map. Further interesting results occurred after Task B5: The gaps between both maps' time consumption consistently decreased in Task B6 (M^{nB6}=577s, M^{eB6}=616s) and Task B7 (M^{nB7}=834s, M^{eB7}=863s). Especially in Task B7, the time-consumption difference between both maps is not significant at all ($p > .05$). For the most difficult route-planning task in the test, participants were an average of 29 seconds faster on the revised map than the existing map.

4.5.4.2. Comparison of information-searching accuracies between existing and new colour system

Figure 4.16 shows the comparison of information-searching accuracies (mean values) between the existing map (blue points) and revised map (green points) in each task; the full score of each task was 10. From Figure 4.16, it is obvious that participants' information-searching accuracy when using the revised map was higher than the existing map in almost all the tasks. The only exception was Task B1, where all participants planned the route correctly with no mistakes in this simplest trip-planning task.

Both transit-line identifications in Task A1 and Task A2 showed larger differences in information-searching accuracy between both maps (M^{nA1}=92.5%, M^{eA1}=80%; M^{nA2}=96.9%, M^{eA2}=90%). The existing map showed a lower accuracy than the revised map in both transit-line identification tasks. The accuracy of both maps in Task A2 was better than in Task A1, which means participants' information-searching accuracy increased after their user experience improved.

In the trip-planning tasks (Task B1 to Task B7), mistakes made by participants consistently increased from Task B2 (M^{nB2}=98.8%, M^{eB2}=95%) with increased levels of difficulty. The accuracy values reached their lowest in Task B7 (M^{nB7}=87.4%, M^{eB7}=83%). This indicates that the more difficult the task is, the more mistakes will be made by the users. Overall, the information-searching accuracies of both maps did not show significant gaps, but the revised map always showed better accuracy than the existing map in trip-planning tasks.

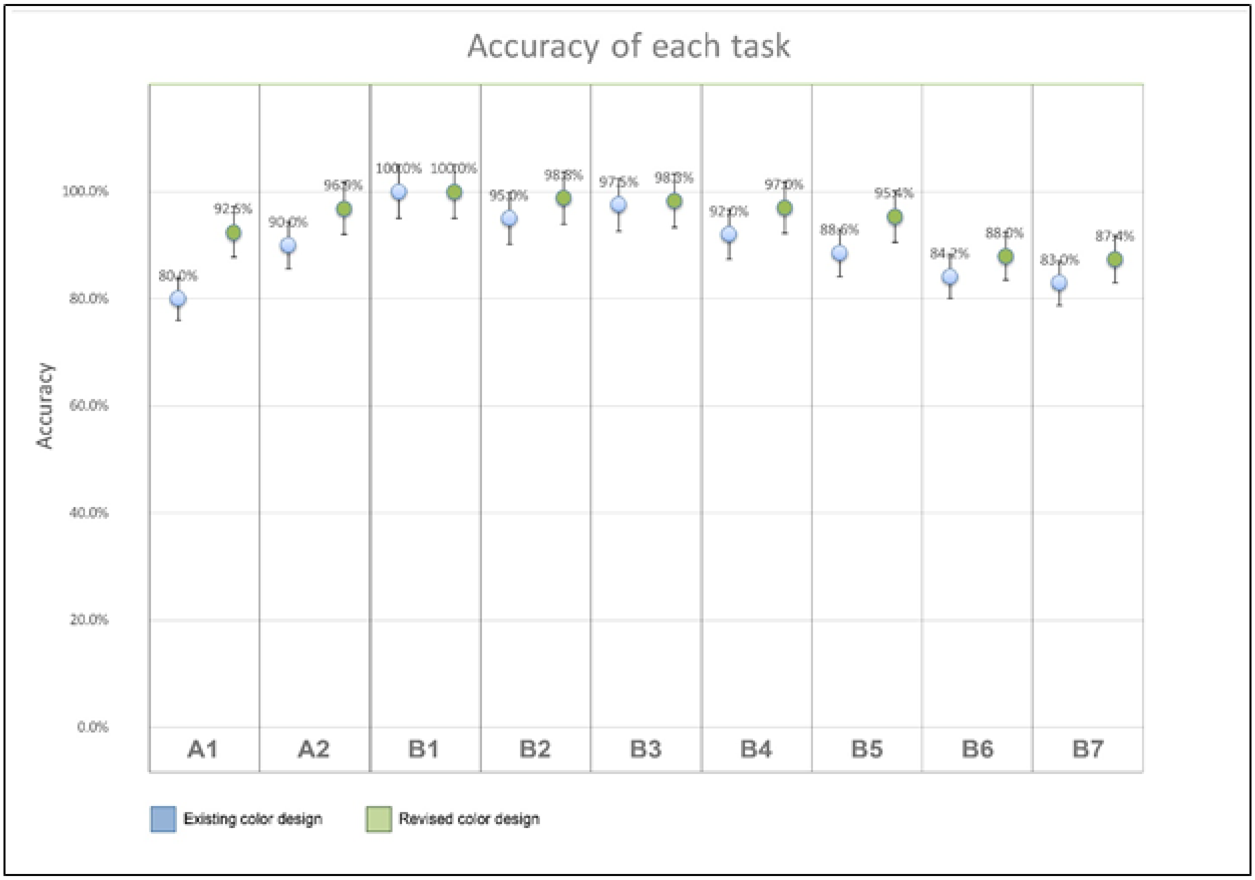


Figure 4.16: Information-searching accuracy of each task

4.6. Discussion

Based on the test results, the design quality of the colour systems of both the existing map and the revised map was effectively compared. Many important findings regarding transit map colour-coding and how colours affect a transit map's legibility were identified. Participants' feedback also provided many valuable insights into the design and evaluation of transit-map colour systems.

4.6.1. Effect of colours on a transit map's usability

In the trip-planning tasks (Figure 4.15), participants organised routes much quicker when using the revised map than the existing map at the beginning (Task B1). The time-consumption gap between both maps consistently became larger, but as the difficulties of tasks gradually increased, the time consumption gap between both maps became smaller after Task B5. This finding is similar to Netzel et al.'s (2016) eye-tracking test result. The authors compared users' reading speed and information-searching accuracy between a greyscale and a colour-coded map of the same transit-line system. The authors found that the colour-coded map showed an advantage in both reading speed and information-searching accuracy at the beginning. Still, as the difficulties of the tasks increased, both maps showed smaller or even no differences in reading speed and information-searching accuracy. This indicated that the advantage of colours might not exist when the complexity of a task reaches a certain level.

In this study, both maps are coded by different colour systems; although the revised map showed its advantage in reading speed at the beginning, but the differences between both maps became smaller after Task B5 (planning a trip contains four destinations and seven interchanges). This finding indicates that colour may not be a key factor in transit-map reading **speed** after the difficulty of the task reaches a certain level (Task B5 in this study). The phenomenon observed by Netzel et al., (2016) does not only exist between the colour-coded and greyscale versions, but also exists between different colour-coded plans of the same transit system.

By examining the trip-planning accuracies (Figure 4.16) of Task B1 to Task B7, it was clear that the more complex the task is, the more mistakes participants would make on both maps. The worst accuracy appeared in the most challenging task (Task B7). Still, the revised map showed a slightly better ($p > .05$) information-searching accuracy than the existing map. But with the difficulties of the tasks increased, the trip-planning accuracy of both maps did not show significant differences. This indicates that colours may have a limited effect on trip-planning **accuracy**.

The feedback from participants explained the effect of colours from the users' perspective. In trip-planning tasks, participants paid more attention to colours at the beginning, as they mentioned that **colours** are the most direct visual elements to target the routes in simple tasks. With the increase in task difficulty, participants started to pay more attention to **texts** from Task B5. They needed to double-check the text information carefully when the complexity of the tasks increased. This showed that the effect of colours on a transit map depends on the difficulty of the tasks. Colours may have weaker effects on a transit map's legibility when the complexity of the task reaches a certain level. However, this finding may not apply to all users. Individual differences cannot be ignored because some participants may prefer to find information based on text rather than colour all the time, or the converse. But at least the result reminds us that not all information on the map can be visualised; the designer should make a balance between texts and visual designs to prevent over-visualisation.

4.6.2. Evaluation of the existing and the new colour system

Unlike the existing map, the new colour system was built based on map colour-design principles and colour harmony theories. The new colour system theoretically showed stronger contrasts and better colour harmony than the existing colour system. Did the redesigned colour system deliver a better design quality in the usability test? This section compares both maps in terms of different aspects.

No matter the transit-line identification or trip-planning tasks, participants always spent less time using the revised map than the existing map (Figure 4.15). Due to the reason that the colour system is the only difference between both maps, this indicates that the new colour system helped users identify the target information and make decisions quicker. This may be credited to the stronger contrast of the newly selected colours that make every transit line more distinct from each other, but it does not mean the existing map failed to represent transit lines clearly. Both colour systems successfully differentiate the transit lines, and the new colour system is superior to the current colour system in reading speed.

Considering the information-searching accuracy of both maps, the differences in both transit-line identification tasks (Task A1 and Task A2) were more observable than that in trip-planning tasks (Task B1 to Task B7). The major mistake made by participants was being misled by the unwanted lines with similar hues to the target lines. For example, in Task A1, 16 (40%) participants mistakenly selected the No. 34 transit line because its red colour looks similar to the target line (No. 7-8). Both colours were found to be close in the colour distance in the previous colour-evaluation work (Figure 3). On the contrary, similar mistakes rarely happened when participants used the revised map, which indicates that the stronger contrasts among colours in the new colour system successfully reduced such confusions and led to better information-searching accuracy. However, this advantage was not very significant in trip-planning tasks. Overall, the new colour system enhanced the reading accuracy of China’s high-speed railway map.

In addition, participants marked scores of both colour systems. The revised colours (M^n=4.2, above "Harmonious") are observably more harmonious than the existing map's colours (M^e=2.7, under "Neutral"). This may be the benefit of the use of complementary colours, as Itten and Birren (1997) stated that complementary pairs or multiple complementary combinations create harmony. Colour harmony is relevant to aesthetics, a transit map with harmonious colours can enhance users' interest in map exploration (Goldstein, 1965; Liu & Lin, 2009). The user's satisfaction with the revised map in colour harmony may directly lead to its strong attractiveness among users. There were 32 (80%) participants who preferred the revised map, which is four times the number of those who preferred the existing map (8, 20%).

Overall, the results showed that the revised map is superior to the existing map in both reading speed and information-searching accuracy. Although both colour systems displayed the transit lines clearly, the new colour system shows overwhelming advantages in colour harmony and attractiveness over the existing colour system.

4.6.3. Contribution to transit map colour-coding

The usability test results showed that the colour-recoding work effectively helped enhance the reading speed and accuracy of the map, as well as its attractiveness. This showed a successful example of a transit map's colour redesign based on map colour-design principles and colour-harmony theories. Some transit map colour-design guidelines can be summarised from this study.

The previous evaluation of the existing map's colours showed that the colour system did not align with any map colour-design principles or colour-harmony theories. Although it could not be considered a mistake in colour selection, the existing map showed that randomly selected colours caused weaker contrasts or indistinctive differences between colours (Stigmar, 2010). These problems caused inefficient reading in the test, which showed the effectiveness of colour contrast when evaluating a colour system of a transit map.

The combination of a qualitative scheme and a sequential scheme is considered a suitable colour-coding plan for a transit map: The qualitative scheme provides multiple selections of hues to represent a large number of different transit lines, and the sequential scheme provides different lightness and saturation values to enlarge the colour distances. The contrasts between colours need to be at least 10% to show sufficient colour differences (Fang et al., 2017;

McGranaghan, 1989). This standard has been enlarged in this study, the colours in each hue category kept ±15% in saturation and ±20% in lightness. This method can create stronger contrasts and richer saturations. Stronger contrasts could also enhance the transit lines' identification for colour-deficient users because they may see weaker contrast than normal colour-vision users (MacEachren, 1995; Hess, 2000; Dent et al., 2009).

In addition, various complementary colours are selected in the new colour system, such as red-green pairs and blue-orange pairs (Figure 4.15). They made transit lines more distinctive and strongly enhanced the colour harmony of the revised map, which provides higher visual comfort to users.

In addition, colours from the same hue category should avoid representing lines located close together on the map; it is better to arrange complementary or adjacent colours together. This method can reduce potential confusion and enhance the colour harmony of specific areas.

4.7. Conclusion

This study evaluated the design quality of China's existing high-speed railway map's colour system. Various problems were found in the experiment, such as insufficient colour contrast, weak colour harmony, etc. A new colour system was established based on transit map colour-design principles and colour-harmony theories, and its effectiveness was proved by users' map reading efficiency. This study demonstrated a successful theoretical and practical evaluation and redesign process of the colour design of a transit map, which filled the gap among studies that focused on comparisons of transit-map colour designs but lacked actual colour-coding practices (Wu et al., 2020), various valuable map colour-coding suggestions were summarised from the test result.

The usability test showed that the colour-recoding work successfully enhanced the legibility of China's high-speed railway map in terms of reading speed and information-searching accuracy. This proved that combining the qualitative and sequential colour schemes was a suitable colour-coding plan in transit-map design. The use of complementary colours was not only helpful to distinguish railway lines but was also helpful in creating a stronger colour harmony, which led to high attractiveness and acceptance among users. Some micro-changes may also contribute to better legibility of the revised map, such as avoiding putting colours with similar hues close to each other on the map. Moreover, this study is concerned about colour-deficient users, which is ignored in most transit-map design studies. The researcher made some improvements to enhance the identification of transit lines for colour-deficient users, such as enlarging colour contrasts and using the same colour to represent lines that belong to the same service. These practical improvements successfully solved the colour design limitations identified from the earlier study and enhanced the legibility of Chia's high-speed railway map (Wang et al., 2021); these design advices can be applied to other transit maps with similar issues in colour design, especially for those that contained a larger number of lines and different transit services.

This study furtherly investigated how colours affect a transit map's usability. The results showed that colours had a significant effect on the reading speed of a transit map in less complicated tasks, but the advantage of the redesigned colour system became weaker after the complexity of tasks reached a certain level. In addition, colours do not have an observable effect on a transit map's information-searching accuracy. Both findings furtherly supplemented Netzel et al.'s (2016) study that when searching for lines, users prefer to focus on colour in simpler tasks and focus on text when the difficulty of the tasks increases. This showed that, apart from colours, typography is also an influential factor in a transit map's usability. Suppose the legibility of a map is not improved after changing the colour system. In that case, the poor legibility could be caused by other design elements, such as the macro-layout of lines or visual-symbol design, which needs further investigation.

Overall, this study carried out detailed colour evaluations, colour re-coding, and a colour-usability test of a complex transit network, which considered both functions (colour effectiveness in terms of response time and accuracy) and aesthetics (colour harmony). The study demonstrated how to improve the colour system of a transit map by using information design knowledge. The research findings contribute to the colour design and provide valuable insights about visual design in cartography. More importantly, the evaluation and redesign methods, as well as the colour design rules practised in the experiment can apply to other information design reading materials, especially those that need to display multi-level information or instructions belonging to different categories. In later studies, the new colour system is applied to the map, and more advantages of the new colour system are shown in Experiment III.

5. Experiment III: Examining the effectiveness of different transit line layouts

5.1. Introduction

Based on the researching findings in Test I, the ineffective transit line layout of China's high-speed railway map caused various information searching confusions and slowed down the overall reading speed. In this stage, the empirical design solutions are taken to solve the problem based on both theoretical and practical principles. The research mainly focused on the **macro layout** of the transit lines and various **micro designs** of China's high-speed railway map.

Firstly, literatures about transit line schematic layouts are furtherly reviewed, research focused on the effectiveness of different transit line layouts and common design problems are discussed. The design principles and suggestions summarised in the section provided strong academic and empirical support for the following map improvement design work.

Secondly, after reviewed the important design principles and rules in transit map design, in this stage, various practical rules were implemented in the revision work. The knowledge tested and proved by the researchers from different research backgrounds not only benefited to the revision work, but also enriched the transit map information design guidance which was summarised and supplied at the end of the research project. In this stage, there are three different transit network layouts (the 45° octolinear layout, the 60° octolinear layout and the curvilinear layout) designed based on octilinear and curvilinear design principles.

In the third step, to compare the legibility between the current layout and the three redesigned transit network layouts, a legibility test was conducted mainly focusing on the participants' information searching speed and accuracy. The aim of this test is to find out which layout achieves the faster reading speed and the higher information searching accuracy among users, which considered to be the best transit line layout for China' high-speed railway map. In addition, the design quality of various micro design revisions was evaluated as well.

The test targeted to explore and answer the following research questions:

1. What is the most effective transit line layout style for China's high-speed railway map based on users' reading speed and information searching accuracy? And why?
2. Are there any differences in users' trip planning performance regards to route choices and route efficiency when using maps with different line layouts?
3. Are there any connections between the line layout effectiveness and users' preference?
4. Is the revised map legend make users feel easier to understand the functions and instructions on the map, especially the interchange system? Are the revised infographics easy to read and understand?

5.2. Transit line schematical layouts

There are many legibility tests to compare the different layouts, especially the performance comparison between octolinear layout and other layouts, such as curvilinearity (Roberts, 2014). In many studies, the **octolinear** layout was the most preferred in linear designs, it also called the **Beck style** layout in some references (Roberts, 2010). Transit maps designed based on the Beck style design principles have been proved effective in legibility in many eye-tracking tests, they also received positive feedback from the public (Burch et al., 2014; Burch, 2016; Burch, Kumar and Mueller, 2018). In Grison's (2019) study, participants were asked to rate the different design examples of schematic maps, results show that for usability the octolinear map was the one with the better rate, followed by the multilinear one and then the curvilinear one. The stylised map was the one with the higher rate followed by the geographical one and then the compact one. Participants judge the octolinear map as the more attractive one followed by the curvilinear and then the multilinear one.

It is a persistent suggestion that the layout using octolinear angles is more likely to achieve the criteria for effective schematic map design, many designers believed in this and used it without consideration, there are many good design examples been created, but most of them are the result of directly applying Beck's rule (Roberts, 2012; Roberts et al., 2013). Ovenden (2005) even mentioned that octolinearity can always result in the most effective design no matter what the structure of the network. Nollenburg and Wolff (2011) furtherly emphasised that the main benefit of octolinearity is the layout that consumes less space and user fewer bends while keeping a tidy and schematic appearance, which is a "hard constraint" that could never be broken. That is the reason why octolinear layout is widely used by most transit maps globally, because it is an important factor that makes a transit map easy to read by most users (Nollenburg and Wolff, 2011). As a result, the octolinear layout usually is chosen as the first option when constructing the network of a transportation system, unless it is not compatible with the network structure (Roberts, Gray and Lesnik, 2017). For such a ready-to-use ‘successful and time-tested' rule, many designers simply believed that Beck was the most reliable ’golden rule’, and ruled out other options, this has led to the beck rule being abused all over the world, half of the world’s transit maps are designed based on the beck rule (Roberts, 2012).

Even so, there are debates that argued the reason why people think octolinear is the best form for schematic mapping layout simply because of its widely utilise (Merrill,2013; Roberts et.al, 2013). Field and Cartwright (2014) mentioned that there could some risks of overusing Beck design style, when people get used to this design and rely on it, this could limit other plans to be created and accepted, which lead to limitations of the map usability. Cheng (2014) also mentioned that the ubiquity of Beck style maps poses a challenge to the invention of new fundamental formats simply because their sheer familiarity inhibits one’s imagination. Beck style may not the best choice for all maps, Mijksenaar and Vroman (1983) analysed the legibility of eight maps designed according to Beck’s design principles, the legibility was different among different maps, some maps showed that Beck style has limitations in the layout of transit networks, straight lines with fixed angles may lead to a rigid and complicated layout in some busy areas.

There were studies that compared the effects of macro layouts of the same railway network by using distinct layout schemes (Roberts, Gray and Lesnik, 2017; Roberts et al., 2003; Roberts and Vaeng, 2016). The researchers questioned the belief among many designers and users that Beck’s rule is the **gold standard** in network schematisation via usability tests, the result showed that Beck style octolinear layout was not the most effective scheme in all cases, other schemes such as **curvilinearity** showed better performance than octolinearity in some usability tests (Roberts, Gray and Lesnik, 2017; Roberts et al., 2003; Roberts and Vaeng, 2016). Roberts (2012) suggested that Beck’s rule seems well-suited for small or medium size transit networks, the rule can simplify the line trajectories and make the network looks compact. However, with the complexity of the network increases, Beck’s rule could not match the trajectories and angles of the network, this may create even more complicated trajectories that unable to achieve the purpose of simplifying the routes. Beck’s rule served its purpose that creating a simplified, easy-to-understand transit map for the winding London Underground lines, but some breaks of Beck’s rule could be better for producing more effective and attractive maps of many other complicated transit networks all over the world (Roberts, 2012).

Moreover, Roberts (2011, 2012, 2014) did numerous research about **curvilinear** maps and their user evaluation. A representative user test that compared the octolinear and curvilinear maps of the Paris underground system (Roberts, Gray and Lesnik, 2014) showed the less efficiency of octolinearity on route planning and time than curvilinearity, the octolinearity's leader position of transit line layout is challenged, it may not be suitable for some areas (country or city) due to the reason of the diversity of topographic environments, individual differences need to be concerned. An interesting finding investigated by Grison (2019) showed that German participants rate the curvilinear map better than people from the USA and Canada, this shows some individual differences between users from different areas.

In addition, Roberts, Gray and Lesnik (2017) suggested that when octollinearity is not the most appropriate plan for a particular transit network, such as, the network has properties that make octolinear layouts struggle to achieve the criteria mentioned previously: simplicity, coherence, harmony, balance, and topographicity. Then the curvilinear layout may be the most preferred plan among users, which can be priorly implemented after octolinearity (Roberts, Gray and Lesnik, 2017). This suggestion is also supported by Silvia and Barona (2009), they found that the high attractiveness for a curvilinear layout shows an intrinsic preference among users that curved shapes make them feel more coherence rather than the awkwardly angled shapes, e.g., multilinear design hardly achieving coherence, which may make users feeling disconcerted. In strict, the curvilinearity avoids using straight lines, S-bends and other points of inflections, compare with octolinearity, the curvilinear layout can connect the dense, intertwined and chaotic transit lines better (Roberts, 2012). Although the octolinear layout may be considered as the best choice for most transit maps, it still shows the need for exploring new design principles to enrich Beck style layout, even beyond it (Cheng, 2014). These findings showed that octolinearity may not the most effective design for all transit networks, no doubt it will explore the design possibilities of layout rules for different networks.

Although researchers focused on the global layout of the transit map failed to show that octolinearity is superior to other layouts, but Roberts, Newton and Canals (2016) found that the octolinear map of the Berlin conventional system has better usability than another design version based on concentric circles and spokes in all aspects (Figure 5.1). The **concentric circles** and spokes map lead to various inefficient route plans and received poor feedback from users. The main reason is that the concentric circle layout made the routes difficult to compare, users found it difficult to make comparisons between route plans and choose the best one. This study showed that concentric circles and spokes layout is not an effective choice for the macro layout of a transportation network. If comparing the transit map layouts of big cities all over the world, there are very few cases using concentric circles and spokes, such as Amsterdam and Cologne, because the concentric circles and spokes layout matches both cities' structure that may cause fewer route plan difficulties (Roberts, Newton and Canals, 2016).

Figure 5.1: Berlin U-Bahn and S-Bahn networks (concentric-circles-and-spokes design and octolinear design)

Apart from the macro layout, the effects of the micro layout cannot be ignored as well. There are many researchers investigated how micro layout affects user's performance, especially focused on choices of routes (Guo, 2011; Morgagni and Grison, 2019; Raveau, Guo and Munoz, 2012; Raveau, Muñoz and Grange, 2011; Roberts et al., 2013; Roberts and Rose, 2016; Xu, 2017, Guo et al., 2017). Relevant research methods to find out how micro layout affected users' route choices are various, Roberts and Rose (2016) observed how participants organising routes on their own, Guo et al (2017) provided various pre-determined routes and see how participants choose between them. All these experimental tests emphasised that micro layout can largely affect user's route choices, users preferred the routes with the fewest interchanges and shortest travel distance (the visual distance on the map), more details regards to micro layouts findings are summarised as follows:

Route complexity: routes with fewer bends are preferred compared with routes with more bends (Roberts et al., 2013).

Direction to the destination: users preferred to choose routes that pointed directly towards the destination from the starting point, routes pointed away are less likely to be chosen (Raveau, Guo and Munoz, 2011).

Interchange positions: users preferred to choose a route with a later interchange than an earlier interchange, even the travel distance is longer (Roberts and Rose, 2016).

Guo et al. (2017) investigated how changes in micro layout affect users' route choices that improved the overcrowding traffic problem of the Washington underground. An overcrowded direct route on the map with no interchanges preferred by users has been extended and twisted, which made the route looks long and less direct. This small change in micro layout successfully shifting users' preference to another less crowded route that contains one interchange, which relived the overcrowding traffic problem. Furthermore, Xu (2017) found that such a method only works on new users who are not familiar with the transit system, frequent users are harder to change their route choices as they preferred to choose routes based on their experience. This indicates that although micro layout changes can affect users' route choices, but this method could only be effective for certain groups, users' individual differences need to be investigated before taking a design solution.

No matter which layout standard is selected, simplifying the trajectories is always the priority work to reduce the number of changes in direction, this can help to minimise visual disruption when users tracing lines. Some transit lines with irregular topographic shapes can be simplified into regular geometrics, such as a circular route can be simplified as a circle, symbolic shapes can increase the visual legibility of the entire network (Roberts, 2019). It is common to see that multiple lines share consecutive stations, there are two main layouts for this in modern transit map design. Bundling multiple lines without gaps in between to show their neighbourhood connections, or spacing adjacent lines to emphasis their separateness. The layout of co-routed lines can be adjusted according to their directions apart from co-routed areas, colours are also helpful to make each line distinct in the co-routed area. However, as Robers (2014) mentioned, schematical simplification of transit lines is in conflict with preserving the topographic representations, it is necessary to find out the compromise between both considerations (Wu et al., 2020).

Roberts, Gray and Lesnik (2017) suggested to avoid using S-bends and other points of inflection in transit line layout where possible, because the prior design aim for an individual transit line is to minimise the number of control points, this can help to maintain interchanges and leave sufficient space for station names. Moreover, it is appropriate to use tangents to represent control points, the cusps need to be avoided. Many world's successful design examples showed the trajectories of all lines smoothed, this design solution can help to simplify the design and to emphasise the underlying structure of the network, reducing the expected cognitive load of using it in comparison (Roberts, Gray and Lesnik, 2017).

When designing the transit system layout, it is always good to minimise the transit line crossings. But research about transit line layout algorithmics found this work may be contracted to the topology if the map needs to preserve it (Avelar, S. and Müller, 2000). In addition, in order to create more space to accommodate the labels, some approaches like stretching edges or bending the corners can be done but remember not to break the layout style. E.g., a very dense octolinear layout transforms into another octolinear layout contains more space for labels by adjusting the length and bends of lines (Anand et al., 2007). According to Avelar (2006), overlapping lines are better to be separated by a minimum legible distance, even no distance in order to create more space for labelling. The smooth and artistic circular arcs can use around bends on adjacent transit lines, but preserving their graphic proximity distance for the most suitable length as possible, the kinks with gentle curves are less disruptive to eyes than the sharp bends (Roberts, 2012). Some small number of breaks or adjustments in line directions can be added if necessary, it can help to enhance visualization and geometry. These works are commonly needed when expanding the scale of the central area, there is a larger number of stations and complicated connections of lines, the larger scale is needed to accommodate all lines and stations, as well as the labels of station names and other relevant information.

There are some **common problems** in the transit line layout, they are misalignment, overlap, and acute bend. This happened when the schematical work is not sufficient to show the topology of lines and accommodate stations appropriately (Sadahiro et al., 2015).

- Misalignment refers to the disagreement of the actual routes and transit lines on the map.
- Overlap refers to the crossing of transit lines that do not actually overlap.
- Acute bend is the bend of transit routes at an acute angle. Acute bends can easily clutter the transit system and mislead users especially when routes are running in parallel (Agrawala and Stolte 2001; Nöllenburg and Wolff, 2006; Moghadam 2013).

There are two other problems relevant to the minimisation of transit line crossing, they are gap and shift (Stott et al., 2011).

- Gap refers to the space between transit lines that running on the same route. The large gaps are not suitable in design, because they can decrease the limited space on the map which required to accommodate all lines.
- Shift refers to a partial translation in direction of transit lines, a large number of shifts can increase the visual complexity and decrease the straightness of lines, which may lead to reading difficulties and searching errors.

Most issues mentioned above were observed from the current map and they are revised in the following process (Chapter 7).

5.3. Revision work of the transit lines

5.3.1. Main transit line design limitations

In both scoping test and the eye-tracking test, the limitations in the transit line layout constantly led to ineffective reading and various errors in users' information searching process. Three main issues were identified in both tests: 1. Lines overlapped with each other, this made users misunderstood that they could transfer between them at the intersected area. 2. the bend of routes at an acute angle made users felt confused if that is a stop or a transfer point at the place. 3. Lines are irregularly curved and disorderly located, this limitation forced the users to spend more time when tracing the lines, especially wasted time when tracing the unnecessary and confusing curves, various information searching and route planning mistakes were made in this process. More details about the three main design limitations are shown in Figure 5.2, these problems are all common design limitations in map design that can weaken the legibility of a transit map (Agrawala and Stolte, 2001; Marcus, 2016; Sadahiro et al., 2015). These problems are mainly caused by the fact that the designer tried to reserve the actual topography as possible and did not sufficiently distort the lines when necessary. Although the trajectories of the lines showed some characters of the octolinearity's required angles, but the shapes of lines did not fulfil the simplicity principles in schematic design, which is more like a multilinear layout and caused the unsatisfied performance in the previous tests (Wang, Lonsdale and Cheung, 2021). Because of this, the participants in both scoping test and eye-tracking test advised the researcher to revise the layout of the transit lines that makes them more schematical and clearer on the map.

Figure 5.2: The three main transit line layout design problems that identified from the previous tests

In order to solve these design limitations of the network layout, the transit lines of China's high-speed railway map should be revised according to the transit map design principles. As previously mentioned, the Linear layout, Curvilinear layout and Concentric layout are the three most common layouts in modern transit map design (Wu et al., 2020). The Linear layout mainly includes octolinear layout, hexalinear layout and tetralinear layout. The octolinear layout is the most commonly used layout in contemporary transit maps globally, although many researchers discussed that the curvilinear layout may perform better in some maps than the octolinear plan, but the octolinearity is still the most commonly used layout all over the world (Roberts, Gray and Lesnik, 2017; Roberts et al., 2003; Roberts and Vaeng, 2016). The curvilinear layout is considered as an alternative plan when the octolinearity does not fit the typography of the lines (Roberts, Gray and Lesnik, 2017), which is selected in the revision plan to tests its effectiveness. The rest two plans of the linear layout are hexalinear layout and tetralinear layout, the hexalinear layout provides 60° angle lines with 6 directions, and tetralinear layout provides 90° angle lines with 4 directions (Roberts, Gray and Lesnik, 2017), which may not be suitable for the complicated networks, because there is a large number of transit lines from different directions on the map, many of them are connected to each other. The octolinear layout can provide 45° angle lines with 8 directions, which is more flexible when constructing the lines compared with both hexalinear and tetralinear layouts. However, Roberts (2009) questioned this Beck's layout rule, the author provided evidence that 45° may not be suitable for all topographies, other angles such as 60° diagonal serves well in some successful design examples. Moreover, the concentric layout is proved to be an inefficient layout plan for most maps, its concentric circles and spokes made users found it difficult to compare the routes, which caused various inefficient route plans (Newton and Canals, 2016; Roberts, Newton and

Canals, 2016). Based on this, the concentric layout is not chosen to re-construct the transit lines in the research.

As mentioned, in most cases, the octolinear layout is selected as the first option when constructing the network of a transit system, because it is more likely to achieve the requirement of an effective transit map (Roberts et al., 2013). If the octolinear layout is not compatible with the topography of the network, then the curvilinear layout is more likely to be the most preferred plan among users, it can be selected as the second prior plan (Gray and Lesnik, 2017; Silvia and Barona, 2009). Therefore, the octolinear layout and the curvilinear layout are selected to re-construct China's high-speed railway lines. In octolinear design, both 45° (Beck's rule) and 60° are designed and tested to see which angle suits the topography better.

The topography of China's high-speed railway system (Figure 5.3) is mainly located in the north-east to the south of China, so the north-south rectangular layout of the existing map has remained.

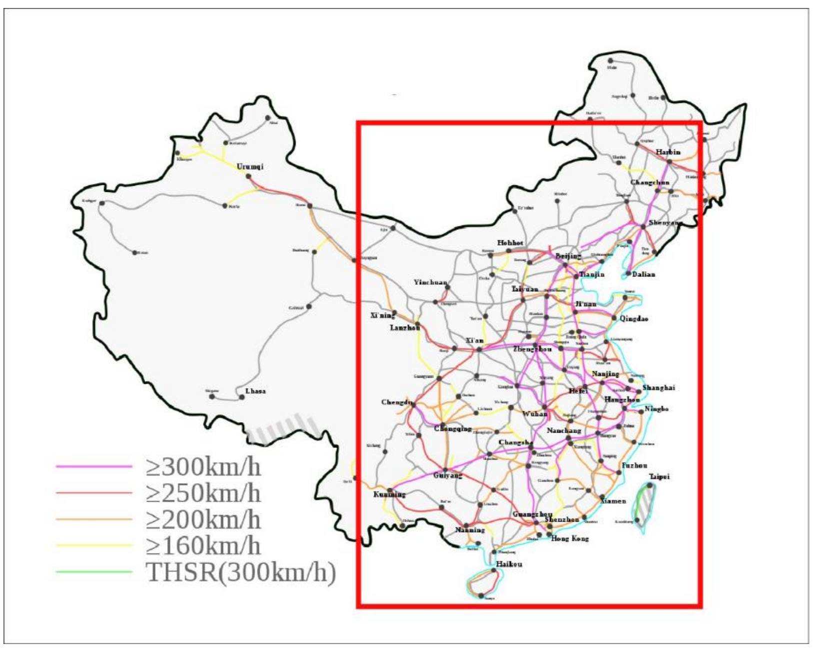


Figure 5.3: China's high-speed railway system

In addition, the revised colour system established in the previous study is applied in the revised maps.

5.3.2. The octolinear plan (45° and 60° angles)

The most representative character of an octolinear layout transit map is the four equally spaced angles for the alignment of lines, they are horizontal (0°), vertical (90°), and two diagonals (45° and 135°), all the lines in the transit network should be accommodated based on this rule when designing an octolinear map, this also known as Beck's Rule (Nollenbur and Wolff, 2011; Roberts, 2012; Wu et al., 2020). In this project, the Beck's rule is broken, another plan with horizontal (0°), vertical (90°), and two diagonals (60° and 120°) is designed to suit a north-south layout of the China's high-speed railway system, which is considered as a hexalinear layout but allows vertical lines, breaking the 45° rule may result in a better network that fits the topography well (Roberts, 2009; Roberts, 2012).

During this process in the revision work, the width of the lines was kept the same as the existing map, some curved topographic lines in the existing map are straightened, and numerous changeable trajectories are simplified as well, because the schematisation and simplification of the lines overweighed their geographical accuracy (Hochmair, 2009; Larkin and Simon, 1987; Mollerup, 2015). The topography of the existing map is reserved as possible, especially the directions of the lines are basically remained the same as their topographic directions, this solution can avoid potential risks that users confusing the directions in route plan. Taking the six lines' intersected area between Nanjing and Shanghai as an example (Figure 5.4), the revised layout simplified the shapes of lines based on the octolinearity design principle, and the directions of the lines have basically remained, which keeps a good balance between the line simplification and the map typography. In addition, station names are horizontally displayed on both octolinear maps compared with the existing map.

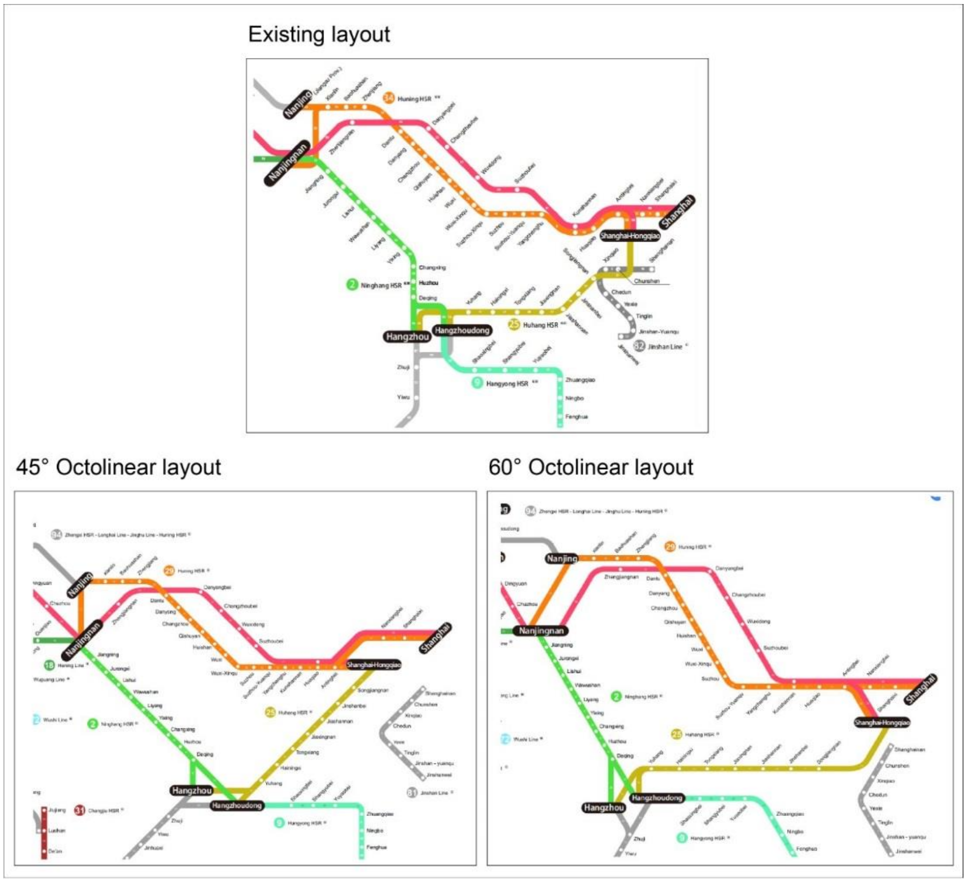


Figure 5.4: The six lines' intersected area between Nanjing and Shanghai (comparison between the existing layout and the 45° & 60° octolinear layout)

When re-constructing the transit network on the existing map, the most important and time-consuming work was to straighten the irregularly shaped geographical accurate lines, which is also advised by participants in the previous tests. At the same time, the misalignment, overlap, and acute bend problems on the existing map are revised accordingly as well. These actions can largely enhance the legibility of the map and reduce the possibility that users get lost in the network when searching for information (Garland, 1994; Roberts, 2012; Sadahiro et al., 2015).

The central area of the map caused many route planning errors in the previous tests, there are more than six lines located in this small area, the complicated trajectories made the network crowded, many lines overlapped with each other, and this area is also a good example to show the differences between the existing layout and the octolinear layouts (Figure 5.5). In order to display the lines schematically, the first work was to expand the central area and enlarged the distances between the four main stations, this helps to provide larger space to accommodate more lines and stations (Roberts and Rose, 2016). Secondly, the trajectories of the lines are reduced as possible to decrease the changes in direction, this can minimise visual disruption when users tracing lines (Roberts, 2019). The S-bends and other points of inflection in the existing map are avoided in the revised layouts to achieve better legibility (Gray and Lesnik, 2017). In addition, the distances between different lines are enlarged to emphasise their separateness, otherwise, the users may think there are neighbourhood connections between the lines if they located too close (Wu et al., 2020). Apart from the adjustment in space and line simplification, the transit line crossings are minimised as possible (Avelar, S. and Müller, 2000), the overlapping problems are basically resolved in this stage. Details of these revisions are showing on Figure 5.5.

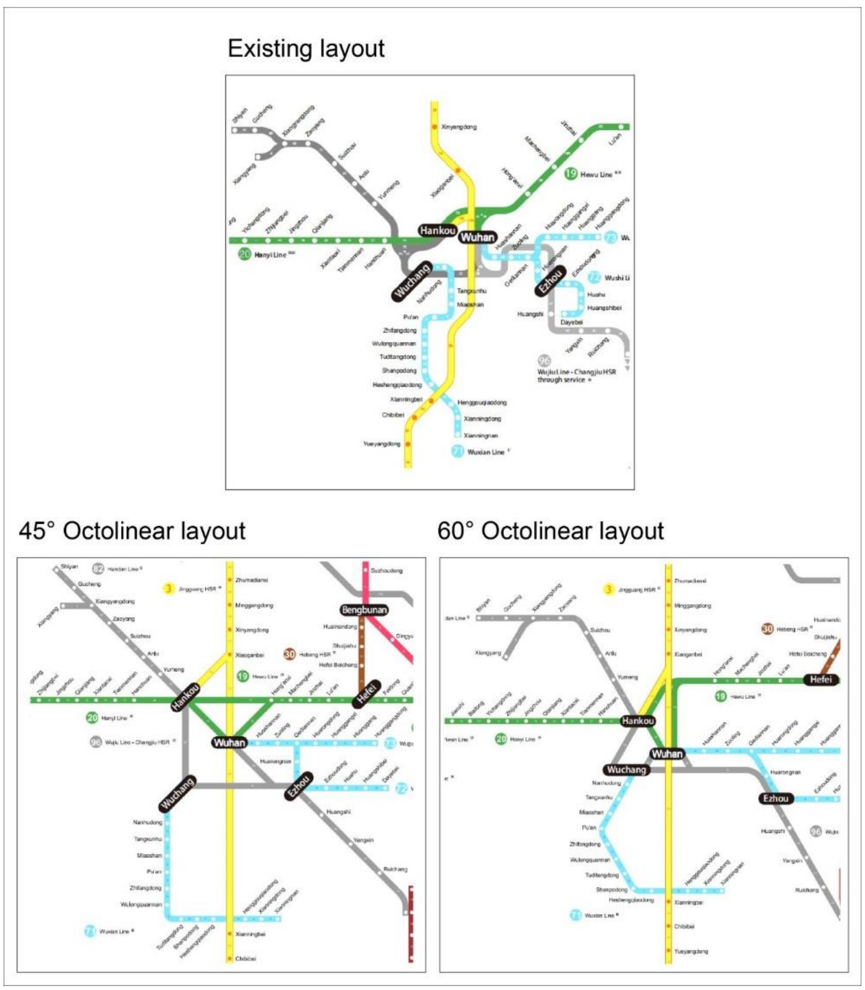


Figure 5.5: The central area of the map (comparison between the existing layout and the 45° & 60° octolinear layouts)

Overall, the 27 transit lines on the map are re-constructed according to the octolinear layout rules, the design limitations of the line layout identified in the previous tests are revised according to the design principles, as well as the users' advice. Compared both octilinear layouts (45° & 60°) and the existing layout (Figure 5.6), the major change is that the octolinear maps reorganised the space between lines and made various simplification design solutions to make the lines more straight with fewer trajectories. During this process, the topography of the existing map and the directions of the lines are preserved as possible. Compared with both octolinear maps, the 60° octolinear seems more suitable and balanced for such a north-south topography, the 60° angles resulted in longer trajectories, which provided more space for station names, and this change made some areas are less crowded than the 45° octolinear map. However, this hypothesis needs to be tested in the next stage.

Overall, this section mainly focused on the macro layout of the network, more details about the micro changes are described in Section 7.4.

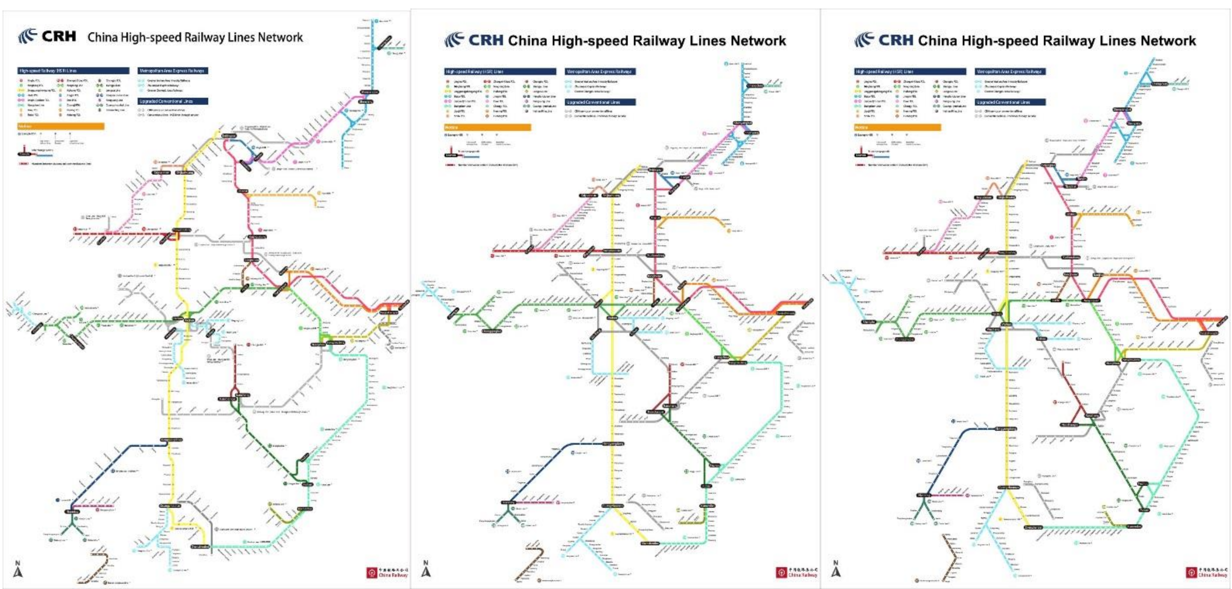


Figure 5.6: The existing map (left), the 45° octolinear map (middle) and the 60° octolinear map (right)

5.3.3. The curvilinear plan

As discussed in the previous design principles, the curvilinear layout of the lines may show better performance than octolinearity in some design cases (Roberts, Gray and Lesnik, 2017; Roberts et al., 2003; Roberts and Vaeng, 2016). The curvilinear layout also shows a higher **attraction** in some tests, and it has been recommended as the second prior plan for transit map design after the octolinear layout (Roberts, Gray and Lesnik, 2017; Silvia and Barona, 2009). In this stage, a curvilinear example is designed in order to test its legibility and make comparisons with the existing layout and the octolinear layouts (45° and 60°).

In most cases, the curvilinear layout displays the transit lines via smooth curves, Bezier curves and circular arcs (Roberts, Gray and Lesnik, 2017; Wu et al., 2020). Some irregular shapes of the lines on the existing map are simplified into regular geometrics, because the symbolic shapes are helpful to enhance the legibility of the network (Roberts, 2019). Such as the four lines around Hangzhou and Hangzhoudong stations (Figure 5.7), the various acute bends of the lines on the existing map are simplified into curves and circles, which also reduced the number of the overlappings.

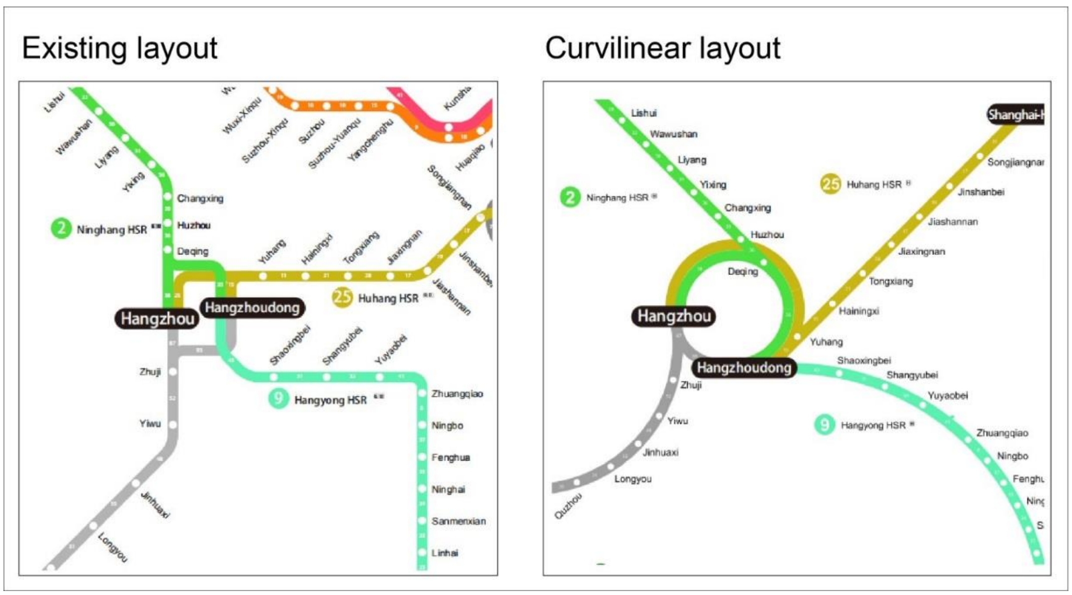


Figure 5.7: The lines around Hangzhou and Hangzhounan (comparison between the existing layout and the curvilinear layout)

In addition, some transit lines are still kept straight to maintain the structure of the whole system, and also avoided the unnecessary curved waves. As Roberts (2009) mentioned that only the lines on the map changing directions back and forth, and interchanging with other lines may need an all-curves design solution.

Similar to the octolinear layout, the typography and directions of the lines were also preserved in curvilinear layout as possible, the shapes of curves were constructed based on both factors. Some edges and corners were stretched or bent in order to make larger space to accommodate the labels, but these changes did not break the overall layout style (Anand et al., 2007). In addition, the smooth and artistic circular arcs are used around bends on adjacent transit lines and kept the suitable distances between different lines to show their separateness (Roberts, Gray and Lesnik, 2017). The north-east area on the map is a good example of these changes (Figure 5.8), the irregular railway line curves and the edges were replaced by smooth circular arcs, and the shapes of lines were stretched to accommodate the station labels horizontally, because the horizontal layout applies to people's daily reading habit (Ovenden, 2003; Ovenden, 2015; Roberts, 2019). In addition, the busy interchange lines were represented by circles, this helped to avoid the design limitation that busy lines overlapped on each other.

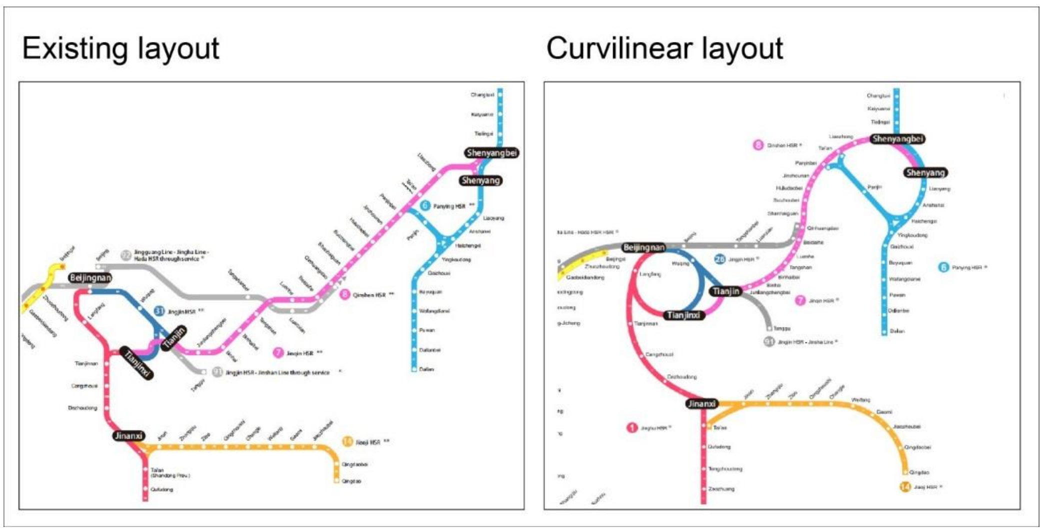


Figure 5.8: The North-east area on the map (comparison between the existing layout and the curvilinear layout)

Overall, compared with the existing layout, the curvilinear layout shows distinctive differences in distortion and line shapes (Figure 5.9). By using the curves and circular arcs, the shapes of the lines are distorted to enhance the aesthetics of the network. The angles of the line curves were keeping consistency, few straight lines were preserved for the purposes of simplicity and balance in layout. In addition, although the overall topography of the existing map is preserved, but some small changes in line directions were made in order to expand the distances between adjacent lines, which helped to avoid overlapping problems as well (Avelar and Hurni, 2006; Stott et al., 2011).

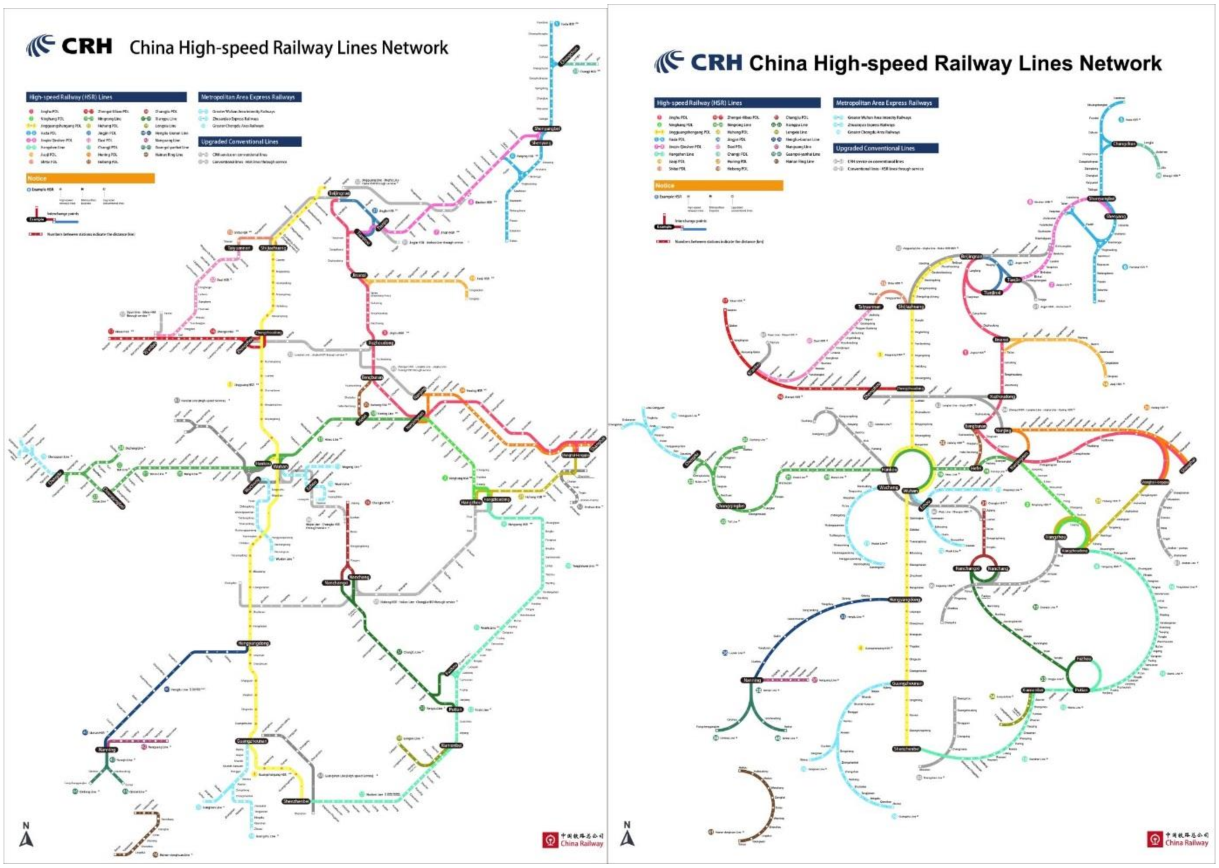


Figure 5.9: The existing map (left) and the curvilinear map (right)

5.3.4. Other micro design considerations

For the macro layout of the lines on a transit map, some micro design includes the station labels, texts, interchanges, the map legend and other information design elements are also important components that affect the legibility of the map. In the revision work, some tiny changes were made based on the design principles and the advice from participants.

In the previous tests, there were no particular problems found regards to the font or size of the station labels and texts, only a few participants found that it is difficult to read the labels if they were not horizontally displayed. Due to this, the revised maps kept using the same label design style and consistent fonts (Figure 5.10) to display the popular stations (white text on the black block, 14pt bold Arial font) and the common stops (black text, 9pt bold Arial font). Figure 5.10 displays the network around Beijing on the existing map and other two revised maps, which is a good example to show changes of the label layout after improved the space between lines and stations. On the existing map, there are many station labels displayed diagonally in order to fit in the limited space, some of them even placed on the different sides of a line (Figure 7.9). By scheming and distorting the shapes of the lines, more labels are allowed to display horizontally, which would be easier to read. More importantly, the labels are placed on the same side of the corresponding line on both revised maps, because a consistent size, side and direction are always recommended in label display (Ovenden, 2015). Moreover, the distances between stations on each line are strictly keeping equal, this can make sure the aligned station points are well-organised on the lines, and the distances between stations on different lines can be adjusted depends on the space limitation or other layout considerations (Degani, 2013; Guo, 2011; Lloyd, 2017).

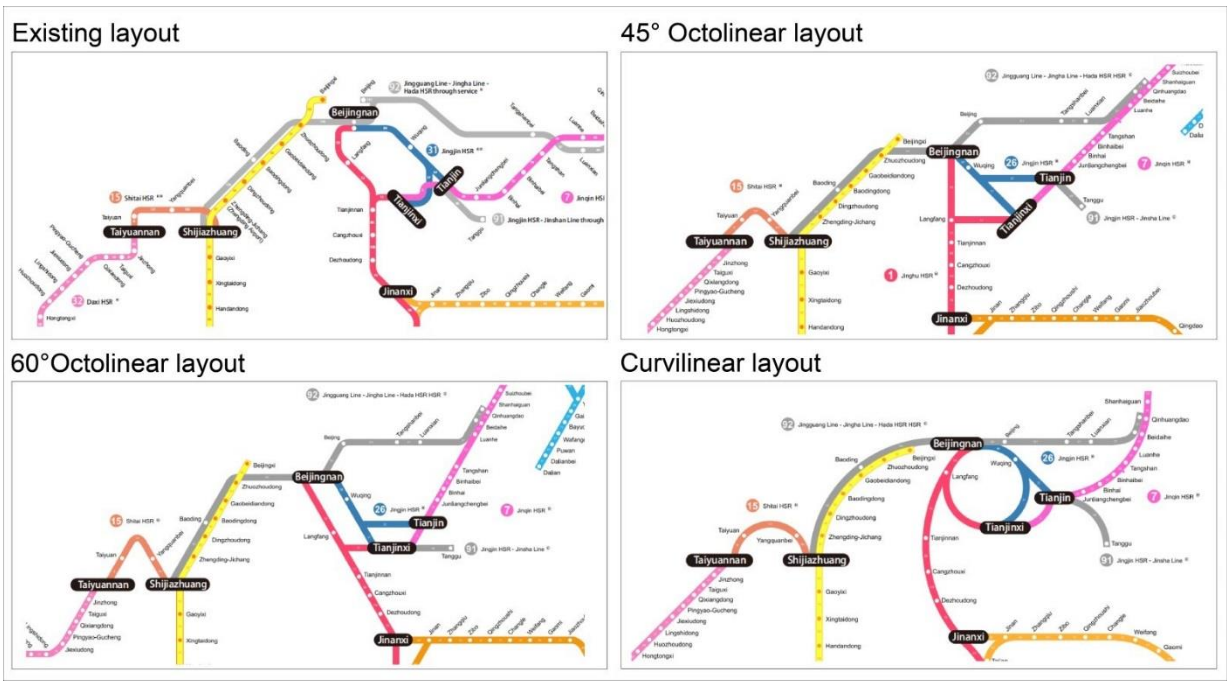


Figure 5.10: The high-speed railway network around Beijing (comparison between the existing layout, the 45° & 60° octolinear layouts and the curvilinear layout)

The **interchanges** on a transit map should be taken into consideration as well, because they can affect users' route plan process and accuracy. According to the result in the previous tests, most participants were able to understand the visual design of interchanges on the existing map, which indicated that the **overlapped** (popular interchanges) and **semi-overlapped** (common interchanges) designs of interchanges on the existing map are clear and understandable. Both interchange design examples are also commonly used globally, but less famous than Beck's "white-line connector" notation (Bain, 2011; Wu et al., 2020). However, some participants mentioned that they felt a bit unconfident to transfer between lines because there are no instructions to show which situation the lines can be transferred between each other. This problem refers to the design limitations of the map legend on the existing map (Figure 5.11). In the revised map legend, a new category "Notice" is added to show more details of the map, includes the interchange instructional examples (Figure 5.12). In addition, other necessary information and instructions were transformed from sentences to visual design examples, such as the visual examples to show the numbers between stops represent kilometres. This applied to the participants' advice that using signs to demonstrate the necessary instructions and functions of the map, rather than the long descriptions in the existing map legend.

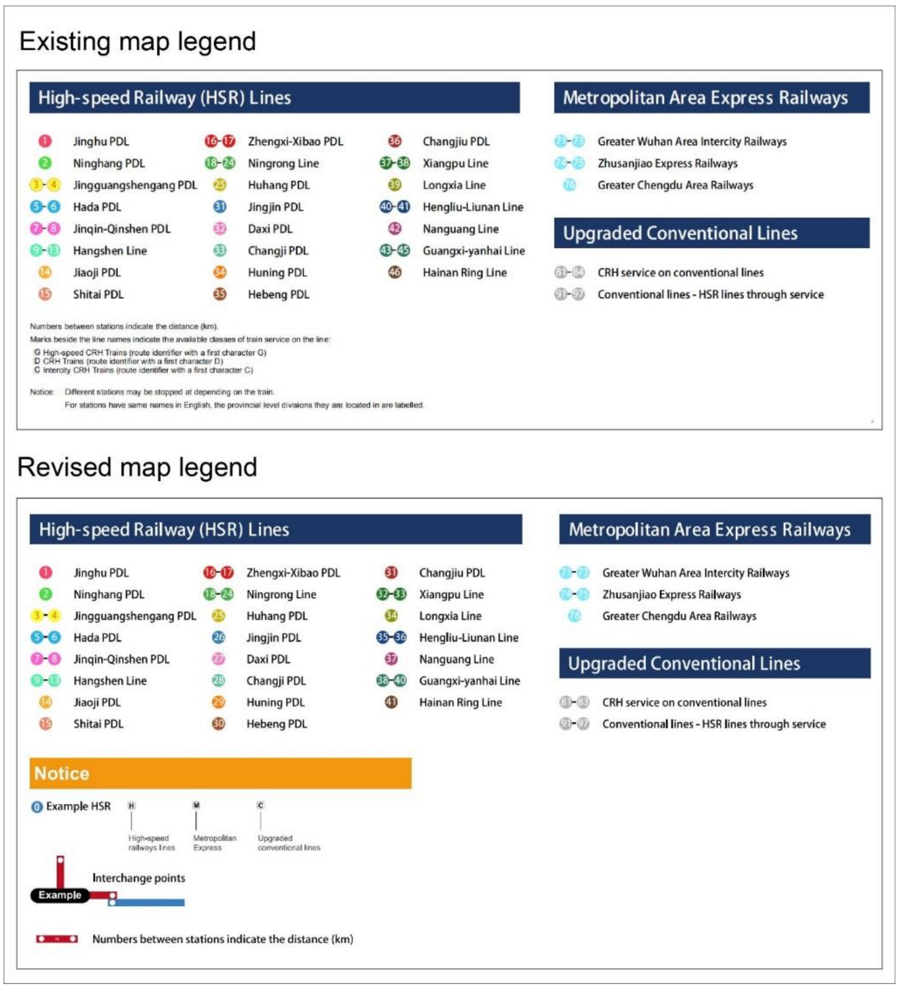


Figure 5.11: The existing map legend and the revised map legend

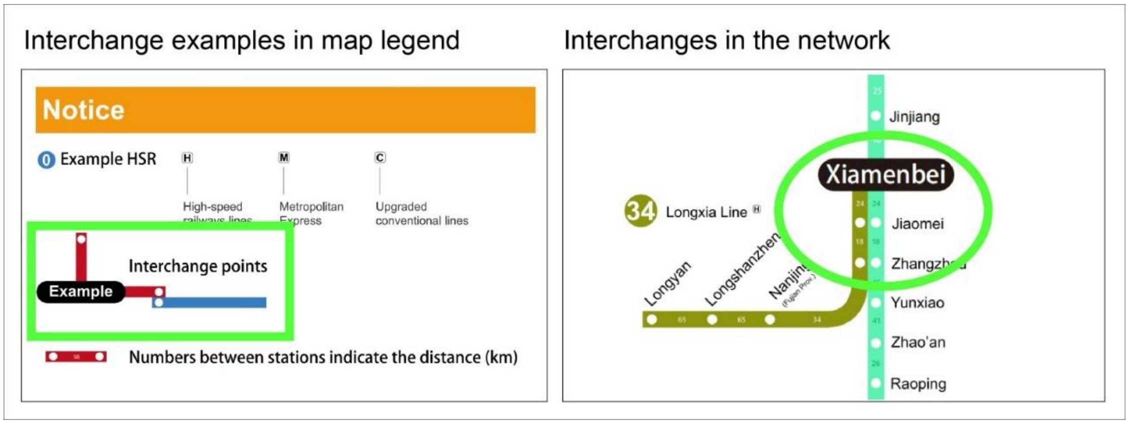


Figure 5.12: The interchange examples in map legend and the interchanges in the network

In addition, it is necessary to mention that all these micro revisions were applied to all four layout examples includes the existing layout, because it is necessary to make sure that the design criteria of the three tested maps keeping the same. In addition, some tasks and questions were set to test the design quality of the micro designs.

5.4. Test process and research methods

5.4.1. Participant recruitment

There were total of 40 non-Chinese participants attended the test, all of them were asked several questions before the test to confirm that none of them had advanced knowledge of Chinese geography, because the objectivity of the test result could be affected that the participant who has relevant knowledge may find information on the map quicker than others. More than half of the participants come from the U.K. (23, 57.5%), the rest of them mainly come from the U.S., Australia, India, Romania, Bulgaria, India, Japan and South Korea.

Although the gender difference is not investigated in the research, but the number of male and female participants still kept the same (20 male participants and 20 female participants). The average age of the participants is 26.6, which applies to the major age group (20-30 years old) of international tourists travelled in recent years from 2015 to 2019 (the data of international travellers in 2020 is not representative due to the reason of the global epidemic).

In addition, before the usability test, every participant needed to pass an Ishihara test (Ishihara, 2018), they were all deemed to have normal colour vision.

5.4.2. Test environment, procedure and materials

In the test, participants needed to complete a total of ten information-searching or route-planning tasks and a questionnaire (Table 5.1) on a computer with a screen resolution of 1920 x 1280 pixels. This screen setting is the same as the screens used in China's railway stations to display maps and relevant travel information. Participants sat in front of the screen at about an 80 cm distance and used a mouse to point out target information. Participants' response time and information-searching accuracy for each task were recorded. In addition, when participants gave feedbacks or answered questions, the keywords of their words were noted as well.

To increase the validity and reliability of the findings, other analysis methods, such as SPSS calculation, were used. In order to make sure that different groups of data were normally distributed, detailed data-distribution analysis, including histogram, was conducted. Moreover, the paired sample t-test was used to make clear comparisons between variables.

5.4.3. Task settings

In the test, there were total of 9 tasks and a questionnaire need each participant to finish. Task A is a transit line identification task, participants need to find out the target lines by using the map legend, this task aims to test the legibility of the improved map legend. Tasks B1 to B7 are trip-planning tasks, similar to the previous colour effectiveness test, the difficulty levels of the seven tasks are increased from B1 (involves 2 destinations and 1 interchange) to Task B7 (involves 7 destinations and 18 interchanges), this aims to find out which layout is the most effective depends on users' trip-planning speed and accuracy. Considered the objectivity of the test, the four testing maps were randomly shown to each participant, participants needed to demonstrate the trips by pointing out all the interchange points and lines correctly, any mistakes such as transferring to the wrong place or planning impossible routes were recorded. After all these tasks, participants needed to finish a questionnaire, this aims to collect participants' feedback on the three tested layouts and various revised visual designs. Participants should finish all the tasks without assistance, and some questions may be asked during the test. For example, when the participant spent a long time searching for information in a certain place, he/she would be asked what element caused confusions after the task finished, this helps to understand the user performance and figure out potential design limitations. More details regarding to the specific instructions and the required information searching targets are listed in Table 5.1.

<table>
<tr><th>Task</th><th>Instructions</th><th>Required targets</th><th>Difficulties</th></tr>
<tr><td>A</td><td>Find out 4 transit lines by using the map legend</td><td>8</td><td>N/A</td></tr>
<tr><td>B1</td><td>Plan a trip that includes 2 destinations and 1 interchange</td><td>4</td><td>Easy</td></tr>
<tr><td>B2</td><td>Plan a trip that includes 2 destinations and 2 interchanges</td><td>6</td><td rowspan="6">↓
Medium
↓
Difficult</td></tr>
<tr><td>B3</td><td>Plan a trip that includes 2 destinations and 3 interchanges</td><td>8</td></tr>
<tr><td>B4</td><td>Plan a trip that includes 3 destinations and 5 interchanges</td><td>13</td></tr>
<tr><td>B5</td><td>Plan a trip that includes 4 destinations and 7 interchanges</td><td>18-20</td></tr>
<tr><td>B6</td><td>Plan a trip that includes 5 destinations and 12 interchanges</td><td>28-30</td></tr>
<tr><td>B7</td><td>Plan a trip that includes 7 destinations and 18 interchanges</td><td>42-45</td></tr>
<tr><td>C</td><td>Questionnaire</td><td>N/A</td><td>N/A</td></tr>
</table>

Table 5.1: the test process

In addition, in each route planning task, there are four different routes at the same difficulty level for the four tested maps, the orders of these routes are changed in turn to make sure that each route can be tested on the four layouts. Taking Task B4 as an example (Table 5.2), the four routes that need participants to plan on the map are at the same difficulty level, each of them contains 3 destinations and 5 interchanges. P1, P2, P3 and P4 in Figure represent four participants, the routes they needed to plan in Task B4 are different to each other, then other participants repeated the same process, and so on, the order of the four routes changed in turn to make sure that each route is tested on all the four layouts for 10 times. This method makes it possible to compare the effectiveness of the four different layouts when participants planning the same route.

1 Dazhou - Gongqingcheng - Longyan
2 Qingdao - Yiwu - Huangshi
3 Beijingxi - Dali - Lushan
4 Qishan - Hefei - Nanchangxi

	P1	P2	P3	P4
Existing map	1	4	3	2
45° Octolinear map	2	1	4	3
60° Octolinear map	3	2	1	4
Curvilinear map	4	3	2	1

Table 5.2: example of Task B4

5.5. Test results

5.5.1. The reading speeds of the different layouts

The participants' time consumption in all eight information searching and trip planning tasks is shown in Figure 5.14, the box plot makes comparisons of time consumption between the existing map (blue box), the 45° octolinear map (green box), 60° octolinear map (yellow box) and the curvilinear map (red box), the mean values, maximum values and minimum values are emphasised. Overall, the result showed that participants spent less time in all tasks when using the 60° octolinear map rather than the existing map, 45° octolinear map and the curvilinear map.

Task A was a transit line finding task that participants needed to find out four target lines from the map by using the map legend, the participants were slightly quicker when using the 60° octolinear map (M=103s, SD=15.42) than the existing map (M=117s, SD=16.18), the 45° octolinear map (M=106s, SD=14.2) and the curvilinear map (M=112s, SD=15.87).

Task B1 to B7 were trip planning tasks, participants needed to plan trips between certain destinations on the map. With the difficulty level of the tasks increased from a trip including two destinations and one interchange (Task B1) to a trip including seven destinations and more than fifteen interchanges (Task B7), participants' time consumption consistently increased. Overall, participants spent less time when using the 60° octolinear map compared with the existing map, the 45° octolinear map and the curvilinear map.

At the very beginning of Task B1, the difference in average time spent on the four tested maps was not significant (M_{eB1}=33s, $M_{45°oB1}$=28s, $M_{60°oB1}$=28s M_{cB1}=35s). From Task B2 to Task B4, the differences between the four values gradually increased in line with the increasing difficulty levels, the trend that participants spent less time when using the 60° octolinear map ($M_{60°oB2}$=33s, $M_{60°oB3}$=59s, $M_{60°oB4}$=68s) than the existing map (M_{cB2}=45s, M_{cB3}=73s, M_{cB4}=103s), the 45° octolinear map ($M_{45°oB2}$=36s, $M_{45°oB3}$=63s, $M_{45°oB4}$=71s) and the curvilinear map (M_{eB2}=46s, M_{eB3}=80s, M_{eB4}=108s) became obvious. The average time participants spent on tasks when using the curvilinear map was a bit slower than the existing map in Task B1 and Task B2, but from Task 3, the reading speed of the curvilinear map became quicker than the existing map, and this trend constantly got larger afterwards. The gap of the reading speed between the four tested maps evidently increased from Task B5, participants' reading speed when using both the 45° octolinear map ($M_{45°oB5}$=129s) and the 60° octolinear map ($M_{60°oB5}$=118s) was significantly quicker ($p < .05$) than both the existing map (M_{eB5}=225s) and the curvilinear map (M_{cB5}=198s). Similar results also showed in Task B6 (M_{eB6}=575s, $M_{45°oB6}$=361s, $M_{60°oB6}$=329s, M_{cB6}=499s) and Task B7 (M_{eB7}=832s, $M_{45°oB7}$=3583s, $M_{60°oB7}$=564s, M_{cB7}=735s). The reading speed of the 60° octoliner map was a bit quicker than the 45° octolinear map in most tasks, but the time consumption differences between both maps are very tiny ($p > .05$). In addition, although the average reading speed of the curvilinear map was quicker than the existing map from Task B3 to Task B7, but the difference was not significant ($p > .05$).

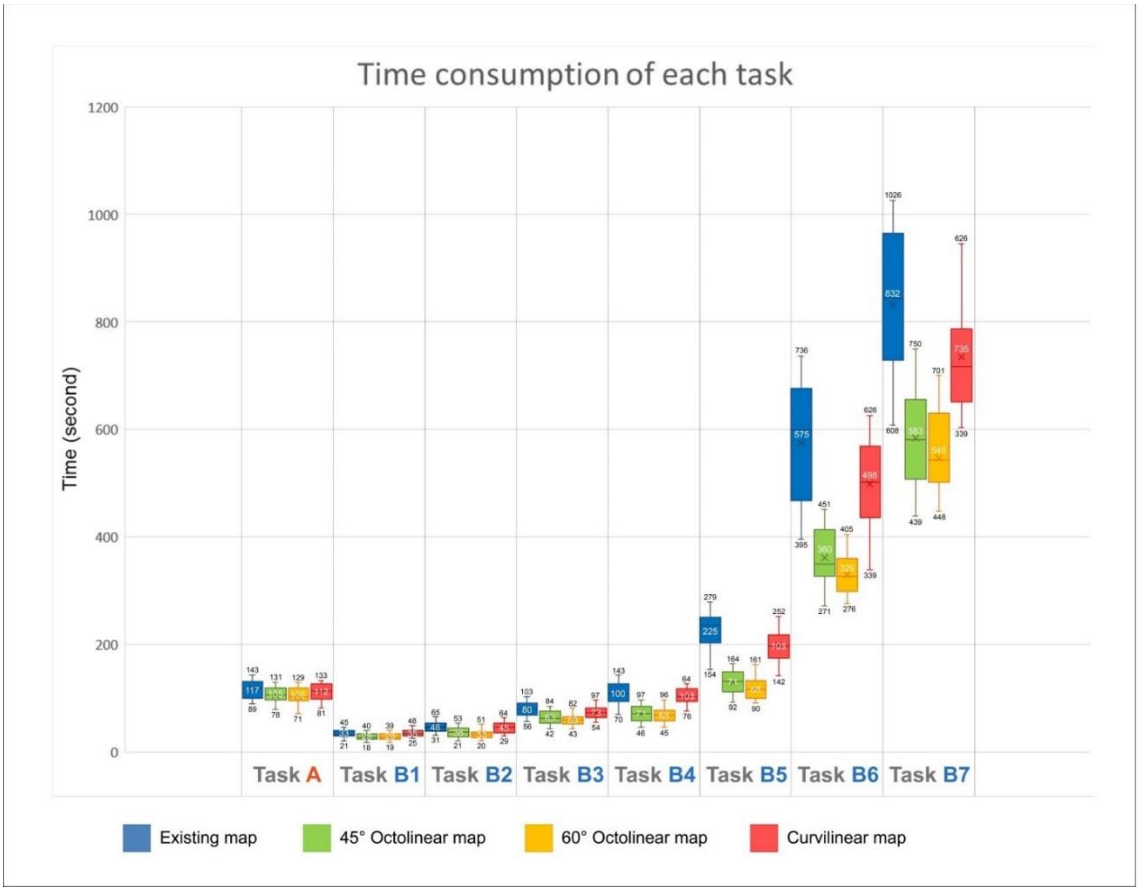


Figure 5.14: Time consumption of each task

5.5.2. The information searching accuracy of the different layouts

Figure 5.15 demonstrated the participants' information searching and route planning accuracy (averagely) in all eight tasks, similar to Figure 5.14, the graph used blue, green, yellow and red boxes to represent the accuracy data of the existing map, the 45° octolinear map, the 60° octolinear map and the curvilinear map. According to Figure 5.15, it is clear that both octolinear maps (45° and 60°) achieved better reading accuracy than the existing map and the curvilinear map.

In the railway line finding task (Task A), participants' searching accuracy when using the curvilinear map (M_{cB1}=98.3%) was slightly lower ($p > .05$) than the existing map (M_{eB1}=99.2%), the 45° octolinear map ($M_{45°oB1}$=99.2%) and the 60° octolinear map ($M_{60°oB1}$=99%).

The result of the route planning task (Task B1 to Task B7) showed a stable trend that with the difficulty level of the tasks increased, participants made more mistakes correspondingly. The lowest accuracy appeared in Task B7, which was the most complicated route includes various interchanges and destinations. Except for Task B1 (M_{eB1}=100%, $M_{45°oB1}$=100%, $M_{60°oB1}$=100%, M_{cB1}=100%), the 60° octolinear map kept the best trip planning accuracy in all route planning tasks, but its advantage was not significant ($p > .05$) compared with other three maps, especially the 45° octolinear map that kept a very similar trip planning accuracy to the 60° octolinear map in all tasks. In addition, the curvilinear map achieved slightly better accuracy than the existing map, the average reading accuracy of both maps was very close in each task ($p > .05$). One thing that needs to be mentioned is, with the routes became more and more complicated, the accuracy gap between the three maps continued to decrease from Task B4 (M_{eB4}=95.1%, $M_{45°oB4}$=99.2%, $M_{60°oB4}$=99.3%, M_{cB4}=95.4%) to Task B7 (M_{eB7}=94.3%, $M_{45°oB7}$=95.5%, $M_{60°oB7}$=95.4%, M_{cB7}=94.6%).

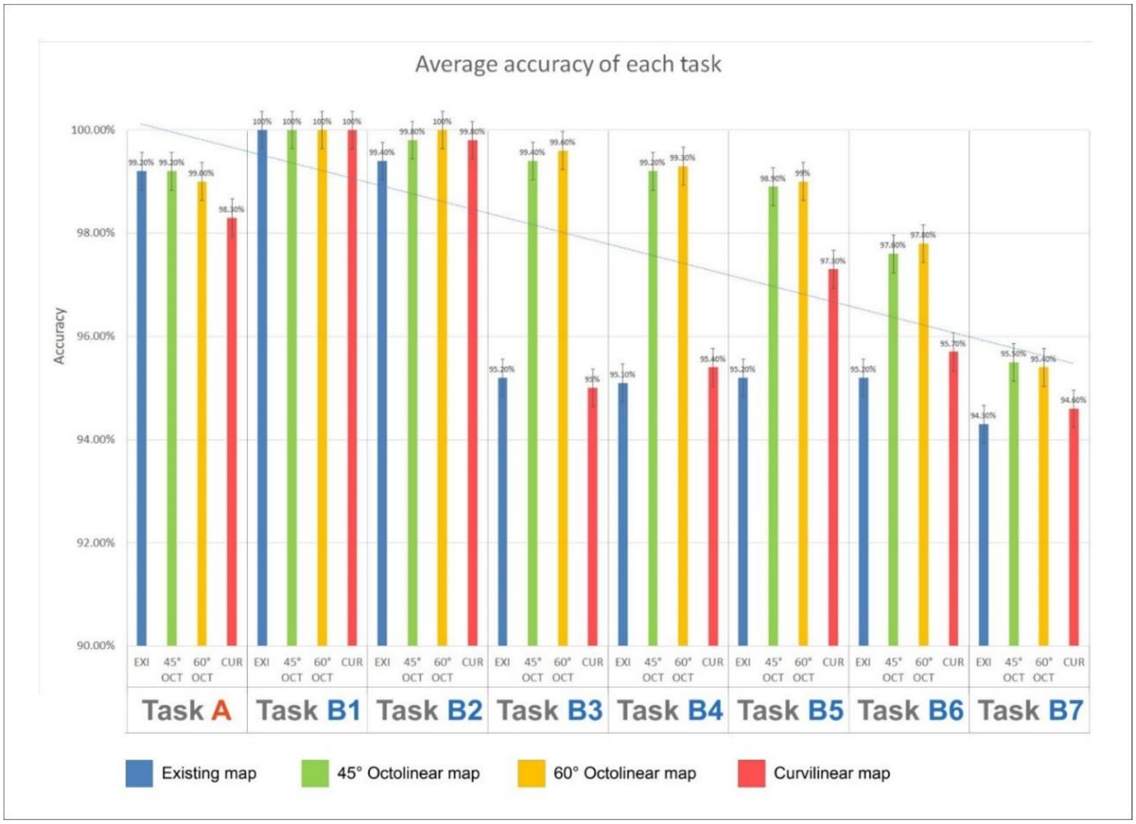


Figure 5.15: Information-searching accuracy of each task

5.5.3. User preference and other feedback

Participants were asked to score the three tested maps regards to readability and attractiveness, the full score is 5, the participants needed to score the attractiveness of the four tested before the test, and score the usability after the test. According to the result (Figure 5.16), the curvilinear map was considered as the most attractive design (*M*=4.5) before the test, the female participants (*M*=4.7) preferred the curvilinear map slightly more than the male participants (*M*=4.3). The 45° octolinear map was the least attractive (*M*=3.2), slightly lower than the existing map (*M*=3.5). The 60° octolinear map was considered as the second attractive design (*M*=4).

After the test, participants thought that the 60° octolinear map (*M*=4.7) was the easiest to use compared with other maps, the curvilinear map received the lowest score (*M*=3.8), which is lower than the existing map (*M*=4.2) and the 45° octolinear map (*M*=4.5).

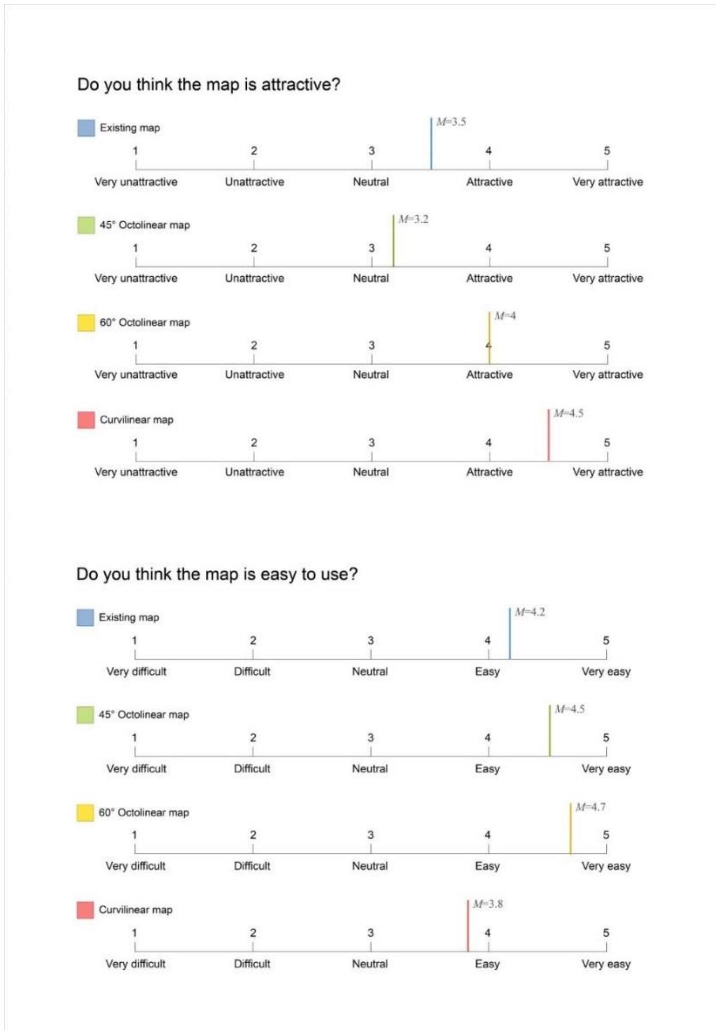


Figure 5.16: User preference survey result

Some other questions regard to the visual element design and typography were investigated among participants. The improved map legend design received good feedback that participants thought the revised map legend was easy to understand (*M*=4.5), and the interchange signs were overall clear and understandable (*M*=4.6). In addition, participants still found some difficulties when reading the non-horizontal station labels (*M*=2.8), which was also observed in the test.

5.6. Discussion

This study thoroughly tested the four different layouts' (existing layout, 45° and 60° octolinearity and curvilinearity) performance in reading speed and information searching accuracy, various important findings of the transit line schematic layout were identified. The participants' feedback also helped to evaluate the design quality of the improved visual and typographic elements. The test results answered the research questions, and the relevant findings are detailly discussed in this section.

5.6.1. Evaluation of the existing layout, octolinear layout (45° & 60°) and the curvilinear layout

In the transit line searching task (Task A), both information searching speed and accuracy of the four layouts did not show any significant differences, which indicated that the different layouts of the transit lines may have very limited influence on railway line identification. According to the previous colour test (Wang, Lonsdale and Cheung, 2011) and Netzel et al.'s (2016) findings, users looking for transit lines mainly based on corresponding colours and texts, this habit may not be changed by the transit line layouts.

The result showed that the transit line layout can largely affect users' route planning speed. Participants spent more time in route planning with the increased number of destinations and interchanges. The 45° and 60° octolinear maps showed slight advantages in route planning speed than the existing map and the curvilinear map beginning from Task B2 to Task B4. This trend became apparent from Task B5 to Task B7; participants' reading time on both octolinear maps was significantly shorter than ($p < .05$) both existing and curvilinear maps. This result explained that the transit line layout only has minor effects on route planning speed in simple route planning tasks; the advantage of both 45° and 60° octolinear layouts only showed when the trip's difficulty reached a certain level. Overall, both octolinear layouts achieved a better performance in reading speed than the existing layout and the curvilinear layout; this result also proved in the questionnaire that both octolinear maps were considered the most accessible maps to use. Many researchers (Nollenburg and Wolff, 2011; Ovenden, 2005; Roberts et al., 2013; Roberts, Gray and Lesnik, 2017) also found that the octolinear layout is more likely to be the most effective schematic layout for most transit networks because of its compact layout saves space, and the fewer bends can save user's time when tracing the routes.

Roberts (2012) mentioned that Beck's rule (horizontal, vertical, 45° diagonal lines) seems well-suited the small or medium-sized networks, it can help to simplify the appearance and reveal the structure of the network, with the complexity increase, this design rule may be less likely to simplify the trajectories. China's high-speed rail system is more complicated than a medium complex network, it contains more than 45 lines, and many of them are long and curved. The reason why the 60° octolinear map behaved better than the 45° Beck's rule map is that the 45° diagonal lines consume more horizontal place than the 60° diagonal lines (Roberts, 2012; Wu et al., 2020), this made the 60° octolinear plan has larger spaces to accommodate the lines station numbers comfortably. In addition, the 60° diagonal lines can create a dynamic impression, which is inherently more compact than 45° diagonal lines (Roberts, 2012), this explained why the 60° octolinear map had a higher attractiveness (M=4) than the 45° octolinear map (M=3.2) ranked by participants. The 45° octolinear map was marked as the least attractive before the test, this surprising result may be due to the reason that the repeated straight schematic lines and breaks may lack in aesthetics that made participants felt crowded and disconnected, and the complex curvature of the existing map lines may create a stronger geometric beauty (Gray and Lesnik, 2017; Silvia and Barona, 2009; Veresi, 2008).

The curvilinear layout was recommended as the second prior layout by many researchers, it showed better reading performance than the octolinear layout in many transit networks (Roberts, Gray and Lesnik, 2017; Roberts et al., 2003; Roberts and Vaeng, 2016). In this test, the curvilinear map showed a faster reading speed than the existing map, but it was still much slower than both 45° and 60° octolinear layouts. There are two main reasons caused this, firstly, the curvilinear layout may not be suitable for all the transit networks, China's high-speed railway network contains more than 45 lines with massive stops and interchanges, the curvilinear layout curves did not sufficiently simplify the network but occupied more space, some areas are still crowded. Similar results also found by Roberts (2012) that when a network does not reach the complexity level that needs an all-curves design, the curvilinear plan may have no benefit for simplification, on the contrary, it may lead to a lower trip planning efficiency (Guo and Wilson, 2011). Roberts (2009) suggested that the all-curves design only suites when the network contains a lot of twisted back and forth lines, and very difficult to make connections between them. Secondly, the Bezier curves and circular arcs extended users' station positioning and route tracing time in the tasks. Due to this, participants marked the lowest score for the curvilinear map in usability after the tests, which considered as the least practical design in all four tested maps. But before the test, the curvilinear map was considered the most attractive design, especially among the female users, this result is slightly different to Roberts's (2012) opinion that there are no male-female differences in preference of curvilinearity. Silvia and Barona (2009) explained that curved shapes make people feel more coherence than other designs. Many people provided positive feedback on various curvilinear transit designs, as they thought the design made the transit network looks more interesting, but the strong individual differences in aesthetic preference are difficult to measure (Roberts, 2012).

The existing map showed the worst performance in both reading speed and accuracy; it kept a close result to the curvilinear map (slightly slower in speed, and slightly lower in accuracy) in almost every task ($p > .05$). This showed that both the existing line layout and curvilinear design might not be suitable for such a complicated topography containing many lines.

Speaking about the information searching accuracy, participants made more mistakes when the tasks became tougher. Like the reading speed, both the 45° and 60° octolinear layouts kept the highest information searching accuracy than the existing map and the curvilinear map. However, the differences between the accuracy of the three maps were not significant ($p > .05$) in every task; this indicated that the layout of the lines might have a minimal influence on users' information searching accuracy.

Overall, the result showed that the 60° octolinear layout achieved the best reading speed and information-searching accuracy compared with other tested maps (the existing layout, the 45° layout and the curvilinear layout). The rank of its attractiveness and usability showed a general preference among participants, which is considered the most suitable layout for China's high-speed railway network.

5.6.2. Evaluation of the improved micro designs

As mentioned in section 3.5.4, the main micro-design improvements focused on visual designs in the map legend and the station labels; these visual elements are essential components for transit line schematic layout.

In the previous eye-tracking test, the long text description about the map functions, instructions and the interchange system wasted users' reading time and led to various confusions; the improved map legend transformed these texts into visual examples and used in all three tested maps. The test result showed that participants understood the revised map legend well. There were no confusions in the information searching process caused by the design limitation of the map legend. Participants marked a high score (4.5 on average) for the map legend design, above the "easy" standard. In addition, with the help of the visual design examples, participants did not confuse whether the transferable stations are connected, participants were more confident than the previous eye-tracking when transferring between the transferable stations, and the transfer system received a satisfied score as well (4.1 in average, above "easy" standard). This can be explained by Chen (2017) and Vanhamaki et al.'s (2017) research findings that the visualised information could be easier to read and understand than raw data or text for most people, especially those not familiar with the content. As a result, the improvement of the map legend design is satisfactory; the visualised information helped simplify the map legend and strengthened the map's legibility.

When reconstructing the network, the topography was distorted to fulfil the different line layout requirements, and the key design principle was simply the trajectories. Roberts (2012) pointed out that the more kinks on the lines can lead to slower trip planning speed and accuracy. As a result, some positions of the stations were adjusted with the topography been distorted, but the topographical alternation was based on the insurance that the traffic relationship between the lines is correct and accurate. The researcher also tried best to maintain the topographical correction between cities; this can help to ensure the credibility of the map, so as not to conflict with people's mental models, because people with lower tolerance may not trust the map because of the topographic 'errors' (Purcell, 2006; Roberts, Gray and Lesnik, 2017). The result showed that the simplification of the network was successful; the newly designed maps showed better performance than the existing map, especially the 60° octolinear map was approximately 40% quicker in route planning than the existing layout. Overall, the topographical accuracy can be maintained as possible, but the advantage of the line simplification overweighs the potential disadvantage of topographical distortion; the topography and station positions can be moderately adjusted to create a better organised and geometrical network.

With the lines been re-organised, the layout of the station labels was improved according to the design rules in section 6.1.4, the improved layout of station labels strictly kept the consistent sizes, typefaces and directions (Ovenden, 2015), especially the disorderly layout station labels were placed on the single side of the line. More importantly, when adjusting the line space on the octolinear (45° & 60°) and the curvilinear maps, the improved labels were horizontally placed as possible. The effect of this revision was proved in the test, similar to the previous eye-tracking test, the nonhorizontal layout of some target stations on the existing map frequently caused reading difficulties and led to time-wasting, although this problem still existed in the octolinear and curvilinear maps, but occurred less frequent compared with the existing map, this is also another reason why the newly designed maps behaved better in reading speed compared with the existing map, because the horizontal layout applies to people’s reading habit and lead to a more comfortable and faster reading (Ovenden, 2003). This showed that both octolinearity and curvilinearity have advantages in station label layout because the better-organised line space allowed more station labels to be spaced horizontally. However, not all the station labels are horizontally placed, because orientations of the station labels need to be adjusted to other directions to adapt to the line layout or avoid conflicting with other labels (Ovenden, 2015; Roberts, 2019), and rotating station labels in 45° angle is acceptable in map design (Roberts, 2012).

Last but not least, it is important to emphasise that the layout of the station labels cannot be carried out separately; it should be done consistently with the transit line layout. In other words, the improved layout of the station labels is the result of that the transit line layout gets improved; the better- organised line layout provides more space to accommodate the station labels according to specific needs.

5.6.3. User performance findings

In the test, participants' reading habit and trip planning behaviour was observed, and some meaningful findings are discussed in this section.

Participants checked the map legend very frequently in the test; this behaviour shows participants believed that their wanted information could be found from the map legend, although this may cause by the settings of the task that participants were required to find out the target information (Krejtz, Duchowski and Coltecin, 2014; Burch et al., 2014). A well-designed map legend can assist users in targeting the lines and understanding the service information quickly and accurately; the importance of the map legend design quality is highlighted again in the test.

During the test, users focused on the destinations more than the origin stations, especially in the complicated tasks; this behaviour was observed in the previous eye-tracking test as well. The interchanges were also frequently double-checked by participants to ensure the selected routes were connected (Grison et al., 2016). This can be explained by the direction-based strategy; this is a very common route planning behaviour that people prefer to pay more attention to the destination and make route plans based on the direction towards it (Conroy Dalton, 2003; Golledge, 1995; Holscher, Tenbrink and Wiener, 2011). This strategy may conflict with the assumption that travellers always try to find the shortest route in trip planning, even though many experiments were designed based on this assumption (Grison, 2019). Is this assumption applied to participants' route choice in the test? Are there any differences in people's route plan when using different layouts? Taking a route in Task B5 as an example (Figure 5.17), an interesting finding was observed that Route 1 was the most popular when participants used the existing map and the 60° octolinear map, which contains 17 stops and one interchange. Around half participants preferred Route 1, and the others chose Route 2 when using the 45° octolinear map. Route 1 was not the most selected when participants used the curvilinear map; more people chose Route 2 (12 stops and two interchanges). This result showed that the layout of transit lines could affect people's route planning behaviour (Grison, 2019). Participants chose the longer route (Route 1) with more stops but fewer transfers when using both the existing map and the 60° octolinear map; this behaviour was a conflict with the "shortest route plan" assumption, but applied to the fact that users prefer the route with no or fewer interchanges even it is slightly longer, the number of transfers is always a key factor that users consider when planning routes in reality (Grison, Gyselinck and Burkhardt, 2016; Guo, 2011; Hine and Scott, 2000; Roberts, 2012). Choosing Route 2 is a good example of the shortest route planning behaviour but contains more transfers; it is difficult to evaluate which route is better, because there are other factors users need to consider in the actual trips, such as travel cost, which is not possible to observe in the laboratory test.

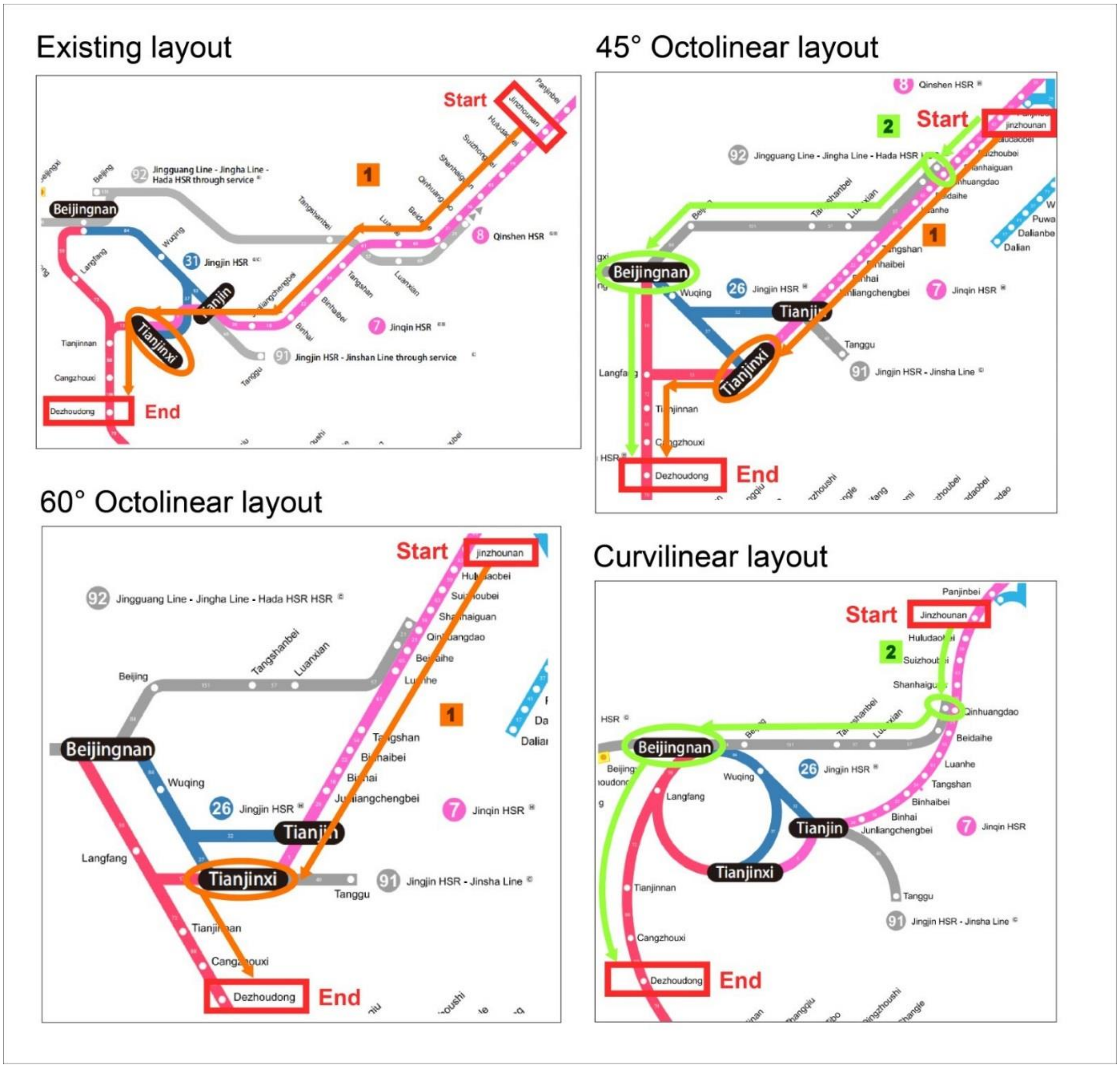


Figure 5.17: A route planning example between different layouts

Moreover, a trend that users prefer to choose the routes with fewer bends is observed, this called the "least-angle" principle in route planning behaviour because the straighter routes look easier to reach the destinations, this also called simplicity preference in route plan (Guo, 2011; Roberts et al., 2013). This trend showed in Figure 5.17 as well; participants avoided the curved busy interchange area and chose the straighter routes. This result may explain the reason why participants scored the curvilinear map as the least effective map; the curved lines may cause the routes look difficult to travel.

In addition, participants' ranks of the tested maps in terms of attractiveness and usability showed some interesting findings. Before the test, the 45° octolinear map was the least attractive map scored by participants, but it showed good performance in both reading speed and accuracy in tests. The curvilinear layout was scored as the most attractive design, especially among female participants, but it did not show satisfying performance in the test result. Interestingly, the curvilinear map was marked as the least easy-to-use map after the tests. This result applies to Grison (2019) and Roberts's (2012; 2019) opinion that there is no strong relationship between users' preference in attractiveness and the actual usability; the map preferred by users may not be the most effective design, such as the curvilinear map in the test. As a result, users' subjective rate of attractiveness **cannot** be used as the only basis for evaluating the objective usability of the map.

5.7. Conclusion

This study thoroughly tested and compared the performance of the four design examples (the existing layout, the 45° octolinear layout, the 60° octolinear layout and the curvilinear layout) of China's high-speed railway map. Both quantitative data (reading time and accuracy) and qualitative data (questionnaire) are collected to evaluate the macro layout design and the micro design of the four layouts. In addition, participants' user behaviours were observed and analysed, which furtherly explained the test result and brought numerous valuable insights into transit map design.

The 60° octolinear layout showed the best reading speed and accuracy performance and is considered the most effective layout design for China's high-speed railway network. Both octolinear layouts showed advantages in organising the complicated network with the straight lines and schematic angles, made the best use of the space and improved the design of overlapped lines. The 60° octolinear map showed slightly better performance than the 45° octolinear map, mainly because of the better geometric structure and larger station label space, which suits the north-to-east vertical layout topography. The curvilinear layout may not be suitable for the network according to the test result, the layout of China's high-speed railway lines does not reach the complexity level of using an all-curves design, the curved angles of the curvilinear plan did not simplify the lines sufficiently, which increased users' route tracing time. Based on this, the octolinear layout is recommended when constructing the network; the curvilinear layout can be selected as the second option when the octolinear layout does not fit the topography of the network. In this study, the 60° octolinearity breaks Beck's 'golden rule' that creates a more dynamic impression than the 45° design; it also reduces the horizontal pressure of the whole network, which suits the vertical rectangle network well. Although the hexalinear layout also contains 60° diagonal angles, but the rule of hexalinearity that whether horizontal or vertical lines should be abandoned consumes larger horizontal or vertical space, which is not suitable for China's high-speed railway system. In brief, the study proved that Beck's rule is not the golden standard for all networks; Beck's rule can be used when starting to construct the lines, it is always wise to try different possible angles or layouts to fit the network. In addition, it is essential to evaluate the designs based on usability tests and user feedback; otherwise, the unwarranted assumption may lead to the failing design.

The study showed that the different layouts of the transit lines have a significant effect on users' reading speed, but this influence will not be substantial when the complexity of the trip reaches a certain level. The line layouts have a limited effect on reading accuracy; users always make more mistakes in more challenging tasks. In addition, the study showed that the layout of transit lines could affect user's route planning behaviour; although there is no evidence to support which layout can always lead to a more efficient route planning result, but users always based on the "least-angle" principle rather than the "shortest route" assumption when planning routes. This result emphasised the importance of the "simplicity principle" in transit map design. Users prefer to select the lines that look easier to travel on the map; it is another reason why the octolinear layouts showed better legibility.

Moreover, the study showed that the typographic design in a transit map, such as the station label layout, is not independent of the transit line layout; it should follow the line layout requirements and make changes correspondingly. The sizes, fonts and directions of station labels should always apply to the spatial relationship between lines and keep horizontally spaced as possible to align with users' reading habits. The study also showed that the visualised instructions in the revised map legend provided users more confidence than the written description. These improved micro visual designs enhanced users' reading comfort and led to better reading speed and information searching accuracy. Long sentences are always recommended to visualise into infographics in transit map design.

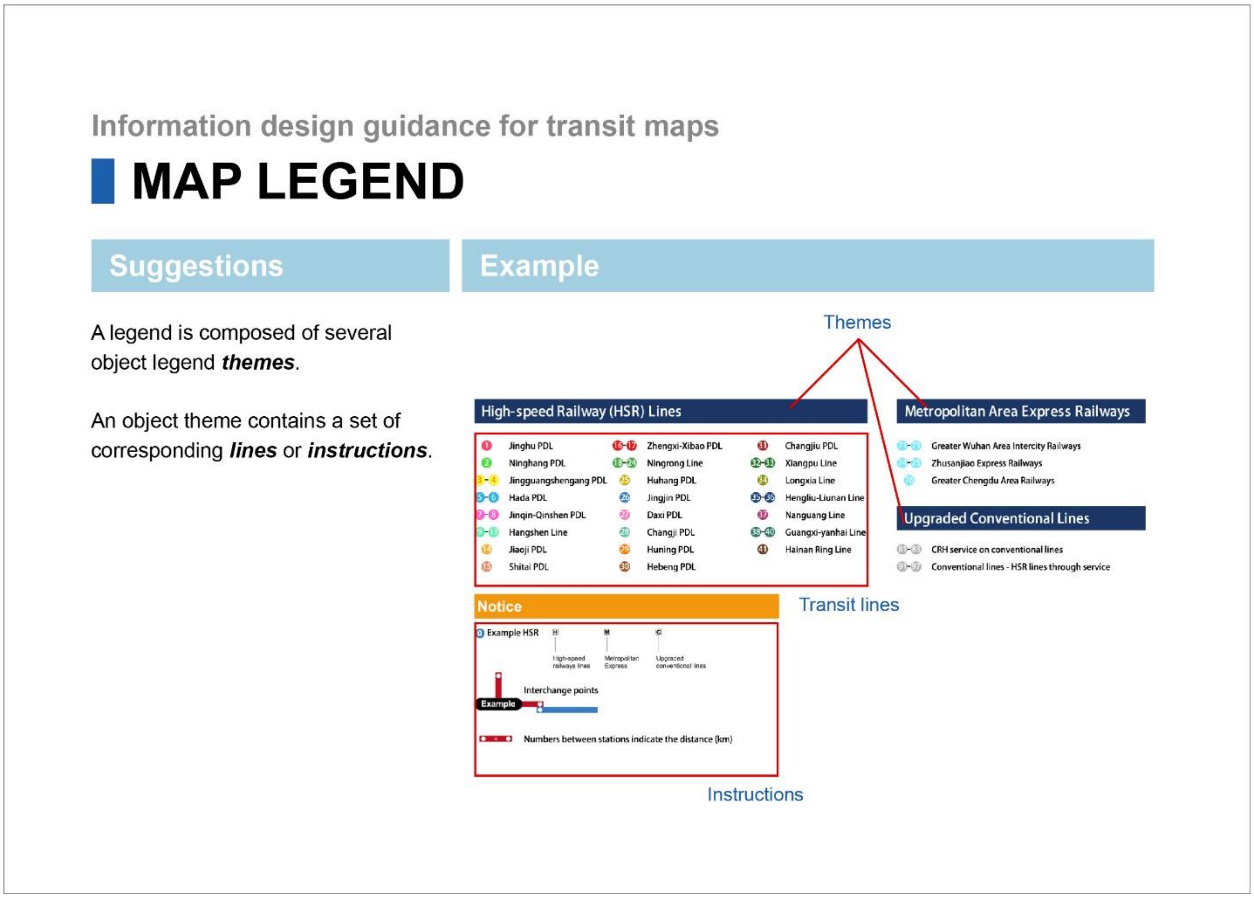
Similar to some other studies, the study proved again that the map with better attractiveness that preferred by users might not be the most effective design; users' preference cannot be used as the only standard when evaluating the effectiveness of a transit map. Although it is necessary to balance the effectiveness and aesthetics of the transit network, a well-organised and simplified layout structure of the lines should always overweigh its attractiveness.

Overall, this study evaluated the transit line layout of a complex transit network; the different design examples were designed and tested using information design and cartographic design knowledge. Finally, the 60° octolinear layout was selected as the most effective design based on its overwhelming reading time and accuracy performance. In addition, various design limitations of the macro line layout and micro visual designs identified from the previous research were improved in this study. More importantly, by observing users' reading behaviour, many research questions were discussed and explained further in more detail, providing numerous valuable insights and practical design guidance in transit map design. In order to display the findings from this study and the previous research, an information design guidance for transit map design is established in the next chapter, which contains the findings from this project, as well as other researchers' empirical theories, which may bring convenience for transit map designers and information design researchers.

6. Information design guidance for transit maps

In this chapter, an information design guidance for transit map design is built based on findings in this research and relevant empirical studies. Design criteria of five main information components of a transit map are demonstrated: map legend, transit line layout, stations and labels, interchanges, and colours. This research detailly investigated these subjects through experiments; various visual design examples and suggestions are provided on each subject.

6.1. Map legend



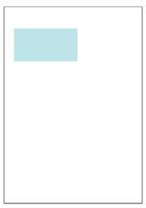
Information design guidance for transit maps

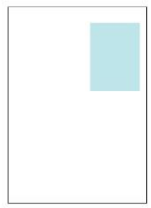
MAP LEGEND

Suggestions	Example

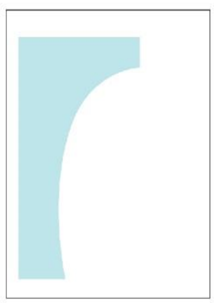
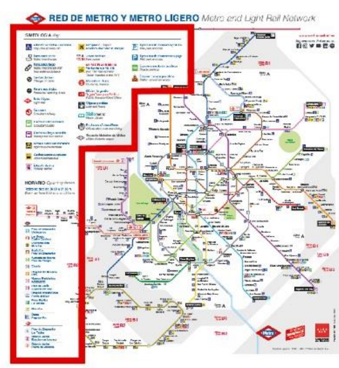
Three main positions on the map:

A. On the top of the map (most commonly used).

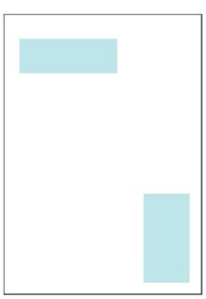


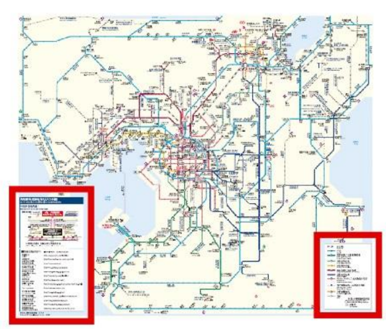



B. On the side of the map, additional information can be added if the space is sufficient.

C. Separately display on the map.



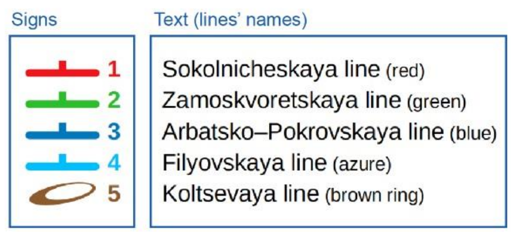


Information design guidance for transit maps

MAP LEGEND

Suggestions	Example

A transit line is suggested to be described by ***texts*** (the line's name) and a ***sign***, the signs of the lines can be distinguished by different ***colours***.

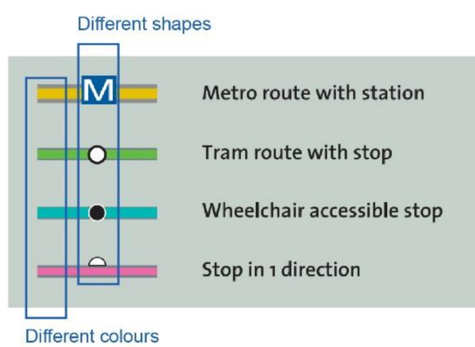


The signs can be visually close if the lines belong to the same theme.

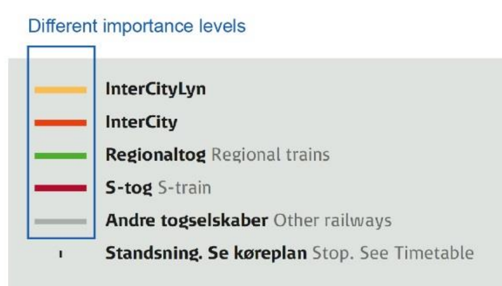
They can be represented by the same/similar hues or the same/similar shapes.

The signs are better to be different if the lines belong to different services/themes.

Different shaps and colours are helpful to distinguish the lines.



If the importance levels of the lines are different, the more important lines are recommended to be represent by more visible colours.

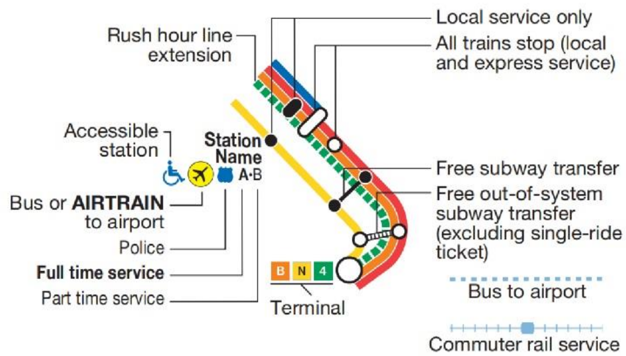


Information design guidance for transit maps

MAP LEGEND

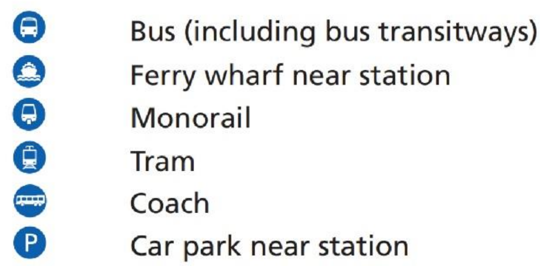
Suggestions	Example

The visual examples of the signs displayed on the map are suggested to be listed in the map legend.

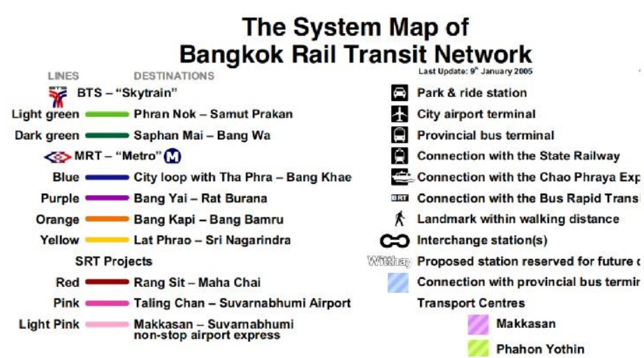


Signs need to be designed ***associate*** with the meaning of the objects.

The visual design style of the signs should be simple and clear.



Normally, the layout of the map legend is ***compact***; the sizes of signs in map legend are better not be too large to accommodate in such a limited space.



6.2. Transit line layout

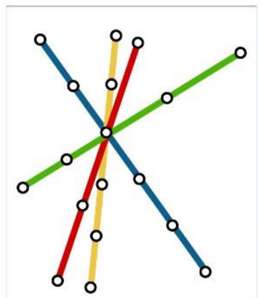
Information design guidance for transit maps

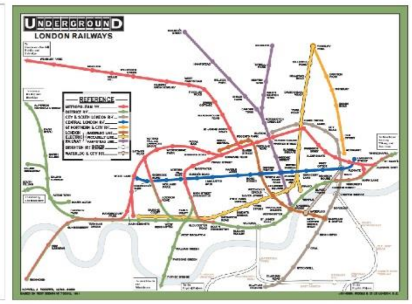
TRANSIT LINE LAYOUT

Suggestions	Example

There are some main schematical layouts for transit maps:

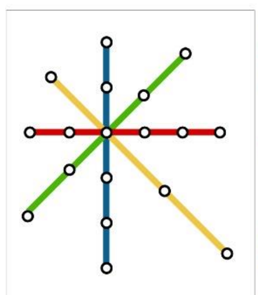
Multilinear layout
Provides the most relaxed plan that transit lines can be displayed in any angles.





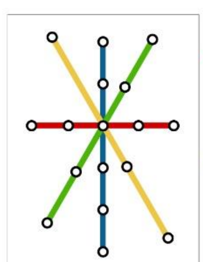
Linear Layouts
Have more strict rules on angles, such as octolinear, hexalinear, and tetralinear layouts, which are the most commonly used layouts in contemporary maps.

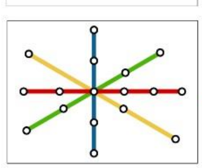
Octolinear layout
Horizontal (0°), vertical (90°), and two diagonals 45° angles.

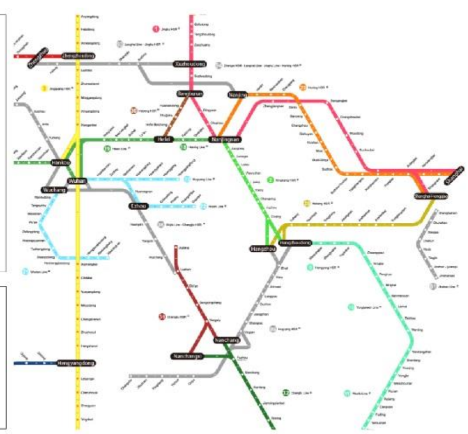


65° Octolinear layout
Horizontal (0°), vertical (90°), and two diagonals 60° angles.

Suitable for the compact layout of north-south or west-east direction middle-complex networks.







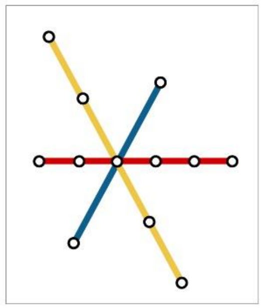
Information design guidance for transit maps

TRANSIT LINE LAYOUT

Suggestions	Example

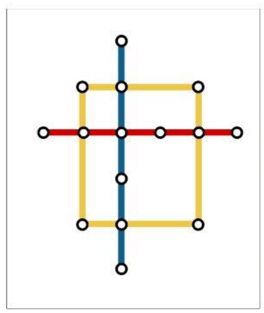
Hexalinear layout

Horizontal (0°), and two diagonals 60° angles.



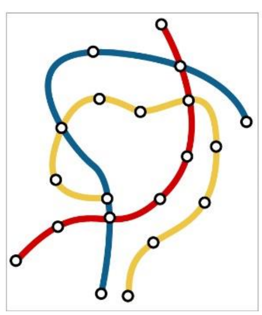
Tetralinear layout

There are only two equally spaced angles are allowed for the alignment of lines: horizontal (0°), vertical (90°).



Curvilinear layout

Each connection is represented by a smooth curve, Bezier curves and circular arcs are commonly used.

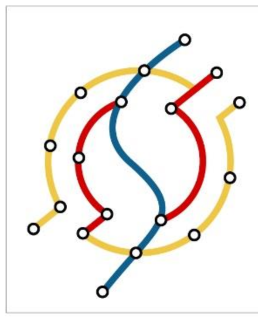


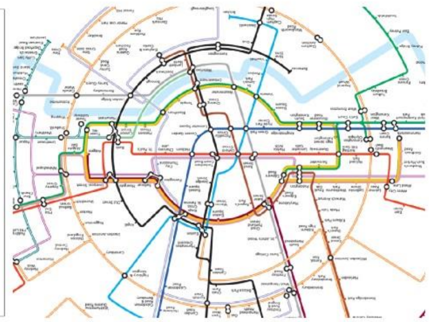
Information design guidance for transit maps

TRANSIT LINE LAYOUT

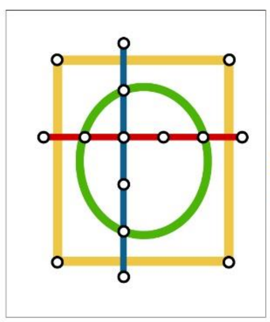
Suggestions	Example

Concentric layout
Each connection runs along an ortho-radial grid that consists of a set of concentric circles and rays emanating from the centre of the circles.



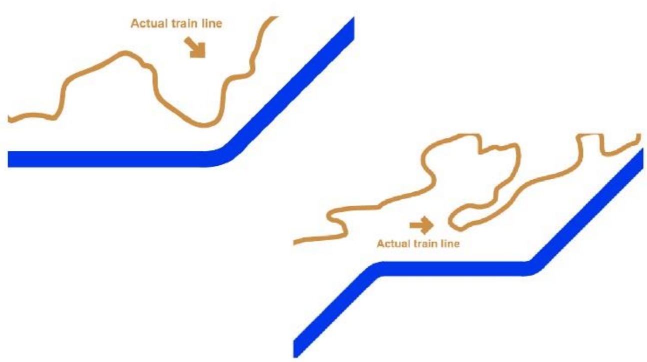


Some transit lines with irregular topographic shapes can be simplified into regular geometrics, such as a circular route can be simplified as a circle.



The irregularly shaped geographical accurate lines can be straightened to enhance the readability.

Simplifying the trajectories is helpful to reduce the number of changes in direction.

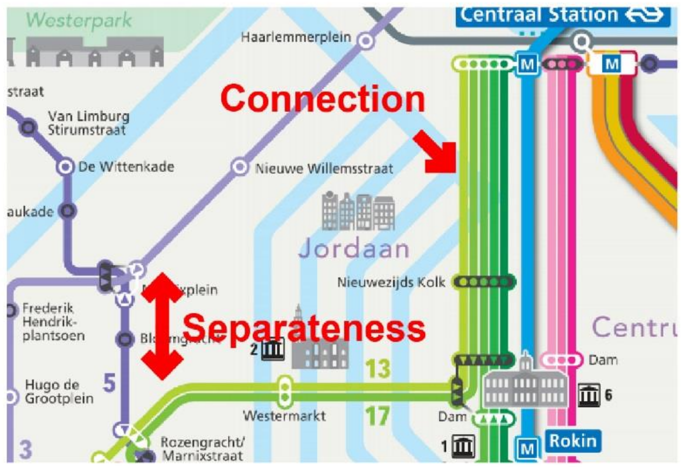


Information design guidance for transit maps

TRANSIT LINE LAYOUT

Suggestions	Example

The gaps between lines can be smaller to show the their neighbourhood connections, or be larger to emphasis their separateness.



S-bends and other points of inflection are not recommended in transit line layout.

When designing the transit system layout, it is always good to minimise the transit line crossings.

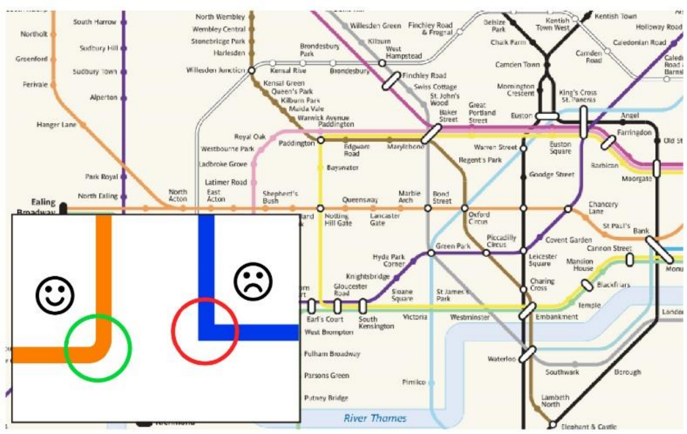
Information design guidance for transit maps

TRANSIT LINE LAYOUT

Suggestions	Example

Some approaches like stretching edges or bending the corners can be done to create more space that accommodating the labels, but not to break the layout style.

It is recommended to keep the trajectories of the lines to be smoothed, it is better to avoid sharp trajectories.



A minimum legible distance between lines is needed to create more space for station labels.

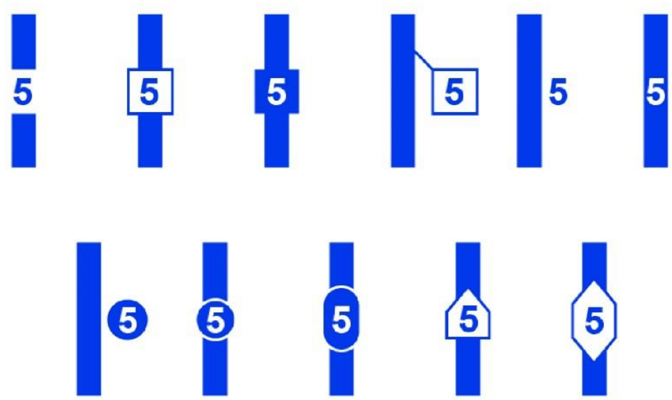
Information design guidance for transit maps

TRANSIT LINE LAYOUT

Suggestions	Example

Small number of breaks or adjustments in line direction can be added if necessary, which helps to enhance visualisation and geometry of line shapes.

The transit lines' name labels need to be displayed clearly, there are design examples can be followed.



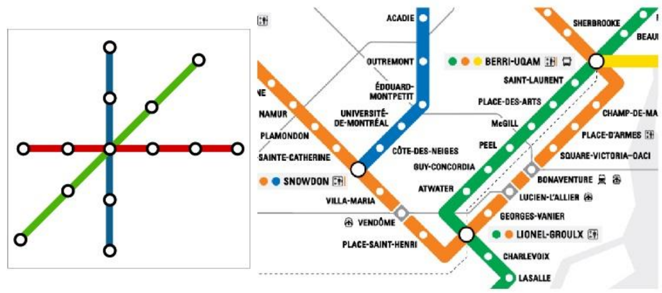
6.3. Stations and labels

Information design guidance for transit maps

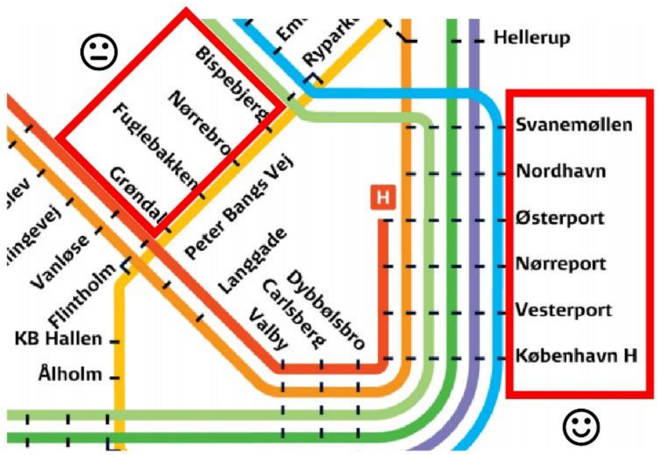
STATIONS & LABELS

Suggestions | **Example**

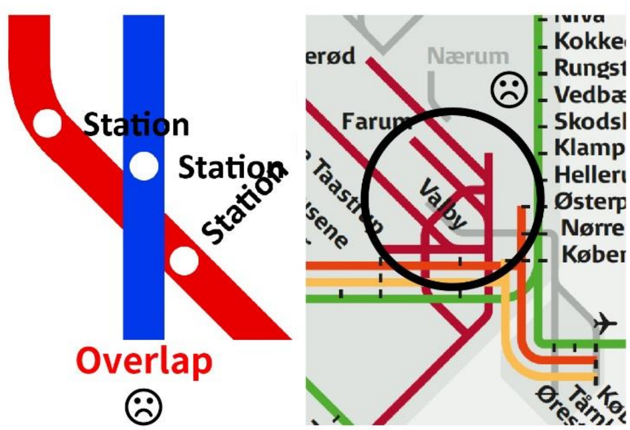
Nodes are commonly used to represent stations, they can be adjusted by size, shape or outline width to show station differences or importance levels



The horizontal layout of the station labels is recommended, but orientations can be switched to other directions to accommodate in the limited space.



Station labels are not recommended to overlap with each other or overlap with transit lines.

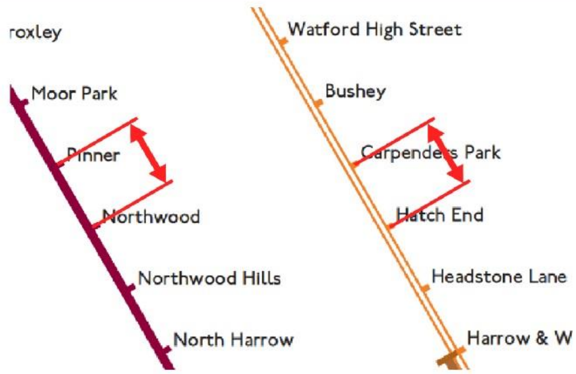


Information design guidance for transit maps

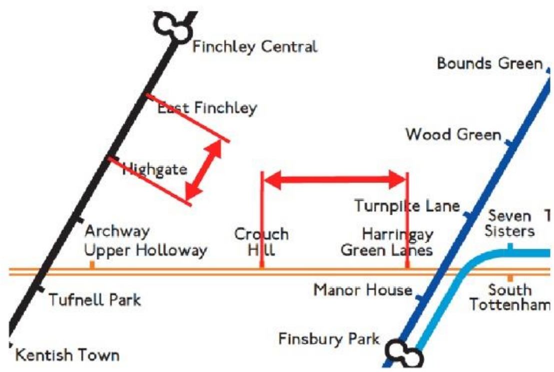
STATIONS & LABELS

Suggestions	Example

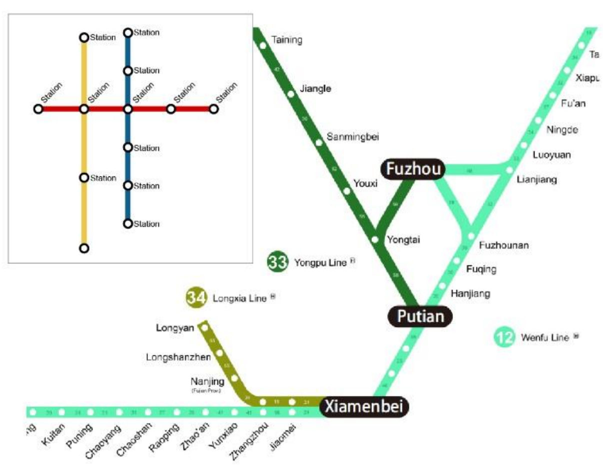
Distances between stations are suggested to be equal, this criterion can lead to a better-organised grid alignment.



The euqal distance between stations on each line can be adjusted depends on sepecific layout needs.



It is recommended to use the same size dot to represent stations on the map, despite the acutual station size differences.



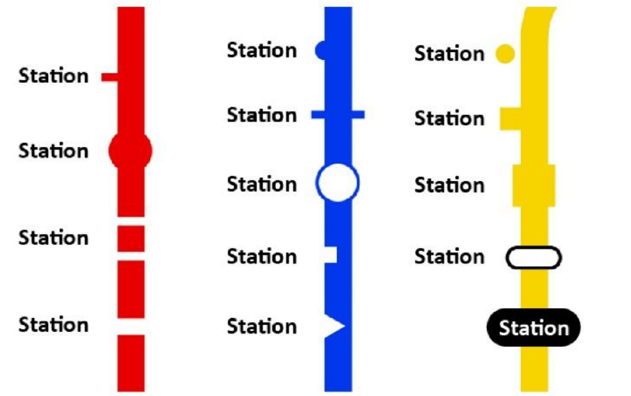
Information design guidance for transit maps

STATIONS & LABELS

Suggestions	Example

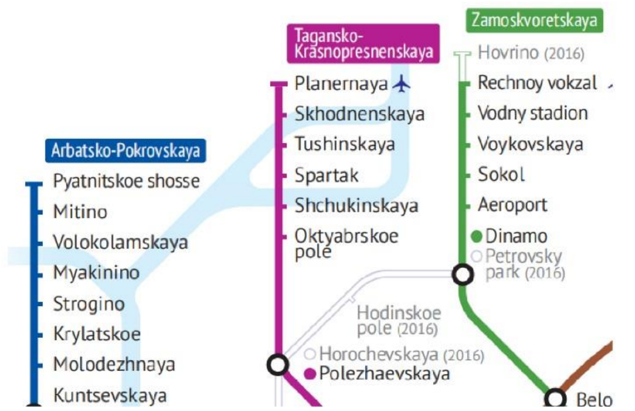
It is recommended to allocate the station labels inside the nodes, beside the nodes or using leader lines to connect the nodes and station names.

There are some design examples can be followed.

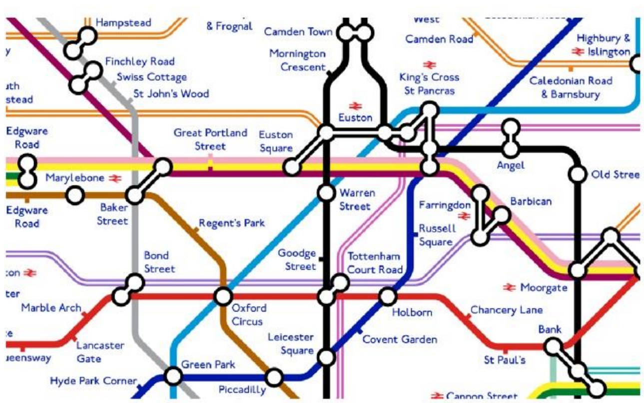


A consistent design style of typeface, direction and size of stations belong to the same service is preferable in design.

Station names are better to be placed on the same side of a line.



Minimising the distances between each other when placing station labels can help to save more space to accommodate more labels.

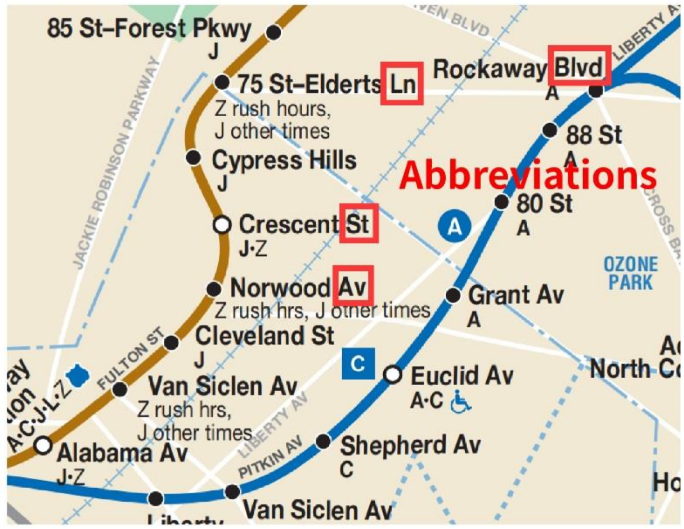


Information design guidance for transit maps

STATIONS & LABELS

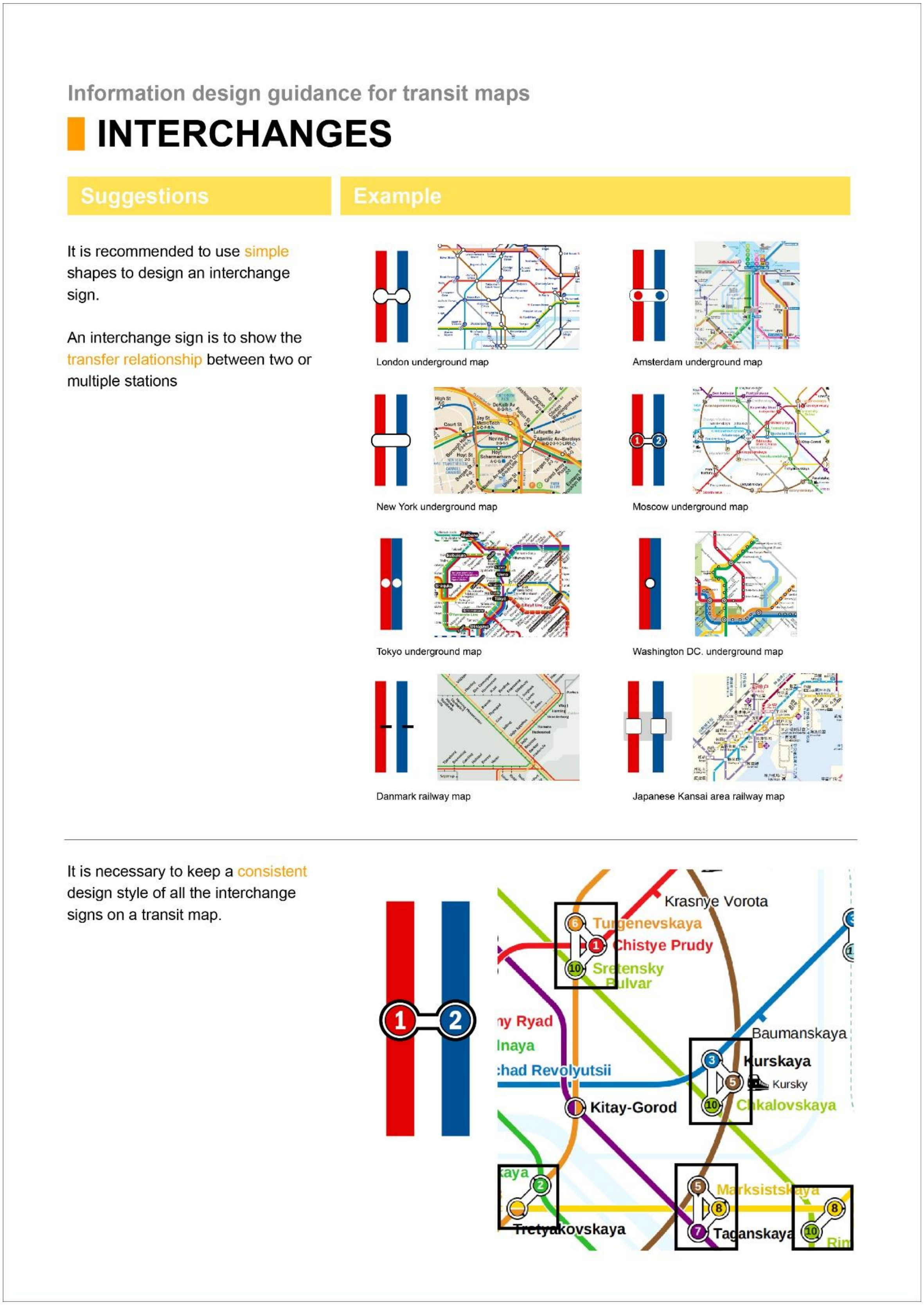
Suggestions	Example

Abbreviations can be used to shorten the long station labels, but it has to be done according to the correct linguistic form.



Different typefaces, sizes and colours of the labels can help to differentiate the information categories, or show the different importance levels of the information.

6.4. Interchange

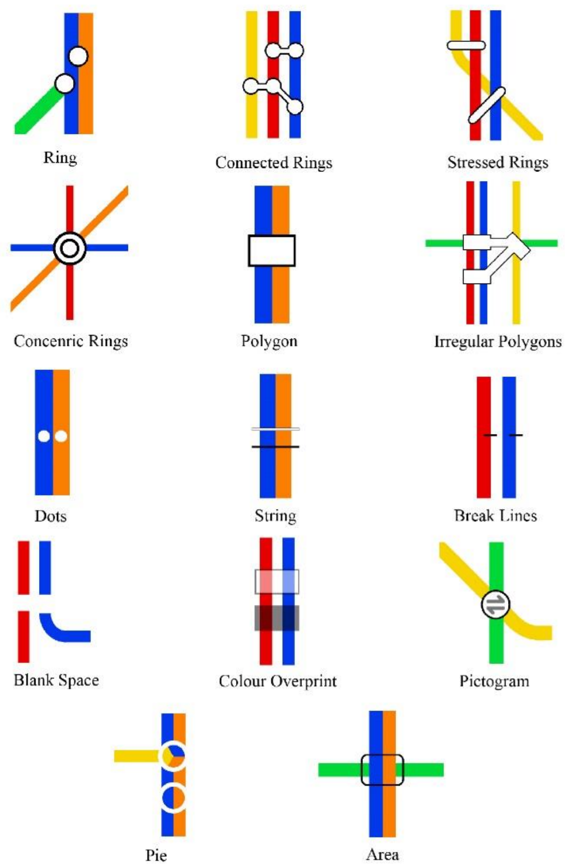


Information design guidance for transit maps

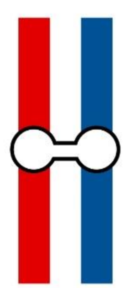
INTERCHANGES

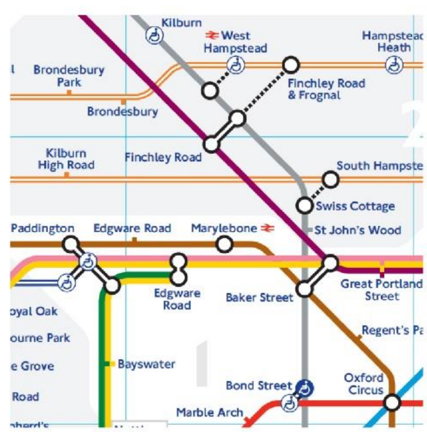
Suggestions	Example

There are various interchange design examples can be followed to represent the transfers.



The "white-line connecter" notation designed by Beck is a famous transfer sign, used on the London Underground map first, then became popular globally.





6.5. Colours

Information design guidance for transit maps

COLOURS

Suggestions

There are four main colour schemes in transit map design: qualitative, binary, sequential and diverging.

Selecting the suitable colour scheme according to the specific needs of the map.

Example

Qualitative scheme

Different hues (not ordered), similar in brightness.

Binary scheme

Neutrals, one hue or one hue step, different brightness steps.

Sequential scheme

Neutrals, one hue or hue transition, single sequence of brightness steps.

Diverging scheme

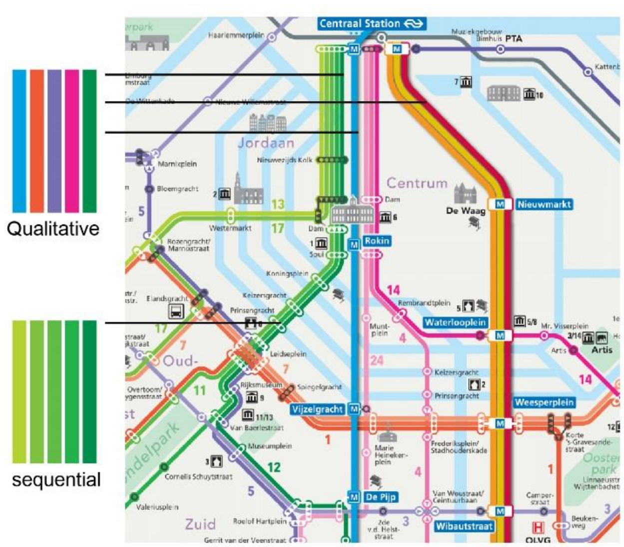
Two hues, one hue and neutrals or two hue transitions, two diverging sequences of brightness steps.

Qualitative scheme and sequential scheme are recommended in maps with a large amount of transit lines.

The qualitative scheme provides multiple selections of hues.

The sequential scheme provides different lightness and saturation values to enlarge the colour distances.

Combining both schemes can create stronger colour contrasts.



Information design guidance for transit maps

COLOURS

Suggestions	Example

The contrasts between colours are better to be at least ±10% in saturation or ±10% in lightness to show sufficient colour differences, this standard can be enlarged to create stronger contrasts.

RGB: 29, 120, 181
S: 84% L: 71%

RGB: 55, 126, 184
S: 69% L: 71%

RGB: 84, 142, 181
S: 54% L: 71%

RGB: 71, 67, 221
S: 69% L: 86%

RGB: 55, 126, 184
S: 69% L: 71%

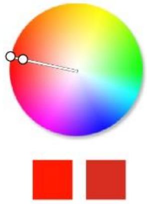
RGB: 41, 103, 137
S: 69% L: 56%

RGB: 45, 179, 232
S: 81% L: 91%

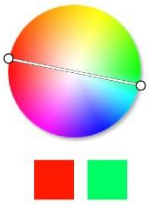
RGB: 55, 126, 184
S: 69% L: 71%

RGB: 25, 68, 130
S: 81% L: 51%

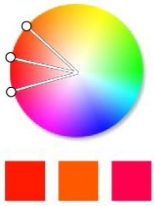
Complementary colours are recommended to create colour harmony, which helps to enhance users' visual comfort.



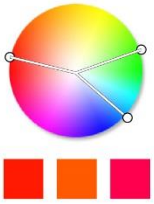
Monochromatic



Complementary



Analogous



Split-complementary

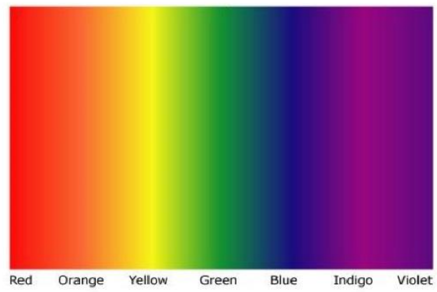
Information design guidance for transit maps

COLOURS

Suggestions

Try not to sort the line colours in the order of rainbow colours, this may confuse the readers that there is a potential order of lines.

Example



7. Conclusion

This chapter summarises what the research set out to do, brings together the leading research findings that respond to the research questions, and emphasises the contribution to knowledge in terms of theoretical, practical and methodological aspects. Finally, the potential limitations of the research and future research plans are proposed.

7.1. Overview of the study

The research set out to structure an information design guidance that had not previously been emphasised and demonstrated. That is, to treat the transit map as an overall information design material that involves two main design subjects, information communication and visual design. Information communication involves infographics, data visualisation, information structure, etc. Visual design contains topographic layout, colour design, typography, symbol design, etc (Chen, 2017; Few, 2012). In addition, the thesis provided effective design suggestions to strengthen the connections between information and visuals presented on a transit map, to make them support each other under a systematic structure. As mentioned in Chapter 1 and Chapter 2, due to the reason that transit map design is traditionally recognised as cartographic or chart design (Roberts, 2012; Netzel, 2019; Wu et al., 2020), different components of the map were investigated and tested separately from the views of cartographic design (mainly focused on topography), computer graphic design (mainly focused on function) or individual visual design (mainly focused on single visual effectiveness). In *Section 2.1*, the researcher emphasised that a transit map is a typical information design material that involves data and visual designs to instruct users to plan and complete their journeys (Dunleavy, 2015; Roberts, Newton and Canals, 2016; Smiciklas, 2012). However, in relevant legibility studies, transit map design has received limited exploration from an information design perspective, especially in transit maps' performance tests relating to users' map using behaviour and habits. To fill this gap and achieve the research objectives listed in *Chapter 1*, the research evaluated, tested and improved the transit map following a user-centred approach, explored how information design knowledge contributes to cartographic design. At the end of the study, an information design guidance was created based on the empirical research findings and existing studies focusing on information and visual designs in transit maps.

The **first objective** was to explore information design knowledge and understand how it affects transit map's legibility. In the first stage, literature looking at both information design and cartography is reviewed in *Chapter 2*. The researcher constructed an initial theoretical information design standard that can evaluate the legibility of a transit map based on empirical experiences. This standard was applied in the eye-tracking performance test (**Experiment I**) to determine the information and visual design limitations that affected users' reading efficiency and potentially changed people's reading behaviour. The key points explored in the experiment (*Chapter 3*) are:

- Investigation of how information communication made travel/service instructions on the transit map confused users when getting access. Some major information design limitations were observed, such as the inaccurate information structure and visual communication of the map legend that caused confusions in map reading.
- Explanation of how visual design limitations (e.g., the unclear colour system, the crowded transit line layout, inappropriate typography, etc.) affected users' map reading speed, information searching accuracy and route planning quality.
- Demonstration of what design limitations on the map can be identified through users' reading behaviour by analysing the eye-movement data (e.g., heatmap, fixation path, and fixation duration).
- Exploration of effective user-centred information design approaches that can be implemented to enhance the legibility of the map.

The **second objective** was to understand the relationship between information and visual components on a transit map, to make them more systematic, relevant, and mutually supportive. In order to achieve the goal, based on the design limitations identified in Experiment I, both Experiment II and Experiment III developed design solutions to improve the legibility of the map, mainly focused on developing information design methods that can assist users in reaching a faster reading speed and a higher information searching accuracy, as well as better route efficiency in trip planning. Both Experiment II and Experiment III are applying to the **third objective** that exploring effective visual design solutions (e.g. data visualisation, colour-coding, typography and transit line schematic layout) to enhance the effectiveness and aesthetics of the map.

In **Experiment II** (*Chapter 4*), the colour system was redesigned and tested, a new colour-coding mode was established based on colour theories. The major research findings are:

- Colours can significantly affect users' efficiency (time & accuracy) and reading behaviour when planning trips on a transit map, but this influence gets weaker when the route planning complexity reaches a certain level.
- A practical colour-coding design solution (a combination of the qualitative and sequential colour schemes) is developed for transit map lines; the mode can also apply to information reading materials containing various themes. The colour system showed its effectiveness (based on map colour design principles) and aesthetics (based on colour harmony theories) in tests.
- The limited focus of existing research in transit map colour design for colour-deficient users was broadened, relevant transit map colour-coding suggestions were provided.

The **fourth objective** was to understand and analyse users' map reading strategy and habits, and develop user-centred design solutions in transit map design. This objective was explored in **Experiment III** (*Chapter 5*):

- Used data visualisation design solutions to visualise the instructional texts in the map legend, to make them more accurate, understandable, and user-friendly.
- Described how visual design factors in both macro line layout and micro visual designs (Inc. Typography) affected the legibility of the map, then developed design solutions to enhance the relationship between them under the thought of a complete information design, rather than considering each design element separately.
- Compared the characteristics and advantages of the major transit line schematic layouts, and summarised potential regulations and suggestions when choosing an appropriate layout plan for a particular transit network.
- Analysed how users' information searching and route planning strategy were affected by different transit line layouts, and the potential risks that caused inefficient route choices when the transit line layout is inappropriate.
- Provided numerous design suggestions on applying to users' map using habit in map design based on test results. The research also explored a user-centred design methodology in both information design and cartographic design research.
- Investigated the conflict between users' preferences and the effectiveness in transit map design, also provided advice on avoiding potential bias in usability test result analysis.

Finally, a transit map design guidance that considered both information communication and visual designs was established, which fulfilled the **fifth objective** of establishing design guidelines for transit map design based on experimental results and relevant empirical studies (not only apply to the map used in this study).

7.2. Major findings and contribution to knowledge

This study investigated the effectiveness of information design and instructional design in transit maps.. Major findings and relevant contributions to knowledge are discussed in this section to emphasise how they strengthen the existing design principles and contribute to future research. There are six major findings that may contribute to the theoretical definition of transit map design, the practical information design solutions that can enhance the effectiveness of a transit map, and the methodological suggestions in both topography and information design research are discussed in the following sections.

7.2.1. Using information design principles to evaluate and improve the legibility of a transit map

This research interprets and evaluates the transit map under the framework of information design and divides the transit map design into two main components, information communication and visual element design. This re-definition breaks the traditional thinking that a transit map is a topographic map or a diagram rather than an infographic (Horne, 2012; Wu et al., 2020), which contributes to the theoretical basis of both cartography and information design. A transit map can visualise the entire process of the user's trip and convey a complete transportation service system; this characteristic is in line with Dunleavy's (2015) theory of infographics (*Section 2.1*). The definition is conducive to a comprehensive and objective information design perspective that examines and evaluates the legibility of a transit map; this may help to avoid the potentially biased conclusions from the performance test of individual design elements apart from the overall information structure of a transit network (Roberts, 2012).

In this study, existing China's high-speed railway map was selected as the example to be evaluated, improved and tested as a complete information design material. The map was designed based on Beck's octolinear layout design principle and kept the topographic accuracy of stations, which is a representative design example of more than half of the world's transit maps (Hochmair, 2009; Larkin and Simon, 1987; Marcus, 2016; Mollerup, 2015; Nollenburg and Wolff, 2011; Ovenden,2005; Roberts, 2012; Roberts et al., 2013; Roberts, Gray and Lesnik, 2017). The user performance tests evaluated the design quality of the map focused on users' reading speed, information searching accuracy, and implemented design solutions applied to user behaviour to improve the map's legibility. Compared with previous studies that focused on the effectiveness of individual cartographic or visual elements (*Section 1.1*), such as topographic distortion, icon design, schematic layout and colour-coding, etc. (Buard, Ruas, 2012; Roberts, Gray and Lesnik, 2017; Roberts and Rose, 2016). This research is one of the first studies that emphasised the connection of information communication and visual designs on a transit map; all the design features are evaluated, modified, and tested accordingly once a particular element is changed. This research pointed out some limitations in relevant studies, especially the biased judgment of the individual design element's effectiveness, without thoroughly considering its relationship with other features and the overall information communication of the map.

Interpreting the transit map as a complete and systematic information design material requires re-classifying the main design elements. The map legend involves all the functions, service information, icon examples, scales and other essential instructions (*Section 2.1.4*) presented on a transit map (Burch, 2018; Slocum, 2014; Spiess, 1995). In all three experiments in the study, participants viewed the map legend more frequently than other information elements to acquire needed information, or double-checked the target information. Therefore, the map legend is the most critical component for conveying map **information communication**, it deicides what traffic and service information needs to be displayed on the map, and what visual designs are used to demonstrate them. Some practical solutions were implemented to improve the deficiencies in the information design of the map legend, the researcher used data visualisation approaches to rearrange the information structure of the legend and visualised the important instructional texts. In particular, the different types of information are summarised into themes, different categories of information are distinguished by graphics and colours, so that they are not only showing the differences, but also clearly showing the association between the information categories. This solution is partly in line with Buard and Ruas's (2009) suggestions on map legend information design, but this study focuses more on the effectiveness of **colour-coding**, which is furtherly discussed in the next section (More details in *Section 2.1.4, Section 3.4.1 to 3.4.2, and Section 4.2.2*).

Visual designs on a transit map include topographic distortion, transit line layout, stations labels, interchanges, the colour system, etc. (Avelar,2006; Guo, 2011; Ovenden, 2005; Roberts, 2012). Through usability tests in Experiment I and redesign practice in Experiment III, the study emphasised that all visual designs should serve the map information structure (e.g., designing corresponding icons to display the different transportation services). In addition, the functional requirements of graphic designs on a map are superior to aesthetics (e.g., simplifying the visual symbols to show their instructional meanings clearly); this suggestion is consistent with Guo (2011), Roberts et al. (2013) and Viera (2012). (More details in Section 2.1.4 and Section 2.2.1 to 2.2.5).

7.2.2. Investigating the effectiveness of colour-systems in transit maps

The research showed a well-designed colour system can largely enhance the reading speed of a transit map in less complicated tasks, but this advantage became weaker after the complexity of tasks reached a certain level, users focused more on instructional words in complex route planning tasks. In addition, colours do not have an observable effect on a transit map's information-searching accuracy, participants showed similar accuracy rates when using maps with different colour systems. Both findings furtherly supplemented Netzel et al.'s (2016) study that when searching for lines, users prefer to focus on colour in simpler tasks and focus on text when the difficulty of the tasks increases.

This study emphasised the effectiveness of **colour-coding** in transit map design, which filled the gap among studies that focused on comparisons of transit-map colour designs but lacked actual colour-coding practices (Wu et al., 2020). In Experiment II, the researcher built up a new colour-coding mode for transit map design, combining both qualitative and sequential colour schemes followed the colour harmony principles (complementary harmony and analogous harmony). The new colour system showed effectiveness in the test that differentiated the lines with strong contrast and harmonious hues; this mode is also effective for designs that need to classify the information into various themes or categories. The qualitative scheme provides various hues to represent different lines, and the sequential scheme allows larger brightness and saturation to strengthen the contrast between colours (Brewer, 1994; Westland et al., 2012). The colour-coding mode (combination of both qualitative and sequential colour schemes) may not only be effective in map design to distinguish the lines or borders, but also apply to other information design materials that involve various categories of information (Chorus, Arentze and Timmermans, 2007). This study showed that the complementary colours are helpful to show the colour differences of the transit lines and enhance the overall colour harmony of the map.

In addition, the newly developed colour-coding mode breaks the commonly used rainbow-colour system or randomly chosen colours that focus on aesthetics purposes in transit line colour-coding. The rainbow-ordered colours are not recommended because users tend to believe there is a potential order of the lines following a rainbow's colour order (from red to purple), which is also observed by Borland and Taylor (2007).

This research also considered the **colour-deficient** users (approximately 10% of the population), and provided design suggestions to make the design material more comprehensive and universal among the population, strengthening the user-centred concept in information design. The research suggests that stronger contrast between colours can make colour-blind users find it easier to perceive the difference in lines. The researcher recommends a colour difference standard of Saturation ±15% and Lightness ±20% between neighbour colours, which helps to create stronger colour difference than Fang et al. (2017) and McGranaghan's (1989) standard of Saturation ±10% and Lightness ±10%. Blue colours with different brightness or saturation are recommended, because they are not confused by the red-green-blind users, which is the most common case among colour-deficient users (Pugliesi and Decanini, 2012). (More details in *Section 2.2.5, Section 4.2.3, 4.4.3, and 4.6.3*). The colour-coding empirical findings in this study do not only contribute to colour theory in map design, but also add knowledge in colour-coding design principles to information design materials apart from maps (More details in *Section 2.2.5, Section 4.2, 4.4 and 4.6*).

7.2.3. Breaking the dominance of Beck's golden rule and exploring alternative layouts

The layout of **transit lines** is the key part of a transportation network map; the researcher analysed the advantages and disadvantages of different schematic layouts based on previous empirical studies, which enriched the knowledge in choosing the suitable line layout for the specific network and designing the corresponding visual instructions to support the overall transit system. The research showed that each transit line layout scheme has its own characteristics and may be more suitable for a certain transit network (Burch, Kumar and Mueller, 2018; Grison, 2019). This research pointed out that the prior principle of the schematic layout is to simplify the trajectories of the lines, especially to geometricize the shape of the lines, to make them more schematically and well-organised (Roberts, 2019).

Through literature review and case study, the author noticed that more than half of transit maps worldwide adopted the 45° octolinear layout, which is also known as Beck's rule (Ovenden, 2003), this layout principle became a global standard for almost a century because of its modern and schematical design, some researchers even emphasised that Beck's 45° octolinear layout is the most reliable 'golden rule'. However, this thinking has been challenged by various studies based on practical design cases (Merrill,2013; Roberts et.al, 2013).

In order to find out if Beck's octolinear layout is the most effective design solution for China's high-speed railway map, the author redesigned, tested and made comparisons between different alternative layout examples. The result showed that curvilinearity might not be suitable for medium-complex or simple transit networks, and it may even increase the visual complexity. Similar results were observed by Roberts (2016), which indicated that the complexity of the network is the key factor that decides which transit line layout scheme is suitable. The opinion supported by Silvia and Barona (2009) that the curvilinear layout is the second prior plan for a transit map after the octolinearity could be limited without considering the route complexity.

More importantly, the research focused on the effectiveness of the 60° octolinearity in the north-south rectangular network, which was ignored by most relevant studies. The 60° octolinear layout combines horizontal, vertical and 60°diagonal angles, which is more compact to accommodate more horizontal layout station labels, and it is more flexible in transit network layout than hexilinearity (horizontal and 60°diagonal angles). It showed the best reading speed and accuracy in route planning tasks, which is considered the most effective layout design for China's high-speed railway network, or similar north-south direction mid-complex networks. Based on this, the research showed a successful example that broken Beck's 45° octolinear layout "golden rule" and created a better layout solution that applies the characteristics of the particular transit network. The research also involved more user-centred and aesthetic insights in transit line layout, such as curving the trajectories of the transit lines to enhance users' visual comfort. (More details in *Section 2.2.2, Section 5.2, Section 5.3.2 to 5.3.4, and Section 5.6.1*).

7.2.4. Establishing information design guidance of a transit map

An **information design guidance** for transit map design was built based on research findings and the review of literature on relevant empirical tests, the corresponding visual examples are provided to demonstrate each design instruction. The design principles summarised from this research and relevant existing studies filled the gap that the transit maps do not have the systematic rules for designers to follow, while there are numerous "ready to use" design principles of conventional maps are established for decades (Avelar and Hurni, 2006). The guidance for transit map design in *Chapter 6* brought valuable insights into both information design and cartographic design subject fields, which also contributes to research methodologies when ascertaining the information design quality and legibility of a transit map.

The research emphasised that it is inappropriate to use long text to describe specific functions or services on the map, and the inaccurate expression of the text confused users and eventually led to information search errors (Mollerup, 2015; Simon and Harlford, 1995). This limitation brought reading difficulties in the map performance tasks (Experiment I and Experiment II), and long texts can cause low-efficient reading. In reality, users often use maps in a time-critical situation, which is difficult to understand the meaning of the text accurately or even have no time to finish the reading. In this case, using systematic and simple visual symbols is an efficient way to convey information, and helped users to remember the key instructions for a longer time (Horn, 1998; Laberge and Samuels, 1974; Ovenden, 2015; Roberts, 2014). However, in both Experiment I and Experiment II, the researcher found that a certain proportion of users had a higher trust in text expression than any other graphical elements. This finding shows that the visual designs cannot completely replace the textual expression in transit map design, especially the necessary text descriptions that need to be retained to enhance the credibility and acceptance of the information on the map. (More details in *Section 3.4.2, Section 5.3.4 and 5.6.2*).

In addition, the principles of data visualisation in transit map design have been furtherly explored, mainly focusing on the systematic form and the correlation between the visualised information, this allows the flat data or text to be expressed in a simplified way without losing its relevance (White, 2002; Tetlan and Marschalek, 2016). Such as, the most intuitive and relevant symbols should be used in transit map icon design to convey accurate information to users, which can avoid possible misunderstandings, similar colours can be used to represent the relevant information, etc. This research also emphasised the "average expression" in information communication. For example, if one of the equally important information categories on the map is represented by a corresponding icon, it is necessary to design corresponding icons for other categories. Otherwise, users may confuse the importance levels of the presented information, which possibly lead to misjudgement or selective ignorance (Roberts, 2012). (More details in *Section 2.1, Section 5.3.4 and 5.6.2*).

The research defined that the macro visual design of a transit map contains the distortion of the transit network and the layout schemes of the lines (Bronzaft and Dobrow, 1984; Roberts et al., 2013, Roberts, 2016). In order to create larger space to accommodate more station labels on the map, the central or busy area in the transit network can be expanded to allow more space for station labels, and the edge area can be compressed correspondingly (Roberts and Rose, 2016). Experiment III showed that when distorting the network, the lines' main direction and the stations' accurate positions should be maintained as much as possible. The essential **topographic accuracy** can strengthen the user's understanding of the spatial relationship between lines and stations displayed on the map; it can also avoid the potential conflict with people's mental model of the area. (More details in *Section 2.2.1, and Section 5.2*). This research also emphasised that micro visual designs on the map should serve the overall information structure and macro transit line layout, including station visualisation, typography, transfer signs, and other visual designs. Taking the station labels' typographic design in Experiment III as an example, when the layout of the transit lines changed, the margins and directions of the station labels were significantly affected, some stations may not be able to be placed horizontally. In this case, the direction of station labels needed to be modified accordingly. According to user feedback, the horizontal layout of station labels applies to people's daily reading habits, which is always recommended to display the station labels in transit map design horizontally (Ovenden, 2003; Ovenden, 2015; Roberts, 2019). Therefore, without considering the macro design, individual testing and improvement of the legibility of micro design elements may lead to biased conclusions. (More details in *Section 2.2.3, Section 5.3.4, and Section 5.6.2*).

The research again showed that an inaccurate e **transfer system** is one of the design limitations that leads to route planning errors. Any visual designs that might make users misunderstand as an interchange point between untransferable lines should be avoided (Roberts, 2019), such as two lines that cannot be transferred are overlapped on each other. A new finding in the test is that the instructional examples of the transfer system must be clearly displayed in the map legend, rather than assuming that users can understand the transfer signs directly in the network. It is necessary to explain to users in the map legend under what circumstances they can or cannot transfer between lines (Bain, 2011). The reading efficiency was significantly enhanced after the relevant improvements were made in Experiment III. (More details in *Section 2.2.4, Section 5.3.4, and Section 5.6.2*).

Although it is almost not possible to build up a series of universal design guidance for all the transit networks (Roberts, 2019; Wu et al., 2020), the effectiveness of design principles suggested in *Chapter 6* are tested in performance tests, and they may also apply to other transportation systems, especially the bus route systems, train/underground networks, and express delivery systems, as they have many similarities in information structure, visual designs and user needs (Ovenden, 2015; Raveau, Guto and Munoz, 2012). It is always suggested to have a thorough understanding of the certain area's topographi c characteristics (Petersen, Vakkalanka and Kuzniarz, 2015), culture and language (Pettersson, 2014) and users' preferences in aesthetics, colours, and reading habits, such as, in some areas in Taiwan, Hongkong and Singapore, a certain proportion of the population may read traditional Chinese characters from right to left (Tian, 2021). Different design solutions may be implemented to achieve better satisfaction among users.

7.2.5. Enhancing the objectivity of eye-tracking test results via qualitative data analysis

Experiment I showed an excellent example of using information design knowledge to evaluate the legibility of a transit map via **eye-tracking** tests, which is a successful demonstration of information design expanding its interdisciplinary possibilities in the field of cartographic design evaluation with the assistance of eye-tracking technology.

The experiment proves that the eye-movement data can intuitively reflect the design quality of the information design of a transit map based on users' reading behaviour, which is also a practical demonstration of the user-centred approach. When users encountered inaccurate information expression or unclear visual design during map using, the eye-movement path and the gaze time can accurately show the specific locations of the confusing areas (Dwyer, 2018; Kang et al., 2016; Kurzhals and Weiskopf, 2017). More importantly, this experiment found that the eye-tracking data should be analysed linking to user feedback; this can effectively eliminate potentially biased conclusions, which is different from Netzel et al.'s (2016) eye-tracking study that only focused on eye-movement paths and fixation time. Taking users' reading behaviour in Experiment I as an example, participants spent most of their time reading the map legend in most tasks, a large number of fixation points showed that the map legend is the "area of interest", it also showed its unreplaceable function in route planning (Bojko, 2006; Ehmke and Wilson, 2017). However, participants mentioned in the later interview that the poor information communication of the map legend slowed down the reading speed. This example showed that eye-movement data could not be used as the only evidence when analysing user behaviour; it is recommended to analyse complemented by other qualitative data, such as participants' feedback; this can help designers to understand users' reading process accurately and avoid potential bias in the analysis. Moreover, although it is difficult to 100% stimulate the reality in laboratory tests, such as time-critical situations (Lloyd, Rodgers, Roberts, 2018, Roberts et al., 2013), but in this study, the author calculated each participant's credits in reading speed and accuracy, the better performance, the higher credits, otherwise lose credits (associate with payments). This method actuated participants to concentrate on tasks and finish them as effective and accurate as possible, which could be implemented in most reading performance tests.

Moreover, the research also found that participants preferred to see the central area of the map first when they started searching for information. This process lasted for more than 2 seconds on average, then started looking for target information. This behaviour challenged Nielsen and Pernice's (2010) opinion, which found that readers prefer to start from the top and review the information following an F shape eye-moving path on screen. This provides evidence that readers have a different reading behaviour when using a transit map compared with other reading materials, the reasonable explanation of this behaviour is that most transit maps expanded the busy networks and allocated them in the central area (Roberts, 2019; Wu et al., 2020), which showed higher importance level than other areas on the map, and may attract users to explore wider travel possibilities, this reading behaviour was observed during the information searching progress.

7.2.6. Exploring user-centred approaches in information design research

The **user-centred** design approaches are investigated in the research to develop design solutions that apply to user habits, and demonstrated a successful example that evaluated, redesigned and tested the legibility of a transit map by using information design knowledge, various practical insights are added into research methodology in both cartographic and information design studies. When evaluating the design quality of a transit map with information design knowledge, the priority is to make sure that the suitable quality and high quantity of information presented on the map; it is always necessary to keep high credibility of the map and avoid potential information pollution, which is in line with many map design researchers (Everett, Andeson and Makranczy, 1977; Manktelow, 2012; Roberts, 2016). Both information quality and quantity of the map are evaluated by observing users' reading performance, the potential visual design limitations can also be identified in this process. In Experiment I, participants frequently searched information in the legend when using the map. This behaviour was explained by Ehmke and Wilson (2017) that users rely on information in the map legend when using a map. Still, it may also indicate that the information structure of the map legend is not well-organised, or the visual designs in the map legend were unclear. In this study, the map showed better performance in reading speed and information searching accuracy after the map legend been improved via visual design solutions, which indicates that the design quality of the legend plays an important role in the readability of a transit map, and visualised information is easier to understand than texts (Mackiewicz, 2004; Petros et al., 1990). However, the researcher observed that users frequently browse the legend mainly because of the task settings; participants wished to complete the experimental task as soon as possible, and the frequent short-time refixations around the map legend area showed that users became impatient once the tasks were getting complicated. This indicates that, in reality, the frequency of browsing the legend would be lower than that in lab experiments. (More details in *Section 2.3 and Section 5.6.3*).

In Experiment I and III, the researcher found that users tended to choose the route towards the destination when planning a route; this direction-based strategy can primarily affect people's determination in route plan (Conroy Dalton, 2003; Golledge, 1995; Holscher, Tenbrink and Wiener, 2011). The research showed that if there are many sharp turns and bends in the route, incorrect or inefficient plans may occur in users' route planning process. Based on this, the simplification and systematisation design of the lines are further implemented in this research. Many minor revisions of the transit network are made based on users' reading habits. (More details in *Section 2.3 and Section 5.6.3*).

In experiment III, the researcher observed that most users did not follow the "shortest distance" strategy when planning routes, but chose routes that contained no interchanges or fewer interchanges as possible. This behaviour has been discovered by Grison (2019) and Guo (2011), but it has not raised enough attention from designers. Many previous route planning tasks in map legibility experiments were designed based on the assumption that users would follow the "shortest distance" strategy, which may lead to inaccurate and biased conclusions. (More details in *Section 2.3 and Section 5.6.3*).

Moreover, when analysing users' feedback in Experiment I and III, the researcher found that user preferences or suggestions may be against the practical design. Design improvements that adapt to user habits must ensure that the information is thoroughly delivered and simplified, rather than prioritising users' aesthetic preferences or other subjective opinions. This insight is helpful when conducting “user-centred” design approaches in most information and instructional designs.

7.3. Future research

The main research aim in the next step is to apply the findings obtained in this study to other transportation maps, such as bus route maps and underground maps, etc. Based on the theoretical basis, experimental findings and the design guidance in this study, continue to explore the application of information design in other transit maps, mainly focusing on improving the user's reading efficiency, accuracy and visual comfort. The corresponding design guidance for different transportation networks combining practical design solutions and visual examples can be developed. In addition, the aesthetics of the map will be investigated in future research; the researcher has a strong interest in the artistry of the transit map, especially focusing on the balance of both aesthetics and functionality of the map so that the transit map can be both practical and decorative, this may involve more graphic design and illustration studies.

Moreover, it is meaningful to explore the legibility of the transit map on electronic terminals, such as touch screens in the station and other commonly used smartphones, pads, etc. Future research will focus on creating interaction with users, determining what travel information or service guide should be displayed when users click on a particular train station. The design solutions focus on communicating the information that applies to user habits could be different on electronic terminals. The information design principles in interactive transit systems will be expanded based on findings in this thesis, which may bring convenience to users in trip planning.

Finally, experimental methods of map legibility research can be further explored in future research to improve the potential research method limitations in this study. For example, to simulate time-critical settings in future experiments, because users may be under a time-critical situation when using a transit map. In addition, some technologies can be integrated into future research, such as virtual reality technology, electroencephalogram technology, etc., which may help expand the empirical research methodology in both information design and cartography. For example, virtual reality technology can stimulate transportation facilities, including train stations, airports, bus stops, etc.; virtual scenes enable participants to use transportation maps in the corresponding environments. As a result, the data collected from such experiments could be more objective and persuasive.

7.4. Summary

In sum, the main contributions and take away tips from this study are as follows.

This thesis **re-interpreted the transit map design** from the perspective of information design in terms of information communication and visual design, which brings new theoretical insights into both cartography and information design fields. Towards this end, an existing China's high-speed railway map was selected, improved and tested. The user performance tests focused on users' reading speed and information searching accuracy, and relevant information design methods applied to user behaviour were implemented to improve the legibility of the map.

A **colour-coding mode for transit map design** was developed that combined both the qualitative and sequential colour schemes, and followed colour harmony principles (complementary harmony and analogous harmony), which demonstrates a practical colour design example that differentiate the transit lines with strong contrast and harmonious hues. This mode is also effective for designs that need to classify the information into different themes or categories. Moreover, it takes into account colour-deficient allowing for more inclusive and universal design solutions.

The research **broke the dominance of Beck's "golden rule" in transit line layout.** The 60° octolinear layout was found to be more effective for north-south direction mid-complex networks, such as the China's high-speed railway map. This research also analysed the advantages and disadvantages of different schematic layouts based on relevant empirical studies. It is necessary to choose the suitable line layout based on the specific network and develop corresponding visual instructions to support the overall transit system.

An **information design guidance** for transit map design was built based on research findings and review of literature on relevant empirical tests. The design principles developed from the study brought valuable insights to both information design and cartographic design subject fields. This research also contributes with guidance on relevant testing methods and methodologies when ascertaining the information design quality and legibility of a transit map.

The research successful demonstrated how eye-tracking technology help to evaluate the information design quality of a transit map, various practical findings in eye-tracking test design and result analysis are provided. The experiments showed that eye-movement data could not be used as the only evidence when analysing user behaviour; it is recommended to analyse complemented by other qualitative data, such as participants' feedback; this can help designers to understand users' reading process accurately and avoid potential bias in the analysis.

This research also shows that **what users perceive does not always match with how users behave**. Therefore, design improvements that adapt to user needs must first be built on well-established and researched information design principles, rather than users' subjective preferences or aesthetic considerations.

References:

Adams S. and Stone T., 2017. *Colour design workbook*. Beverly, MA: Rockport Publishers.

Agrawala, M. and C. Stolte., 2001. Rendering Effective Route Maps: Improving Usability through Generalization. In Proceedings of the 28th *Annual Conference on Computer Graphics and Interactive Techniques*, pp.12–17.

Amare, N. and Manning, A. D. 2013. *A Unified Theory of Information Design: Visuals, Text & Ethics*. Amityville, NY: Baywood Publishing Company, Inc.

Anand S., Avelar S., Ware J. M. and Jackson M., 2007. Automated schematic map production using simulated annealing and gradient descent approaches. *The GIS Research Conference UK* (07), pp.414–420.

Arditi, A. 2002. *Effective Colour Contrast: Designing for People with Partial Sight and Colour Deficiencies*. [http://lighthouse.org/research; Accessed in June, 2020.]

Arditi A. and Cho J., 2005. Serifs and font legibility. *Vision Research*, 45(23), pp.2926-2933.

Atchison, D.A. Pendersen, C. Dain, S. and Wood, J.M. 2003. Traffic signal colour recognition is a problem for both protean and debutant colour–vision deficient. *Human Factors*, 45(3), pp.495-503.

Avelar, S. and Hurni, L., 2006. On the Design of Schematic Transport Maps. *Cartographica The International Journal for Geographic Information and Geovisualization*, 41(3), pp.217-228.

Avelar, S. and Müller, M., 2000. *Generating Topologically Correct Schematic Maps*. [online] Citeseerx.ist.psu.edu. Available at: <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.17.2741> [Accessed 17 August 2020].

Avineri, E. and Prashker, J., 2006. The Impact of Travel Time Information on Travelers' Learning under Uncertainty. *Transportation*, 33(4), pp.393-408.

Baer, K. and Vacarra J., 2010. *Information design workbook*. Beverly: Rockport.

Bailenson, J. N., Shum, M. S., Uttal, D. H., 1998. Road climbing: Principles governing asymmetric route choices on maps. *Journal of Environmental Psychology*, 18(3), pp.251–264.

Bailenson, J. N., Shum, M. S., Uttal, D. H., 2000. The initial segment strategy: A heuristic for route selection. *Memory and Cognition*, 28(2), pp.306–318.

Bain, P., 2010. Aspects of Transit Map Design. *PARSONS journal FOR INFORMATION MAPPING*, 2(3), pp.6-11.

Barnes S., 2016. Appearance and explanation: advancements in the evaluation of journalistic information graphics. *Journal of Visual Literacy*, 35(3), pp.167-186.

Bartusch, C. and Porathe, T., 2011. Climate-smart information design. *Information Design Journal*, 19 (1), pp.3-17.

Bartz, B., 1970. Maps in the Classroom. *Journal of Geography*, 69(1), pp.18-24.

Beck, M. R., Trenchard, M., van Lamsweerde, A., Goldstein, R. R., & Lohrenz, M., 2012. Searching in clutter: Visual attention strategies of expert pilots. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 56, pp.1411–1415.

Bekhit E., 2009. Infographics in the United Arab Emirates newspapers. *Journalism: Theory, Practice and Criticism*, 10(4), pp.492-508.

Benson, P. J., 1985. Writing visually: Design considerations in technical publications. *Technical Communications Journal. Fourth Quarter*, pp.35-39.

Berend, T. B., Rauh, R., Barkowsky, T., 1997. *Spatial thinking with geographic maps: An empirical study.* Herausforderungen and die Wissens organisation.

Bertin, J., 2010. *Semiology of Graphics: Diagrams, Networks, Maps*. Redlands CA: ESRI Press.

Best J., 2017. *Colour design: theories and applications*. Oxford: Woodhead Publishing.

Birch, J., 1997. Efficiency of the Ishihara test for identifying red-green colour deficiency. *Ophthalmic and Physiological Optics*, 17(5), pp.403-408.

Black, A. L., Luna, P., Lund, O. and Walker, S. (2017). *Information design*. New York: Routledge.

Blattner M., Sumikawa D. and Greenberg R., 1989. Earcons and Icons: Their Structure and Common Design Principles. *ACM SIGCHI Bulletin*, 21(1), pp.123-124.

Bojko, A., 2006. Using Eyetracking To Compare Web Page Designs: A Case Study, *Journal of Usability Studies*, I3 (1), pp.112-120.

Borkin M.A., Vo A.A., Bylinskii Z., Isola P., Sunkavalli S., Oliva A., Pfister H., 2013. What makes a visualization memorable? *IEEE Transactions on Visualization and Computer Graphics*, 19(12), pp.2306–2315.

Borland, D. and Taylor Ii, R., 2007. Rainbow Colour Map (Still) Considered Harmful. IEEE Computer Graphics and Applications, 27(2), pp.14-17.

Bransford, J. D., Brown, A. L. and Cocking, R. R., 1999. *How people learn: Brain, mind, experience, and school*. Washington: National Research Council.

Brasseur, L. E., 2003. *Visualizing technical information: A cultural critique. Amityville.* New York: Baywood.

Brewer, C. A., 1994. Colour *Use Guidelines for Mapping and Visualization. In Visualization in Modem Cartography*, ed. A. M. MacEachren and D. R. F Taylor, pp. 123-47. Tarrytown, NY: Elsevier.

Briones, M., 2017. Information Design for Supporting Collaborative Communities. *The Design Journal*, 20(sup1), pp.S3262-S3278.

Bronzaft A. L., Dobrow S. B., 1984. Improving transit information systems. *Journal of Environmental Systems*, 13(2), 365–376.

Brunye, T. T., Mahoney, C. R., Gardony, A. L., & Taylor, H. A. , 2010. North is up(hill): Route planning heuristics in real-world environments. *Memory and Cognition*, 38(6), pp.700–712.

Brunye, T. T., Andonova, E., Meneghetti, C., Noordzij, M. L., Pazzaglia, F., Wiedemann, R., Taylor, H. A. 2012. Planning routes around the world: International evidence for southern route preferences. *Journal of Environmental Psychology*, 32(4), pp.297–304.

Broome K. and Boldy, D., 2011. Characteristics of age-friendly bus information. *Journal of public transportation*, 14(4), pp.43-61.

Buard, E. and Ruas, A., 2009. *Processes for improving the colours of topographic maps in the context of Map on Demand* [online] Available at:<https://www.researchgate.net/publication/228488125_Processes_for_improving_the_colours_of_topographic_maps_in_the_context_of_Map-on-Demand> [Accessed 30 March 2020].

Buard, E. and Ruas, A., 2012. *Evaluation of colour contrasts by means of expert knowledge for on-demand mapping*. [online] Icaci.org. Available at:

<https://icaci.org/files/documents/ICC_proceedings/ICC2007/abstracts/html/3_Oral1-2_4_EVALUATION%20OF%20COLOUR%20CONTRASTS.htm> [Accessed 31 March 2020].

Burch M., 2016. Time-preserving visual attention maps. *The Intelligent Decision Technologies*, 57(1), pp. 273–283.

Burch M., 2018. Which symbols, features, and regions are visually attended in metro maps? *The Intelligent Decision Technologies* 73(4), pp.237–246.

Burch, M., Kumar, A. and Mueller, K., 2018. *The Hierarchical Flow of Eye Movements*. [online] Narcis.nl. Available at: <https://www.narcis.nl/publication/RecordID/oai%3Apure.tue.nl%3Apublications%2F3458960b-9132-4fd8-9843-2f2373c4c973> [Accessed 17 August 2020].

Burch, M., Raschke, M., Blascheck, T., Kurzhals, K., Weiskopf, D., 2014. How do people read metro maps? An eye tracking study. In: Proc. of the *1st International Workshop on Schematic Mapping (Schematics)*.

Brychtova, A. and Coltekin, A., 2016. An Empirical User Study for Measuring the Influence of Colour Distance and Font Size in Map Reading Using Eye Tracking. *The Cartographic Journal*, 53(3), pp.202-212.

Brychtova, A. and Coltekin, A., 2015. Discriminating classes of sequential and qualitative colour schemes. *International Journal of Cartography*, 1(1), pp.62-78.

Cartwright, W., 2014. Rethinking the definition of the word ‘map’: an evaluation of Beck's representation of the London Underground through a qualitative expert survey. *International Journal of Digital Earth*, 8(7), pp.522-537.

Casakin, H., T. Barkowsky, A. Klippel, and C. Freksa., 2000. Schematic Maps as Wayfinding Aids. *In Lecture Notes in Artificial Intelligence-Spatial Cognition II*, ed. C. Frcksa, W. Brauer, C. Habel, and K.F. Wender. Berlin: Springer. pp.54-71.

Chabris, C., Simons, D., 2010. *The invisible gorilla*. New York: Crown Publishing.

Chen, H., 2017. *Information visualization*. Chicago: ALA TechSource.

Cheng, P. (2014). Beyond Beck: Design of Schematic Maps From (Representational Epistemic) First Principles. [online] Users.sussex.ac.uk. Available at:

<http://users.sussex.ac.uk/~peterch/papers/ChengSchematicMap2014+details.pdf> [Accessed 24 August 2020].

Chesneau E., 2005, *Colour Contrasts Analysis for a Better Legibility of Graphic Signs on Risks Maps*. ICA, La Coruna, Spain, July 2005, p. 10.

Chesneau, E., 2011. A model for the automatic improvement of colour contrasts in maps: application to risk maps. *International Journal of Geographical Information Science*, 25(1), pp.89-111.

Chorus, C.G., Arentze, T.A., Timmermans, H.J.P., 2007. Information impact on quality of multimodal travel choices: Conceptualizations and empirical analyses. Transportation 34 (6), pp.625–645.

Coltecin, A., Fabrikant, S., Lacayo, M., 2010. Exploring the efficiency of users' visual analytics strategies based on sequence analysis of eye movement recordings. *International Journal of Geographical Information Science*, 24(10), pp.1559-1575.

Conroy, D.R., 2003. The secret is to follow your nose: Route path selection and angularity. *Environment and Behavior*, 35(1), pp.107–131.

Crisp D., Temple W. and Davis M., 2012. *Typography*. New York: Thames & Hudson.

Davis, M. 2012. *Graphic design theory*. London, UK: Thames & Hudson.

de Smet, M., Leijten, M. and Van Waes, L., 2018. Exploring the Process of Reading During Writing Using Eye Tracking and Keystroke Logging. Written Communication, 35(4), pp.411-447.

de Smet, M., Leijten, M. and Van Waes, L., 2018. Exploring the Process of Reading During Writing Using Eye Tracking and Keystroke Logging. *Written Communication*, 35(4), pp.411-447.

Degani, A., 2013. A Tale of Two Maps: Analysis of the London Underground “diagram”. *Ergonomics in Design: The Quarterly of Human Factors Applications*, 21(3), pp.7-16.

Delaney, J., 2012. *First X, The Y, Now Z: An Introduction to Landmark Thematic Maps*. Princeton: Princeton University Library.

Dent, B.D. Torguson, J.S. Hodler, T. 2009. *Cartography: Thematic Map Design*. 6th ed. Dubuque: Wm. C. Brown Publishers.

Dondis, D.A., 2003. *A Primer of Visual Literacy*, 1st ed. Cambridge, MA: MIT Press.

Dow, A., 2005. Telling the passenger where to get off: George Dow and the evolution of the railway diagrammatic map. Harrow, UK: Capital Transport Publication.

Dragoicea M., Constantinescu D. and Cunha J. F., 2016. Experience from a Modelling and Simulation Perspective in Smart Transport Information Service Design. *Exploring Services Science*. Bucharest: Springer, pp.75-88.

Dukhovny E. and Zhou Y., 2016. Effects of icon size and location on speed and accuracy of SGD access. *Augmentative and Alternative Communication*, 32(4), pp.241-248.

Dunleavy, D., 2015. Data Visualization and Infographics. *Visual Communication Quarterly*, 22(1), pp.68-68.

Dwyer, F. M., 1978. *Strategies for Improving Visual Learning.* State College, PA: Learning Services.

Dwyer, T., 2018. *Seeing into screens: eye tracking and the moving image*. New York: Bloomsbury Academic.

Dyson M.C., 2011. Do Designers Show Categorical Perception of Typefaces? *Visible Language*, 45(3), pp.194-220.

Dziekan, L., 2008. The transit experience of newcomers to a city – learning phases, system difficulties, and information search strategies. *The 87th Meeting of the Transportation Research Board*, Washington DC.

Ehmke, C. and Wilson, S., 2007. Identifying Web Usability Problems from Eyetracking Data. Paper presented at the *British HCI conference 2007*, 03-09-2007 - 07-09- 2007, University of Lancaster, UK.

Endsley M. and Jones D., 2012. *Designing for situation awareness*. Boca Raton, FL: CRC Press

Everett, P.B., Andeson, V.B., and Makranczy, U., 1977. Transit route pamphlets: Do they work? *Transit Journal*, 1(3), pp.59-70.

Fairs M., 2006. *21st century design: new design icons, from mass market to avant-garde/Marcus Fairs; foreword by Marcel Wanders*. London: Carlton.

Fang, H., Walton, S., Delahaye, E., Harris, J., Storchak, D. and Chen, M., 2017. Categorical Colourmap Optimization with Visualization Case Studies. *IEEE Transactions on Visualization and Computer Graphics*, 23(1), pp.871-880.

Feisner, E., 2006. *Colour*. London: Laurence King.

Few S., 2012. *Show me the numbers*. Burlingame: Analytics Press.

Field K., Cartwright W., 2014. Becksploitation: The over-use of a cartographic icon. *The Cartographic Journal*, 51(11), pp.343–359.

Findlay, J. M. & Golchrist, I. D., 2003. Eye Movements in Visual Search. *Active vision: Psychology of looking and seeing*, 4(2), pp.112-128.

Finke T. and Manger S., 2012. I*nformotion: Animated infographics*. Berlin, Germany: Gestalten.

Forrest, D., 2014. Causes and consequences of scale change in schematic maps: are users aware and do they care? Schematic Mapping Workshop 2014, University of Essex, April. https://sites.google.com/site/schematicmapping/Forrest_ScaleChange.pdf

Garland, H., Haynes, J. and Grubb, G., 1979. Transit Map Color Coding and Street Detail. *Environment and Behavior*, 11(2), pp.162-184.

Garland, K., 1994. *Mr. Beck's Underground Map*. Harrow Weald: Capital Transport Publishing.

Goldstein S. P., 1965. *Methods of improved subway information*. NYCTA publisher.

Golledge, R., 1995. Path selection and route preference in human navigation: A progress report. *In A. U. Frank & W. Kuhn (Eds.), Spatial information theory: A theoretical basis for GIS (COSIT'95)*., 988, pp. 207–222.

Granville, W., 1987. Colour harmony: What is it? *Colour Research & Application*, 12(4), pp.196-201.

Grison, E., 2019. Schematic map design: from performance to preference? *In Proceeding of the 2nd Schematic Mapping Workshop*.

Grison, E., Gyselinck, V., Burkhardt, J. and Wiener, J., 2016. Route planning with transportation network maps: an eye-tracking study. *Psychological Research*, 81(5), pp.1020-1034.

Grison, E., V. Gyselinck, V., Burkhardt J.M., 2016. Exploring factors related to users' experience of public transport route choice: influence of context and users' profiles, *Cognition*, 18, pp.287-301.

Gump J. E., 2001. The readability of typefaces and the subsequent mood or emotion created in the reader. *Journal of Education for Business*, 76, pp.270–273.

Guo, Q., 2016. *An Icon Preferences Study on Colours*. Graduate Theses and Dissertations. Iowa State University, Ames.

Guo, Z., 2011. Mind the map! the impact of transit maps on path choice in public transit. *Transportation Research Part A: Policy and Practice*, 45(7), pp.625 – 639.

Guo, Z., Wilson, N.H.M., 2011. Assessing the cost of transfer inconvenience in public transport systems: A case study of the London Underground. *Transportation Research*, 1(45), pp.91-104.

Guo, Z., Zhao, J., Whong, C., Mishra, P., Wyman L., 2017. Redesigning subway map to mitigate bottleneck congestion: An experiment in Washington DC using mechanical turk. Transportation Research Part A: Policy and Practice 106, 158 – 169.

Hadlaw, J., 2003. The London Underground Map: Imagining Modern Time and Space. *Design Issues*, 19(1), pp.25-35.

Harrie, L. and Stigmar, H. 2009. *An evaluation of measures for quantifying map information*, ISPRS Journal of Photogrammetry and Remote Sensing, 65, pp. 266–274.

Harris R., 2007. *The Elements of Visual Style*. New York: Houghton Mifflin Company.

Harrower, M. and Brewer, C., 2003. ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps. *The Cartographic Journal*, 40(1), pp.27-37.

Hartley J. and Burnhill P., 1977. Fifty guide-lines for improving instructional text. *Innovations in Education and Teaching International*, 14(1), 65-73.

Hartley, J., Bartlett, S., & Branthwaite, A., 1980. Underlining can make a difference–sometimes. *Journal of Educational Research, 73,* pp.218–223.

Healey C. G., 1996. Choosing Effective Colours for Data Visualization, Proc. *IEEE Visualization*, IEEE CS Press, pp. 263-270.

Hess, R. 2000. Can colour-deficient users see your site? Microsoft MSDN Library. *Microsoft Corporation*. [http://msdn.microsoft.com/en-us/library; Acessed in June, 2004].

Heller S. and Ilic M., 2001. *Icons of Graphic Design*. London : Thames & Hudson.

Henestrosa C., Meseguer L., caglione ., Burke C., C rdoba P. and Leonidas G., 2017. *How to create typefaces*. Madrid: Tipo e Editorial.

Hine, J., & Scott, J., 2000. Seamless, accessible travel: users' views of the public transport journey and interchange, *Transport Policy*, 7(3), pp. 217–226.

Hochmair, H., 2009. The Influence of map design on route choice from public transportation maps in urban areas. *The Cartographic Journal*, 46 (3), pp.242–256.

Holmqvist, K., Nyström, N., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J., 2011. *Eye tracking: A comprehensive guide to methods and measures*. Oxford: Oxford University Press.

Holscher, C., Tenbrink, T., and Wiener, J. M., 2011. Would you follow your own route description? Cognitive strategies in urban route planning. *Cognition*, 121(2), pp.228–247.

Holt D., 2014. *How Brands Become Icons*. Boston: Harvard Business Review Press.

Holtzschue, L., 2017. *Understanding Colour*. Hoboken, New Jersey: Wiley.

Horn, R. E., 1999. *Information Design: Emergence of a New Profession*. In R. Jacobson (Ed.), *Information Design.* Cambridge, MA: MIT Press.

Horton, W., 1994. *The Icon Book*. New York: Wiley.

Horne, M. A. C., 2012. Information design aspects of the London underground map. Available from http://www.metadyne.co.uk/UndMap.html

Hyndman S., 2015. *The type of taster: How fonts influence you*. London: Type Tasting.

Imhof E., 1975. Positioning names on maps. *The American Cartographer*, 2(2), pp.128–144.

Iliinsky N. and Steele J., 2011. *Designing data visualizations: Representing informational relationships*. Sebastopol, CA: O'Reilly.

Itten, J. and Birren, F., 1997. *The Elements of Colour*. New York: Wiley.

Ivory, M. Y., Sinha, R. R. and Hearst, M. A., 2001. *Empirically validated web page design metrics.* SIGCHI 2001: NY: ACM.

Jones, J., 2015. Information Graphics and Intuition. *Journal of Business and Technical Communication*, 29(3), pp.284-313.

Judd, D. and Wyszecki, G., 1975. *Colour In Business, Science and Industry*. New York, N.Y: Wiley.

Just, M. and Carpenter, P., 1980. A theory of reading: From eye fixations to comprehension. *Psychological Review*, 87(4), pp.329-354.

Kang, Z., Mandal, S., Crutchfield, J., Millan, A. and McClung, S., 2016. Designs and Algorithms to Map Eye Tracking Data with Dynamic Multielement Moving Objects. *Computational Intelligence and Neuroscience*, 16(1), pp.1-18.

Keates, J., 1989. *Cartographic design and production*. Harlow: Longman Scientific & Technical.

Kiefer, P., Giannopoulos, I., Raubal, M., 2014. Using eye movements to recognize activities on cartographic maps. In: *Proc. of the 21st ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. pp.488-491.

Kimball M., 2013. Visual design principles: An empirical study of design lore. *Journal of Technical Writing and Communication,* 43(1), pp.3-41.

Krejtz, K., Duchowski, A.T., Coltecin, A., 2014. High-level gaze metrics from map viewing - charting ambient/focal visual attention. In: Proc. of the *2nd International Workshop on Eye Tracking for Spatial Research*, pp.37-41.

Kruger, J., Dunning, D., 1999. Unskilled and unaware of it. *Journal of Personality & Social Psychology*, 77, pp.1121-1134.

Krum R., 2013. Cool Infogra*phics: Effective Communication with Data Visualization and Design*. Indiana: John Wiley and Sons, Inc.

Kurzhals, K. and Weiskopf, D., 2017. Eye Tracking for Personal Visual Analytics. *IEEE Computer Graphics and Applications*, 35(4), pp.64-72.

LaBerge, D. and Samuels, S.J., 1974. Toward a theory of automatic information processing in reading. *Cognitive Psychology*, 6(1), pp.293-323.

Larkin, J., Simon, H.A., 1987. Why a diagram is (sometimes) worth 10 000 words. *Cognitive Science 11*, pp.65–99.

Lee G., 2015. *Creating an Inclusive colour-coded bus route map in Leeds*. MA. Thesis, University of Leeds.

Lindell, A. K., & Mueller, J., 2011. Can science account for taste? Psychological insights into art appreciation. *Journal of Cognitive Psychology*, 23, pp.453–475.

Lipton, R., 2007. *The Practical Guide to Information Design.* Hoboken, NJ: John Wiley and Sons, Inc.

Liu, Y. and Ho, C., 2012. The effects of age on symbol comprehension in central rail hubs in Taiwan. *Applied Ergonomics*, 43(6), pp.1016-1025.

Liu X. and Lin Y., 2009. The vivid colour in the metro station figures identity of city. In Proceedings of the *Computer-Aided Industrial Design Conceptual Design*, pp. 1682–1685.

Livingstone, M. and D. Hubel, 1988. *Segregation of form, colour, movement, and depth: anatomy, physiology, and perception*, Science, Vol. 240, pp. 740-749.

Lloyd, P. B., 2017. From Modernism to Metro Maps: Mondrian, Beck, and Salomon. *Brief Encounters*, 1(1), pp.4-11.

Lloyd, P. and Ovenden, M., 2012. *Vignelli transit maps*. Rochester, New York: RIT Cary Graphic Arts Press.

Lloyd P. B., Rodgers P., & Roberts M. J., 2018, Metro map colour-coding: Effect on usability in route tracing, *Diagrammatic Representation and Inference*. pp. 411- 428.

Lonsdale M., 2016. Typographic features of text and their contribution to the legibility of academic reading materials: An empirical study. *Visible Language*, 50(1), pp.80-111.

Macdonald, R. M. and Waller, R., 1998. The transformer visited. *Information design Journal*, 9(2), pp.177-193.

MacEacgren, A. M., 2004. How Maps Work: Representation, *Visualisation and Design*. New York: The Guilfdor Press.

Mackiewicz, J., 2004. What Technical Writing Students should Know about Typeface Personality. *Journal of Technical Writing & Communication*, 34 (1/2), pp.113-131.

Manktelow, N.J., 2012. *Thinking and reasoning*. Hove: Psychology Press.

Mannion, A. and Leader, G., 2014. Attention-deficit/hyperactivity disorder (AD/HD) in autism spectrum disorder. *Research in Autism Spectrum Disorders*, 8(4), pp.432-439.

Marcus, A., 2016. Underground maps unravelled: Explorations in information design. *Information Design Journal*, 21(1), pp.64–66.

Mcdowell J., 2008. Design of a colour sensing system to aid the colour blind. *IEEE Potentials*, 27(4), pp.34-39.

McDougall S.J.P., Curry M. B. and de Bruijn O., 1999. Measuring symbol and icon characteristics: Norms for concreteness, complexity, meaningfulness, familiarity, and semantic distance for 239 symbols. *Behavior Research Methods Instruments & Computers*, 31(3), pp.487-519.

McGranaghan, M., 1989. *Ordering choropleth map symbols: the effect of background*, The American Cartographer, Vol. 16, No. 4, pp. 279-285.

Meirelles, I., 2013. *Design for information*. Rockport MA: Rockport publisher.

Merrill S., 2013. The London Underground diagram: Between palimpsest and canon. *The London Journal*, 38(3), pp.245–264.

Mijksenaar P., Vroman R., 1983. London Transport map: A delft project. *TYPOS*, pp.36–40.

Mollerup P., 2015. *Data design*. New York: Bloomsbury Academic, an imprint of Bloomsbury Publishing Plc.

Monmonier, M., 1993. Mapping It Out: Expository Cartography for the Humanities and Social Sciences. Chicago: University of Chicago Press.

Monmonier, M., 2010. N*o Dig, No Fly, No go: How Maps Restrict and control*. Chicago: University of Chicago Press.

Morgagni, S., Grison, E., 2019. East or west? Map design and passenger path decisions on mass transit networks. In Proceeding of *the 2nd Schematic Mapping Workshop*.

Moriarty, S. E., 1991. *Creative Advertising. Theory and Practice.* Englewood Cliffs, NJ: Prentice Hall.

Morrison, A., 1996. Public Transport Maps in Western European Cities. Cartographic Journal, 33(2), pp.93-110.

Mullet, K. and Sano, D., 1995. *Designing Visual Interfaces Communication Oriented Techniques.* Mountain View, CA: SunSoft Press A Prentice Hall Title.

Netzel, R., Burch, M., Ohlhausen, B., Woods, R., Weiskopf, D., 2016. User performance and reading strategies for metro maps: An eye tracking study. Special Issue on Eye Tracking for Spatial Research in Spatial Cognition and Computation: An Interdisciplinary Journal.

Newton E. J., Roberts M. J., 2018. Concentric circles maps: Data and implications. In Proceedings of *the Theory and Application of Diagrams* (Edinburgh, U.K.).

Nickel, S. and Nöllenburg, M., 2019. Towards Data-Driven Multilinear Metro Maps. [online] arXiv.org. Available at: <https://arxiv.org/abs/1904.03039> [Accessed 14 August 2020].

Nielsen, J. and Pernice, K., 2010. *Eyetracking web usability*. Berkeley, Cal.: New Riders.

Nollenburg, M., 2014. *A Survey on Automated Metro Map Layout Methods*. In Schymbolsematic Mapping Workshop 2014. Essex.
http://i11www.iti.unikarlsruhe.de/en/members/martin_noellenburg/publications

Nollenburg, M. and Wolff, A., 2011. Drawing and Labeling High-Quality Metro Maps by Mixed-Integer Programming. *IEEE Transactions on Visualization and Computer Graphics*, 17(5), pp.626-641.

Norman, R. B., 1990. *Electronic Colour: The Art of Coloured Applied to Graphic Computing*, New Jersey: John Wiley & Sons Inc.

Olson, J.M. Brewer, C.A. 1997. An Evaluation of Colour Selections to Accommodate Map Users with Colour-Vision Impairments. Annals of the Association of American Geographers, 87(1), pp.103-134.

Ooms, K., Coltecin, A., Maeyer, P.D., Dupont, L., Fabrikant, S.I., Incoul, A., der Haegen, L.V., 2015. Combining user logging with eye tracking for interactive and dynamic applications. *Behavior Research Methods*, 47(4), pp.977-993.

Ou, L., 2016. *A Comparison Between Colour Preference And Colour Harmony — DRS2016*. [online] Available at: https://www.drs2016.org/089

Ou, L., Chong, P., Luo, M. and Minchew, C., 2010. Additivity of colour harmony. *Colour Research & Application*, 36(5), pp.355-372.

Ovenden, M., 2003. *Metro Maps of the World*. Harrow Weald: Capital Transport Publishing.

Ovenden, M., 2005. Metro maps of the world. Harrow, UK: Capital Transport. Wagner, F., Wolff, A., Kapoor, V., & Strijk, T. (2001). Three rules suffice for good label placement. Algorithmica, 30(2), 334–349. doi:10.1007/s00453-001-0009-7

Ovenden, M., 2015. *Transit Maps of the world*. New York: Penguin Books.

Palmer, S. E., Schloss, K. B., Sammartino, J., 2013. Visual aesthetics and human preference. *Annual Review of Psychology*, 64, pp.77-107.

Passini, R., 1984. Spatial representations, a wayfinding perspective. *Journal of Environmental Psychology*, 4(2), pp.153-164.

Petros, T. V., Bentz, B., Hammes, K., & Zehr, D. H., 1990. The components of text that influence reading times and recall in skilled and less skilled college readers. *Discourse Processes,* 13, pp.387–400.

Petersen, K., Vakkalanka, S. and Kuzniarz, L., 2015. Guidelines for conducting systematic mapping studies in software engineering: An update. *Information and Software Technology*, 64, pp.1-18.

Pettersson, R., 1989. *Visuals for Information, Research and practice.* Englewood Cliffs. NJ: Educational Technology Publications.

Pettersson, R., 2010. *Information Design-Principles and Guidelines*. Journal of Visual Literacy, 29 (2), pp.167-182.

Pettersson, R., 2014. Information Design Theories. *Journal of Visual Literacy*, 2014, 33, (1), pp.1–94.

Pettersson, R., 2016. *Information Design Theories*. Tullinge, Sweden: Institute for Infology.

Pettersson, R., 2019. ID practice and theory. *Information Design Journal*, 25(3), pp.242-248.

Philips, R.J., Noyes, L., 1982. An investigation of visual cutler in the topographic base of a geological map. *The Cartographic Journal*, 19, pp.122-132.

Pokorny, J.V.C. Smith, Verriest G. and Pinkers, A.J.L. 1979. Congenital and Acquired Colour Vision Defects. Grune and Stratton, New York.

Pridmore, R., 2011. Complementary colours theory of colour vision: Physiology, colour mixture, colour constancy and colour perception. *Colour Research & Application*, 36(6), pp.394-412.

Pugliesi, E. and Decanini, M., 2012. Cartographic Design Of In-Car Route Guidance For Colour-Deficient Users. [online] Icaci.org. Available at: <https://icaci.org/files/documents/ICC_proceedings/ICC2011/Oral%20Presentations%20PDF/E3-Mapping%20for%20colour-deficient%20or%20deficient%20users/CO-470.pdf> [Accessed 11 September 2020].

Raveau, S., Guo, Z., Munoz, J, 2012. Route choice analysis for metro networks: a comparison between Santiago and London. In Proceedings of *the 15th Meeting of the EURO Working Group on Transportation (EWGT 2012).*

Raveau, S., Muñoz J. C., DE Grange L., 2011. A topological route choice model for metro. *Transportation Research Part A: Policy and Practice*, 45(2), pp.138 – 147.

Reavy, M., 2003. Rules and the real world an examination of information graphics in time and Newsweek. *Visual Communication Quarterly*, 10(4), pp.4-10.

Roberts, M. J., 2009. *Henry Beck Rules, not OK? Breaking the Rules of Diagrammatic Map Design*. Available at: http://www.tubemapcentral.com/writing/webarticles/Roberts_BeckRules_2009.pdf [Accessed 24 Jan 2021]

Roberts, M. J., 2010. *All Washington DC Metro Stations on A Map*. [online] JetPunk. Available at: <https://www.jetpunk.com/user-quizzes/1260664/all-washington-dc-metro-stations-on-a-map> [Accessed 14 August 2020].

Roberts, M. J., 2011. DLR Route Diagrams: A usability study. Unpublished technical report, University of Essex, Colchester, UK.

Roberts, M. J., 2012. *Underground Maps Unravelled*: *Explorations in Information Design*. Self-published, Wivenhoe, Essex.

Roberts, M. J., 2013. *Integrating the mind*. Hove: Psychology Press.

Roberts, M. J., 2014. Schematic Maps in the Laboratory, Schematic Mapping Workshop, Essex, UK.

Roberts, M. J., 2014. *What Is Your Theory of Effective Schematic Map Design?* [online] Core.ac.uk. Available at: <https://core.ac.uk/display/74370544> [Accessed 14 August 2020].

Roberts, M. J., 2017. From reasoning and intelligence to information design. *The Thinking Mind*. Psychology Press.

Roberts, M.J., 2019. *Roche Diagram — The Decade of Diagnostics*. [online] Diagram. Available at: <https://rochediagram.com/the-decade-of-diagnostics/> [Accessed 14 August 2020].

Roberts, M. J., 2019. Us versus them: Ensuring practical and psychological utility of measurements of schematic map usability. In *Proceeding of the 2nd Schematic Mapping Workshop*.

Roberts, M. J., Gray, H. and Lesnik, J., 2017. Preference versus performance: Investigating the dissociation between objective measures and subjective ratings of usability for schematic metro maps and intuitive theories of design. International Journal of Human-Computer Studies, 98, pp.109-128.

Roberts, M. J., Newton, E.J., Lagattolla, F.D., Hughes, S., & Hasler, M.C., 2013. Objective versus subjective measures of Paris Metro map usability: Investigating traditional octolinear versus all-curves schematic maps. International Journal of Human Computer Studies, 71, pp.363-386.

Roberts, M. J., Newton E. J., Canals M., 2016. Radi(c)al departures: Comparing conventional octolinear versus concentric circles schematic maps for the Berlin U-Bahn/S-Bahn networks using objective and subjective measures of effectiveness. *Information Design Journal*, 22 (4) pp.92–114.

Roberts, M. J., Rose, D., 2016. Map-induced journey-planning biases for a simple network: A Docklands Light Railway study. *Transportation Research Part A: Policy and Practice*, 94, pp.446-460.

Roberts, M.J. 2019. Roche Diagram, *The Decade of Diagnostics*. [online] Diagram. Available at: <https://rochediagram.com/the-decade-of-diagnostics/> [Accessed 14 August 2020].

Roberts M., Vaeng I., 2016. Expectations and prejudices usurp judgements of schematic map effectiveness. *In Proceedings of the DRS2016: Design + Research + Society — Future-Focused Thinking.*

Robinson, A. H., 1952. *The Look of Maps: An Examination of Cartographic Design*, ESRI Press, Redlands, CA.

Robinson, A.H., Morrison J.L., Muehrcke P.C. and Kimerling A. J., 1995. *Elements of Cartography*, Sixth Edition. New York: John Wiley & Sons.

Rosenholtz R., 2011. What your visual system sees where you are not looking. *In Proceedings of the Human Vision and Electronic Imaging,* 16(7865), pp.343 – 356.

Sadahiro, Y., Tanabe, T., Pierre, M. and Fujii, K., 2015. Computer-aided design of bus route maps. *Cartography and Geographic Information Science*, 43(4), pp.361-376.

Salman Y., Cheng H. and Patterson P., 2012. Icon and user interface design for emergency medical information systems: A case study. *International Journal of Medical Informatics*, 81(1), pp.29-35.

Saliha A. and Menekse S., 2015. Optical illusions and effects on clothing design. *International Journal of Science Culture and Sport*, 3(2), pp.137-157.

Shedroff, N., 2001. *Experience design*. Indiana: New Riders.

Silvia, P. J., and Barona, C. M., 2009. Do people prefer curved objects? Angularity, expertise, and aesthetic preference. *Empirical Studies of the Arts*, 27, pp.25-42.

Simon, T. and Halford, G., 1995. *Developing cognitive competence*. Hillsdale: NJ: Lawrence Erlbaum Associates.

Slocum, T., 2014. *Thematic cartography and geovisualization*. Harlow, Essex: Pearson Education limited.

Smiciklas, M., 2012. *The Power of Infographics: Using Pictures to Communicate and Connect with Your Audiences*. Indianapolis, Ind.: Que Pub.

Sort, J., 2006. *Metropolitan Networks*. NAI Boekverkopers.

Stigmar, H., 2010. *Making 21st Century Maps Legible – Methods for Measuring and Improving the Legibility and Usability of Real-Time Maps*, Lund University, Lund.

Stott, J. M., and P. Rodgers., 2004. Metro Map Layout Optimization Using Multicriteria. In Proceedings of the Eighth *International Conference on Information Visualisation*, pp.14–16.

Stone G. and Hall P., 1997. Do newspaper graphic have two dimensions? *Visual Communication Quarterly*, 4(4), pp.4-10.

Strickfaden M. and Devlieger P., 2011. Empathy through Accumulating Technology: Designing an Accessible Metro. *The Design Journal*, 14(2), pp.207-229.

Strickfaden, M. and Devlieger, P., 2011. The Brussels Metro: Accessibility through Collaboration. *Journal of Visual Impairment & Blindness*, 105(10), pp.638-647.

Sweller, J. and Chandler, P., 1994. Why Some Material is Difficult to Learn. *Cognition and Instruction*, 12(3), pp.185- 233.

Tanyoung K. and DiSalvo C., 2010. *Speculative Visualization: A New Rhetoric for Communicating Public Concerns*. Design Research Society International Conference Design and Complexity, Montreal: DRS Conference Proceedings.

Tetlan L. and Marschalek D., 2016. How Humans Process Visual Information: A focused primer for designing information. *Visible Language*, 50(3), pp.65-88.

Tian, T., 2021. *Effective visual instructions for Chinese characters learning: The specific case of learning Chinese semantic radicals by non-specialist beginners - White Rose eTheses Online*. [online] Etheses.whiterose.ac.uk. Available at: <https://etheses.whiterose.ac.uk/28787/> [Accessed 23 December 2021].

Vanhamaki S., Heinonen A., Manskinen K. and Kälviäinen M., 2017. Information design as a tool for promoting renewable energy. *The Design Journal*, 20(1), pp.1827-1835.

Velasco, C., Woods, A., Hyndman, S. and Spence, C., 2015. The Taste of Typeface. *I-Perception*, 6(4), pp.1-10.

Vertesi J., 2008. Mind the gap: The London Underground map and users' representations of urban space. *Social Studies of Science*, 38(1), pp.7–33.

Viera, X.G., 2012. A diverse and driven crew at the New York Times. A look at one of the world's most admired graphics desks. In SND-E (Ed.), Malofiej 19: *International infographics awards*, pp.52–65. Pamplona, Spain: Universidad de Navarra.

Waller, R., 2011. *Simplification: what is gained and what is lost.* Technical paper 1. Reading, UK: Simplification Centre, University of Reading.

Wang L. J., Giesen J., McDonnell K., Zolliker P. and Mueller K., 2008. Colour Design for Illustrative Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 14(6), pp.1739-1754.

Ware C., 2004. *Information Visualization: Perception for Design,* San Francisco: Morgan Kaufmann.

Ware, C., 2008. *Visual Thinking for Design*. Burlington, MA: Morgan Kaufmann.

Wang S., 2016. *Typography: exploring the limits*. Barcelona: Denise Gonzales Crisp.

Wang, Z., Lonsdale M.D.S. and Cheung V., 2020. An eye-tracking study examining information search in transit maps: Using China's high-speed railway map as a case study. *Information Design Journal*. 26(1), pp.1-26.

Westland, S., Laycock K., Cheung V., Henry P. and Mahyar F., 2012. Colour harmony. *Colour: Design & Creativity*, 1(1), pp.1-15.

White, A., 2002. *The Elements of Graphic Design*. New York: Allworth Press.

William, C., 2018. *Typographic emphasis and contrastive focus: an eye tracking study*. PhD thesis, University of Leeds.

Williams, R. and Tollett, J., 1998. *The Non-Designer's Web Book: An Easy Guide To Creating, Designing, And Posting Your Own Web Site*. San Francisco: Peachpit Press.

Wolfe, J. M., 1994. Guided Search 2.0 a revised model of visual search. *Psychonomic Bulletin and Review,* 1(2), pp.202–238.

Wong, W., 1986. *Principles of Colour Design*. New York: Van Nostrand Reinhold Co.

Wu, H., Niedermann, B., Takahashi, S., Roberts, M. and Nöllenburg, M., 2020. A Survey on Transit Map Layout – from Design, Machine, and Human Perspectives. *Computer Graphics Forum*, 39(3), pp.619-646.

Xu J., 2017. Map sensitivity vs. map dependency: A case study of subway maps' impact on passenger route choices in Washington DC. *Behavioral Sciences,* 7(4), pp.112-129.

Wurman R., Whitehouse K., Sume D. and Leifer L., 2001. *Information anxiety 2*. Hayden, Quebec: Pearson Education.

Yau N., 2013. *Data points: Visualization that means something*. Indianapolis, IN: John Wiley and Sons.

Yoeli P., 1972. The logic of automated map lettering. *The Cartographic Journal*, 9(2), pp.99–108.

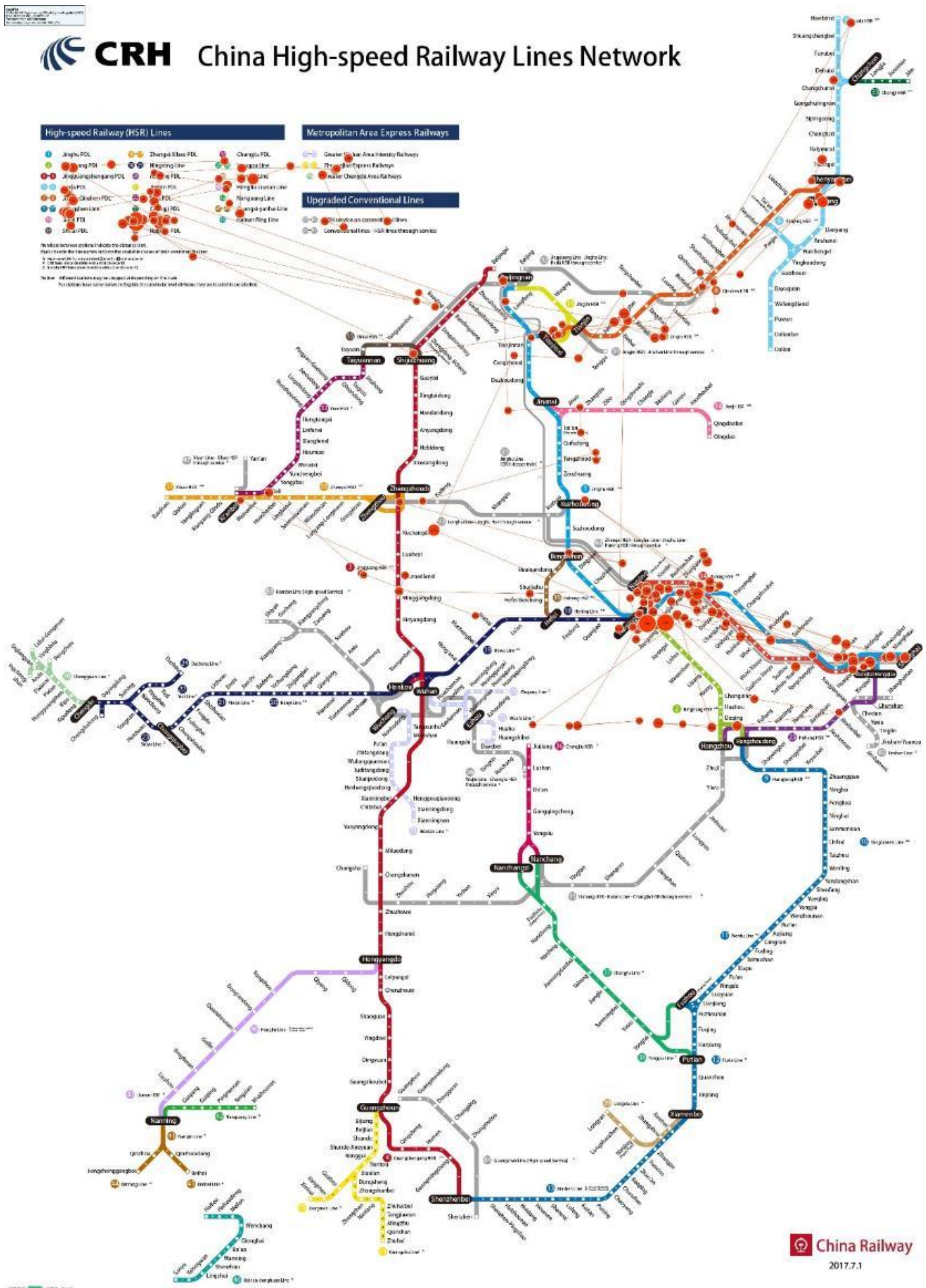
Zender M. and Cassedy A., 2014. (Mis)understanding: icon comprehension in different cultural contexts. *Visible Language*, 48(1), pp.69-96.

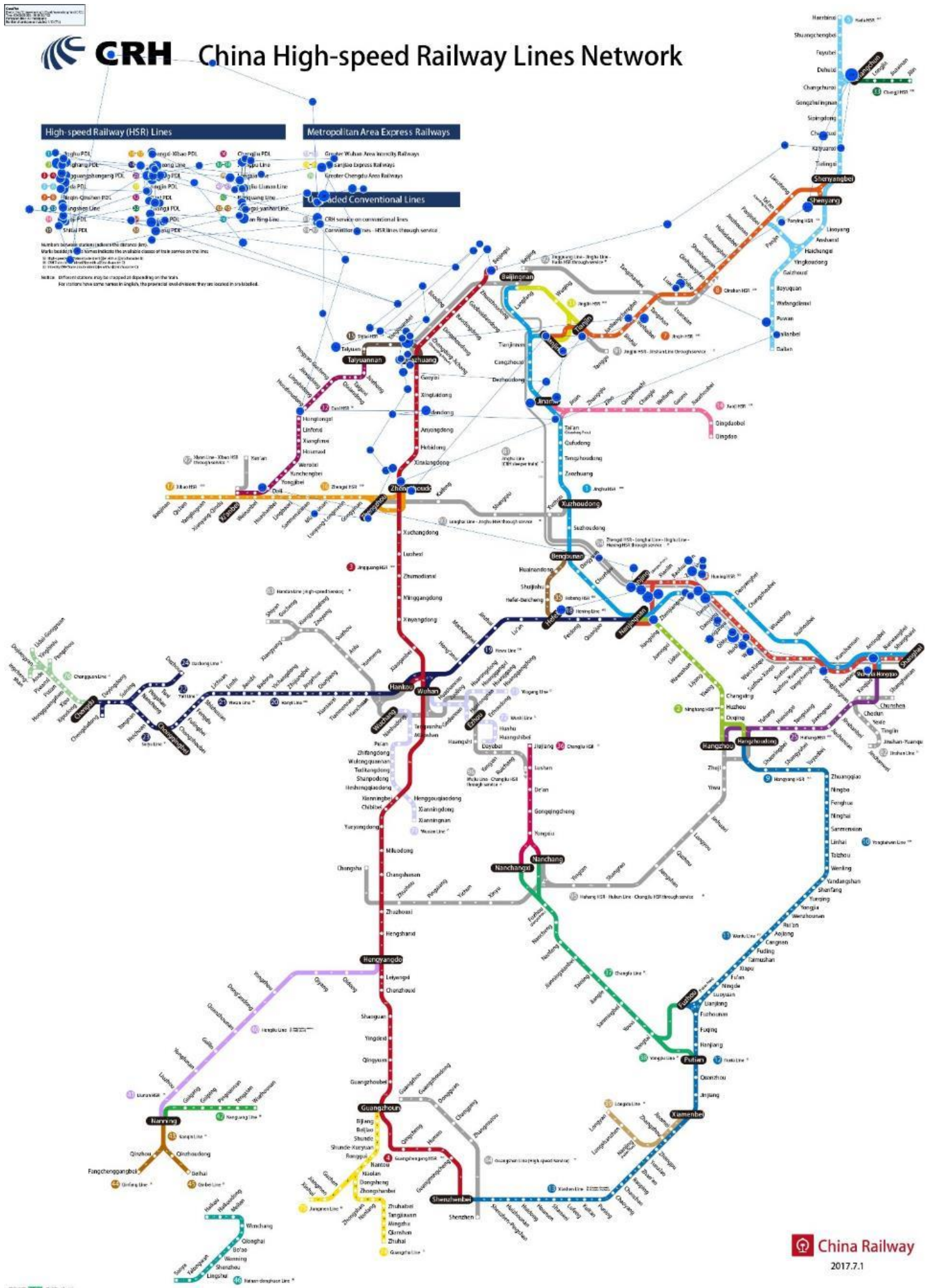
Zoltowski C. B., W. C. Oakes and M. E. Cardella. (2012). tudents' Ways of Experiencing Human-centered Design. *Journal of Engineering Education*. 101 (1), pp.28-59.

Appendices:

Appendix I: Eye-tracking gaze-plot maps and hotspot maps

Experiment I, Task 1

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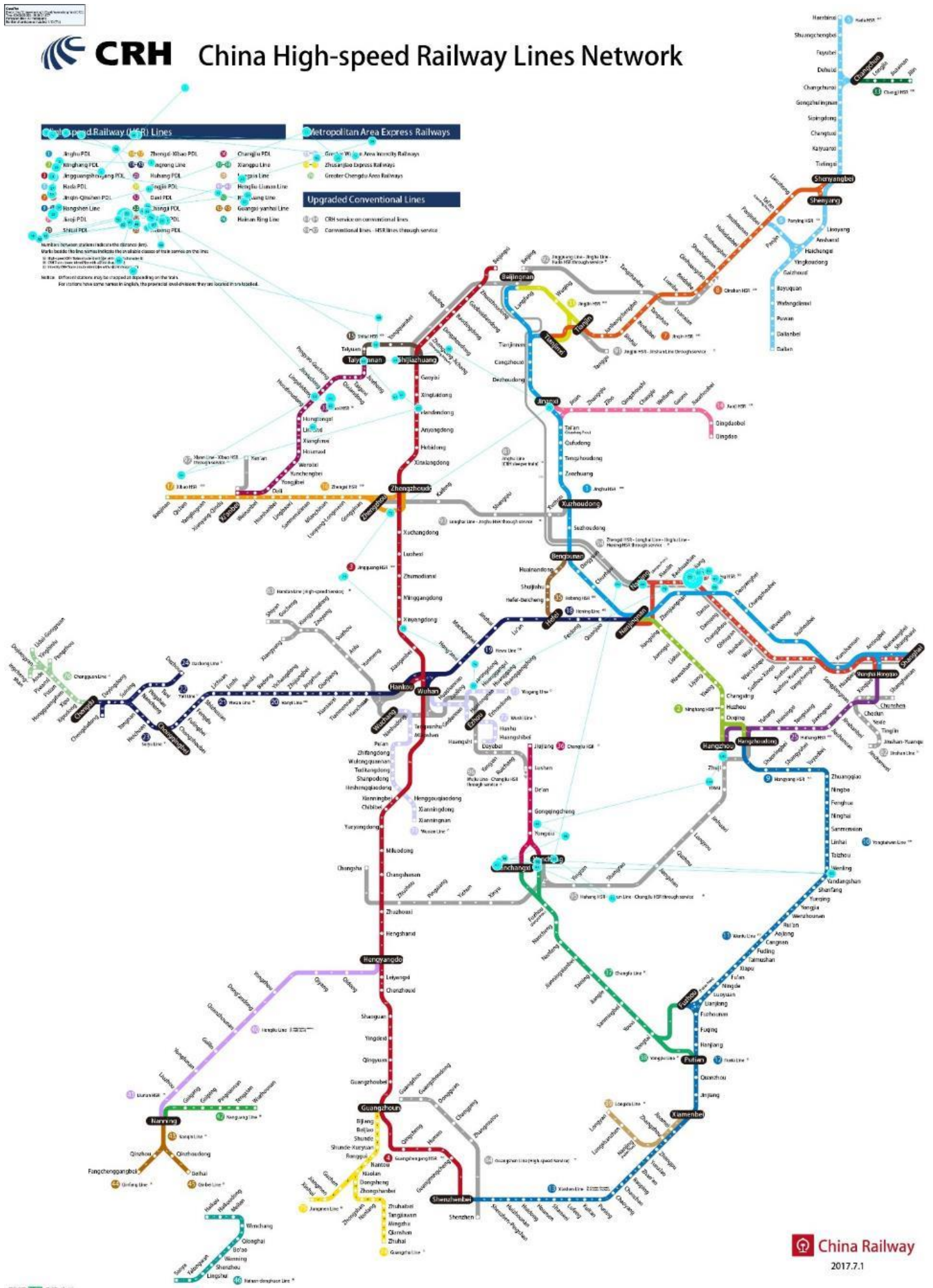
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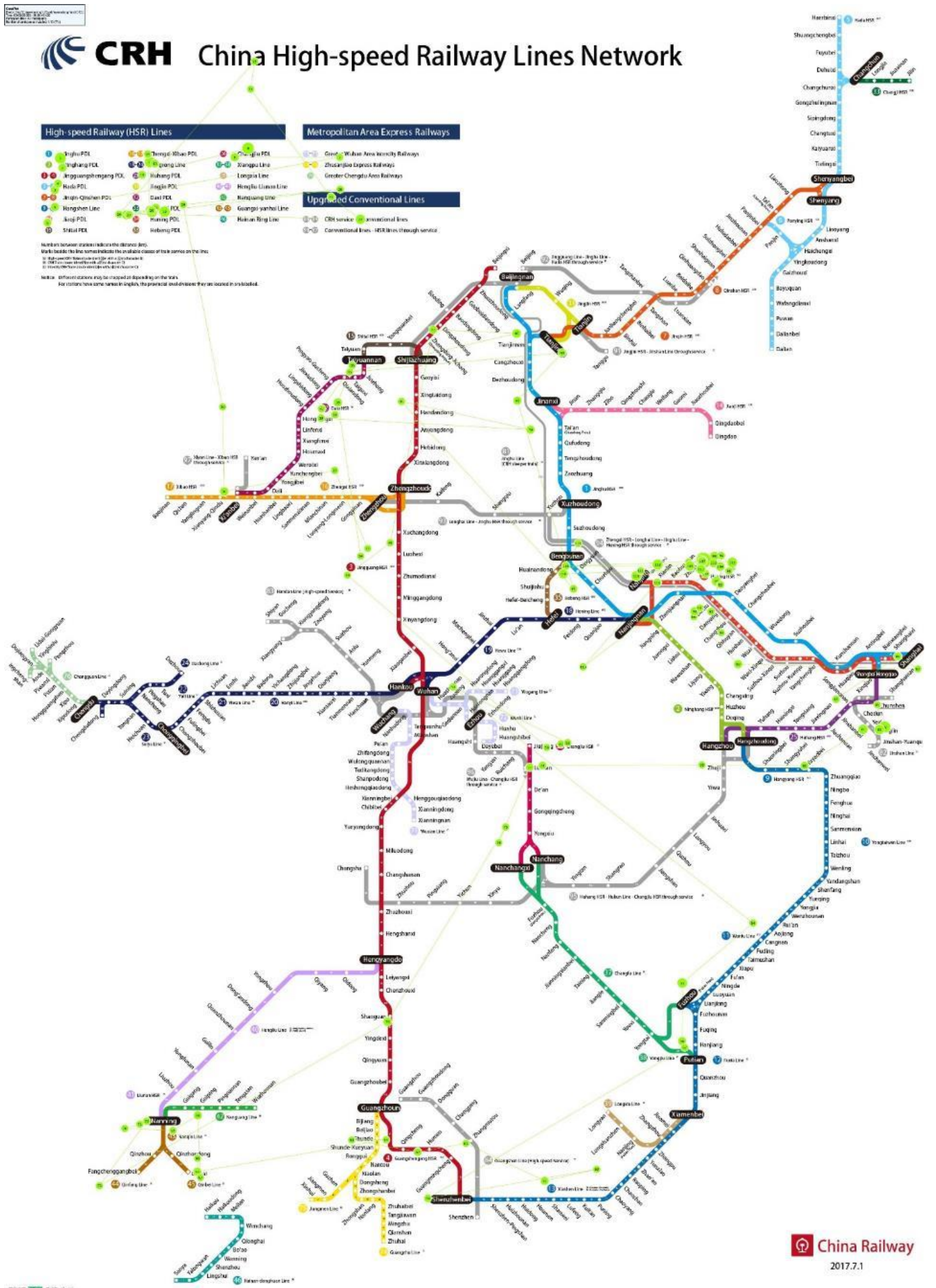

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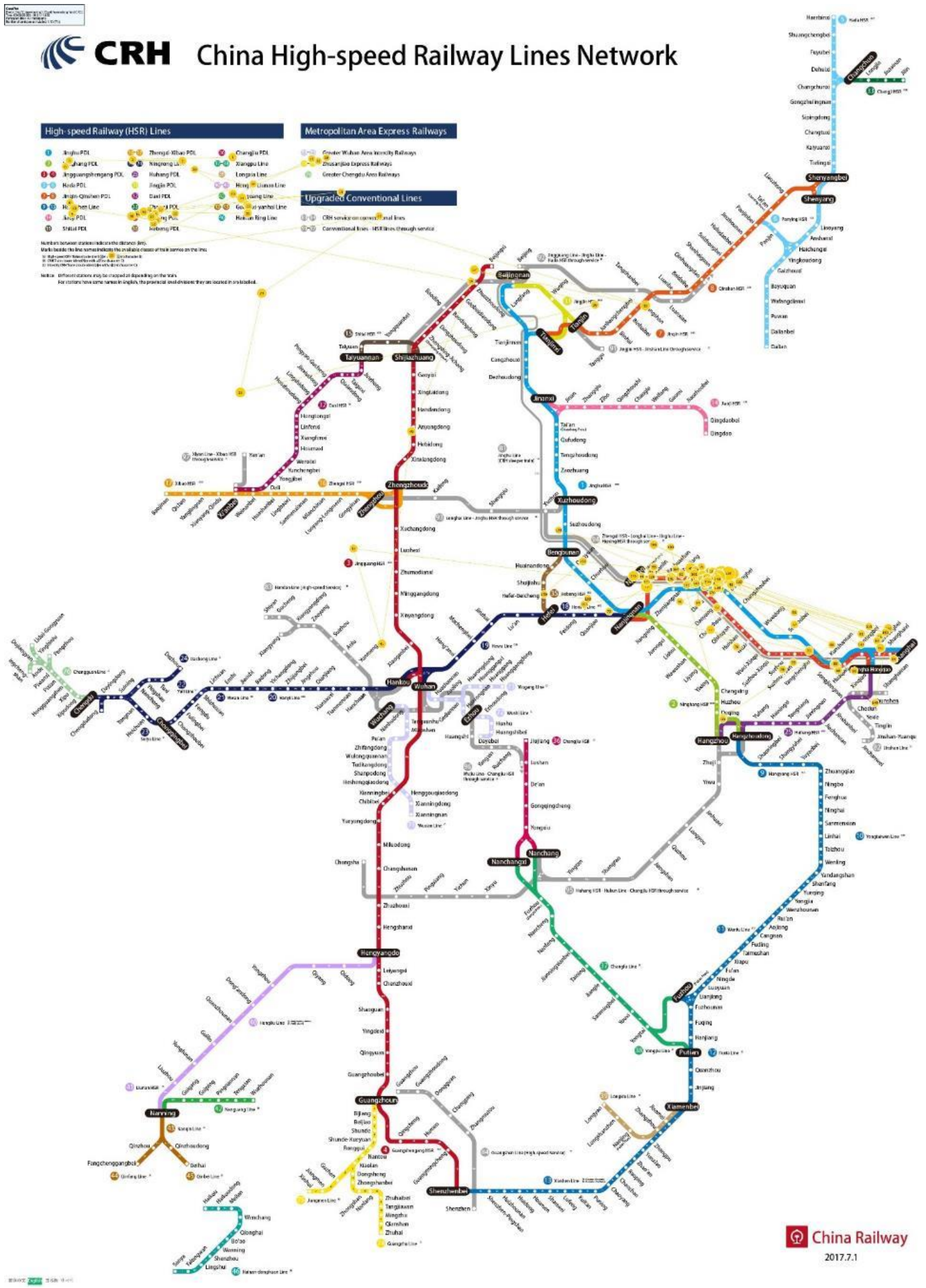
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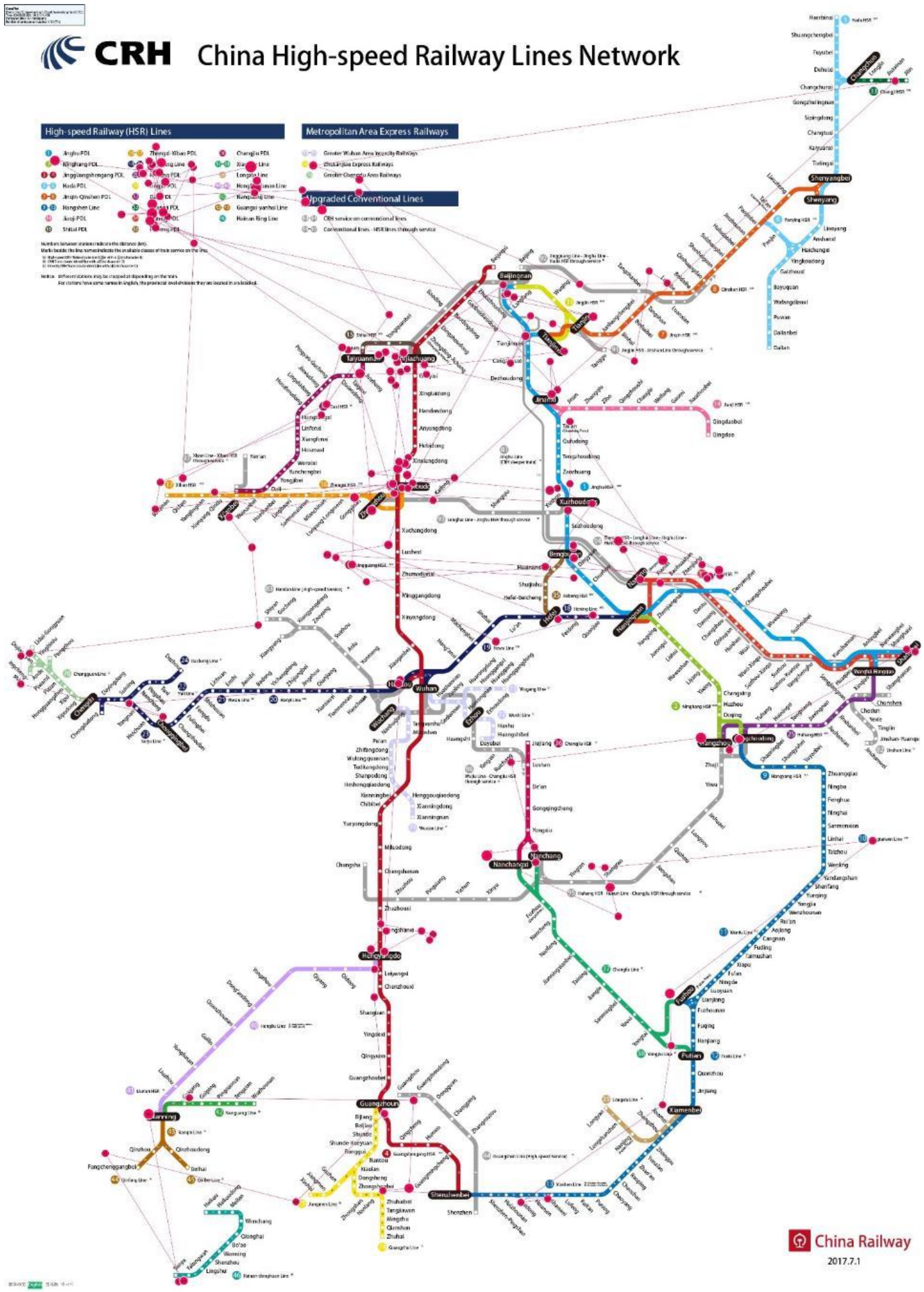

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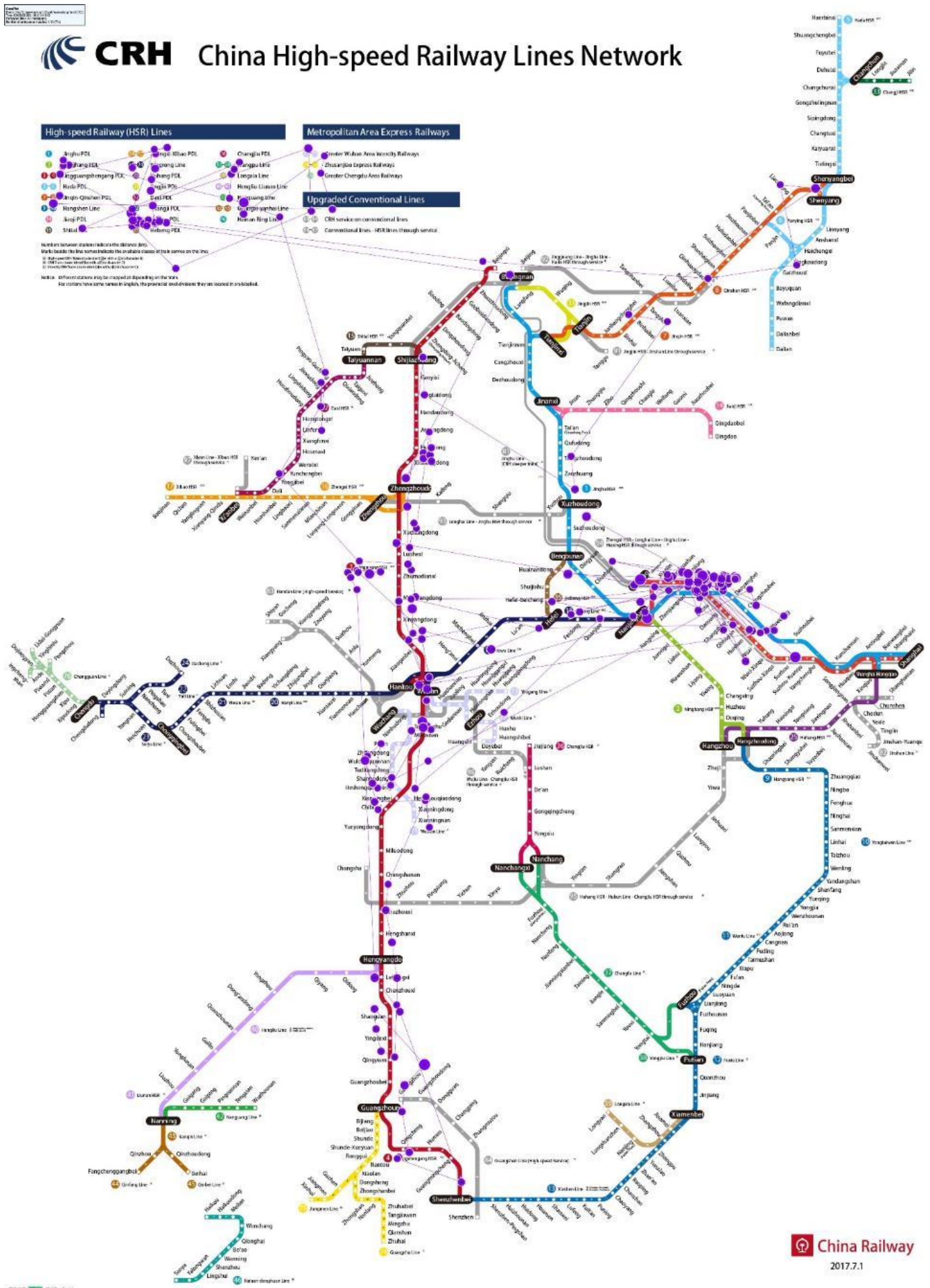
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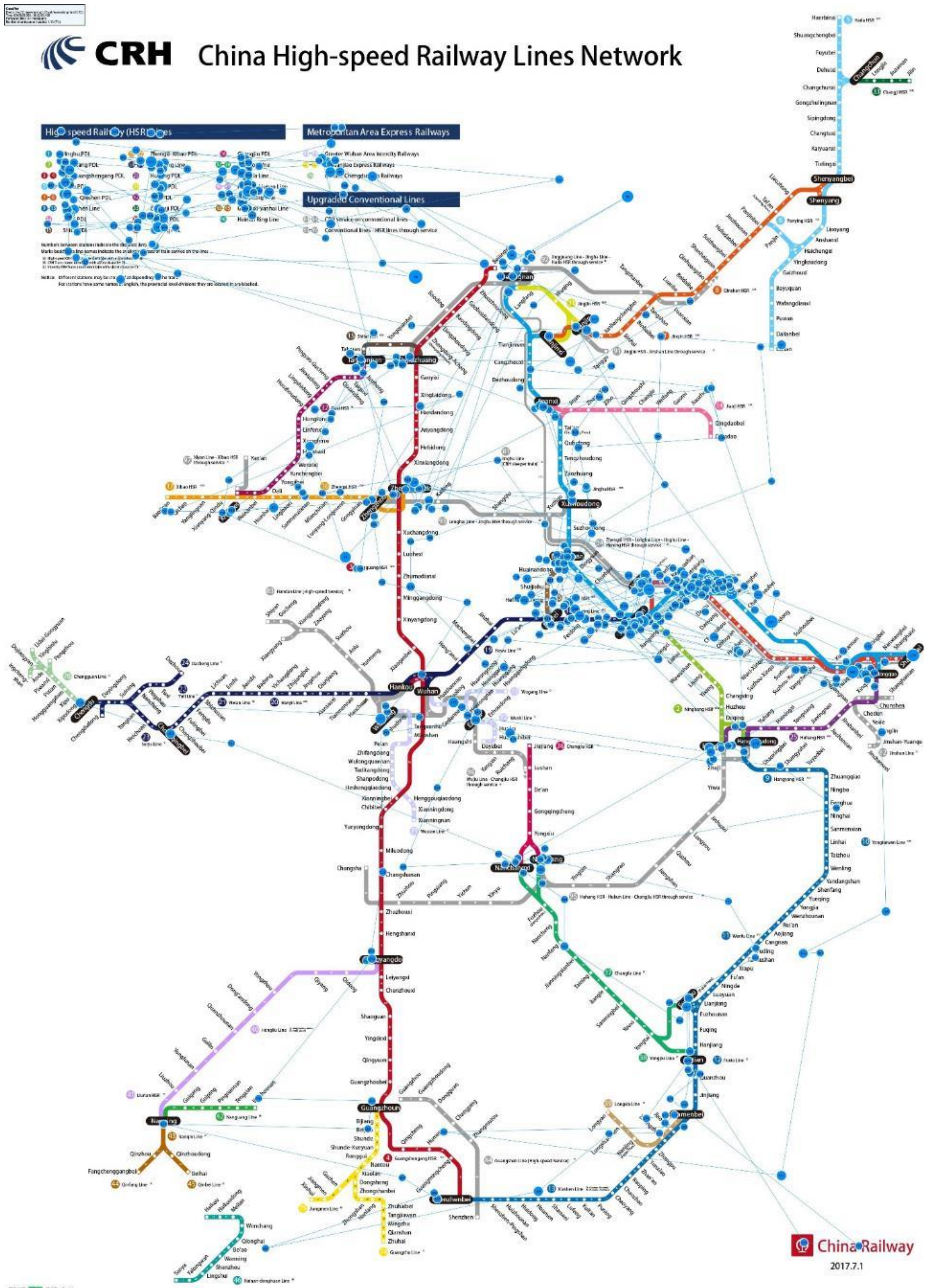
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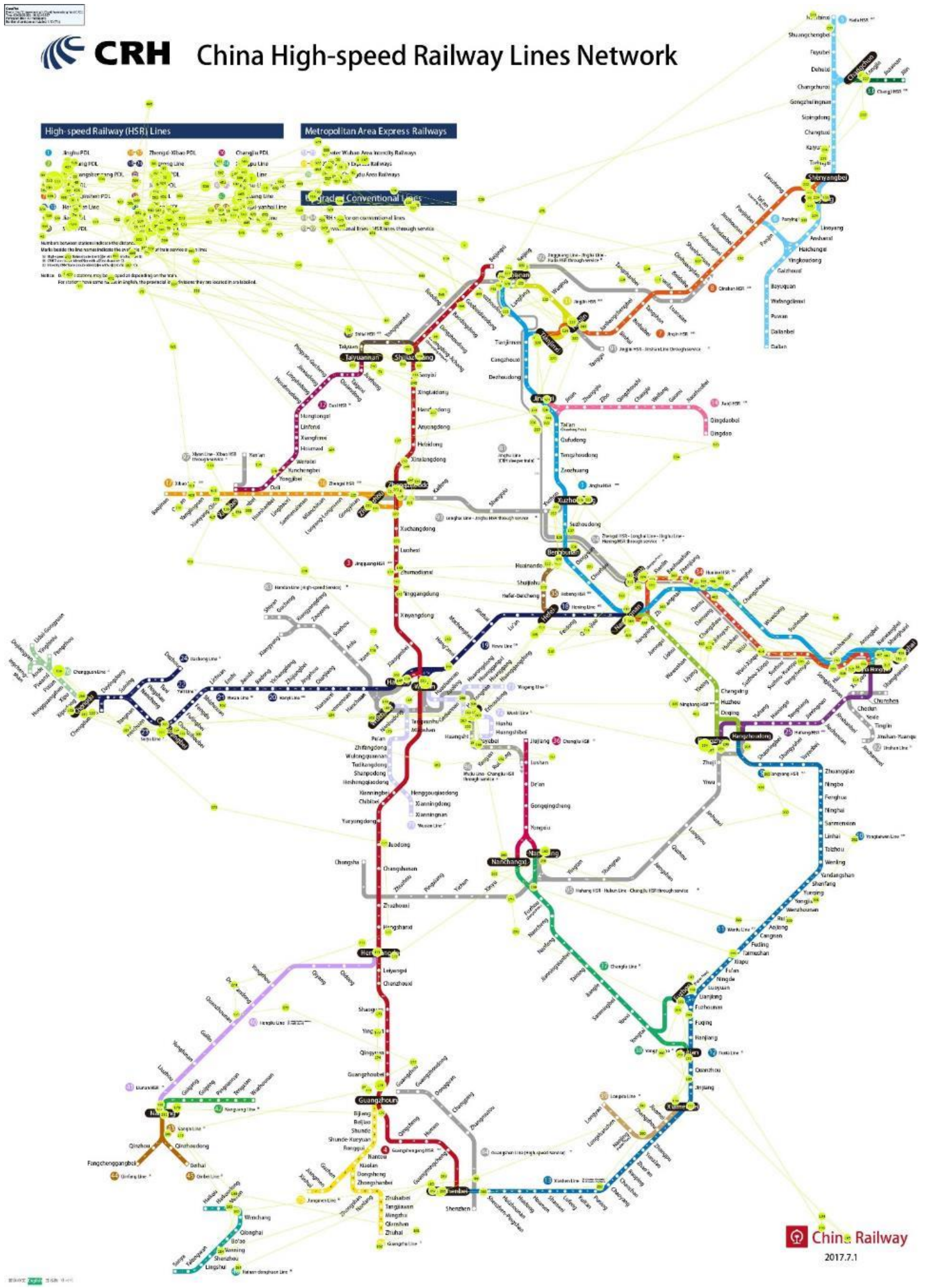
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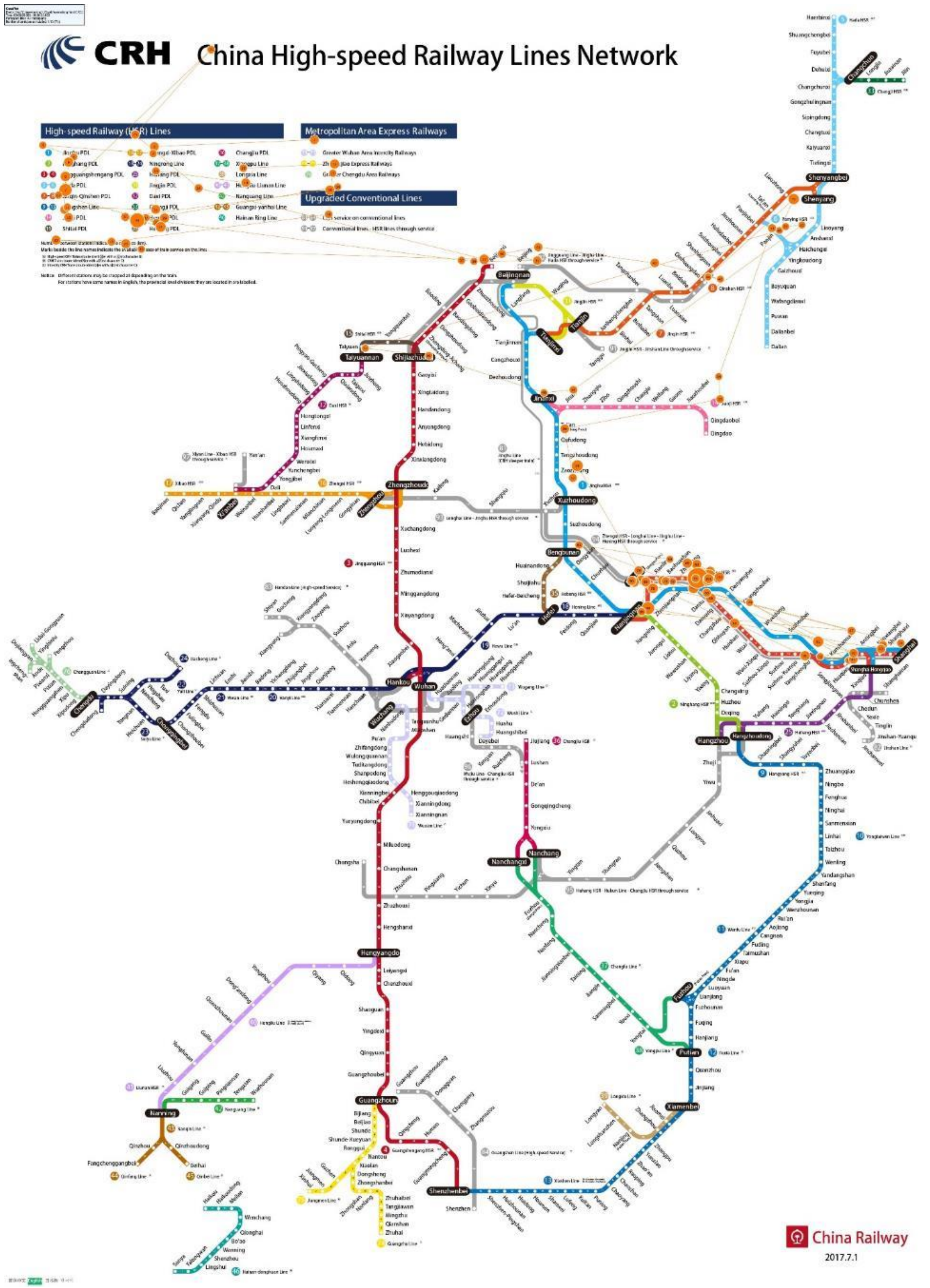
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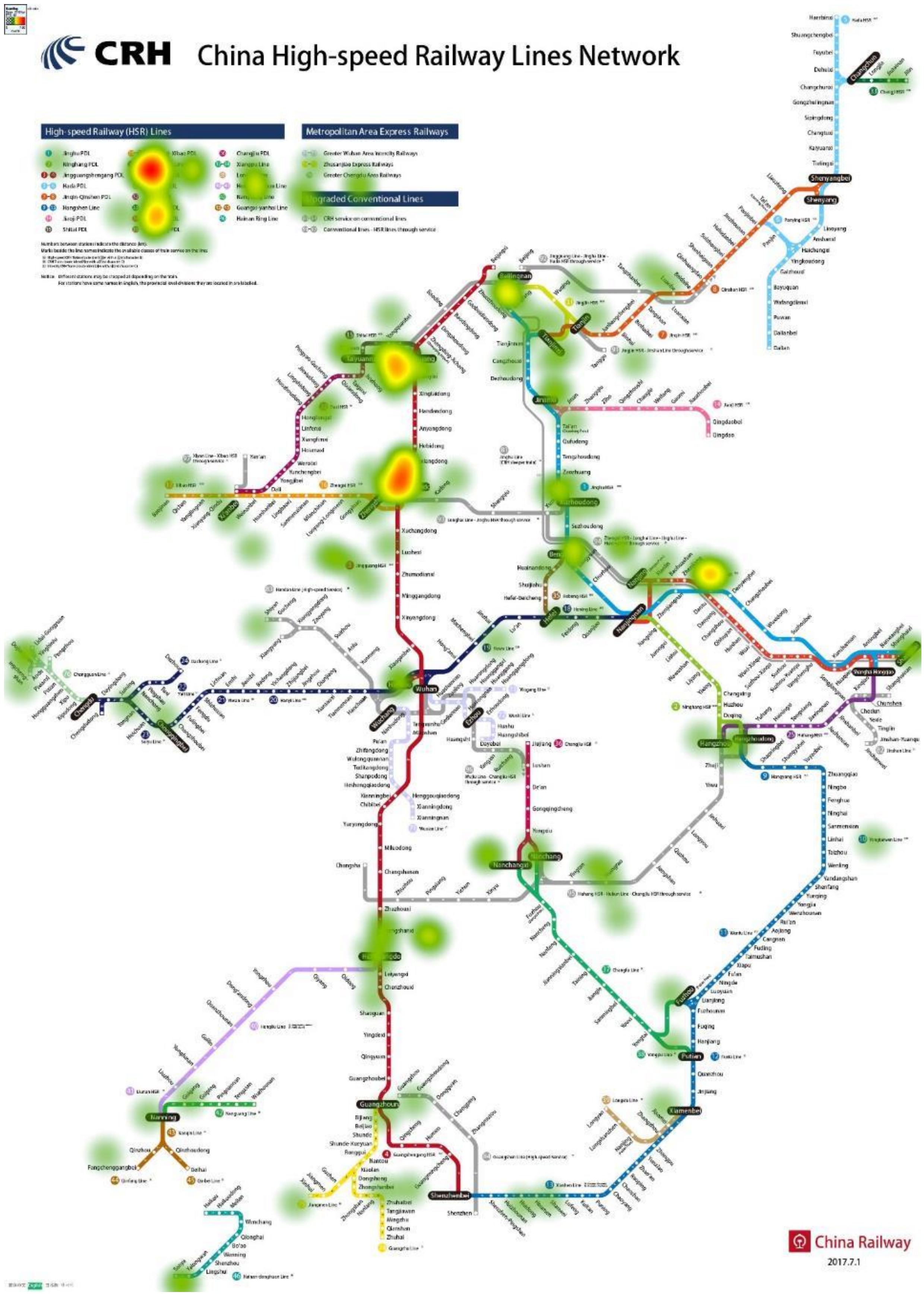

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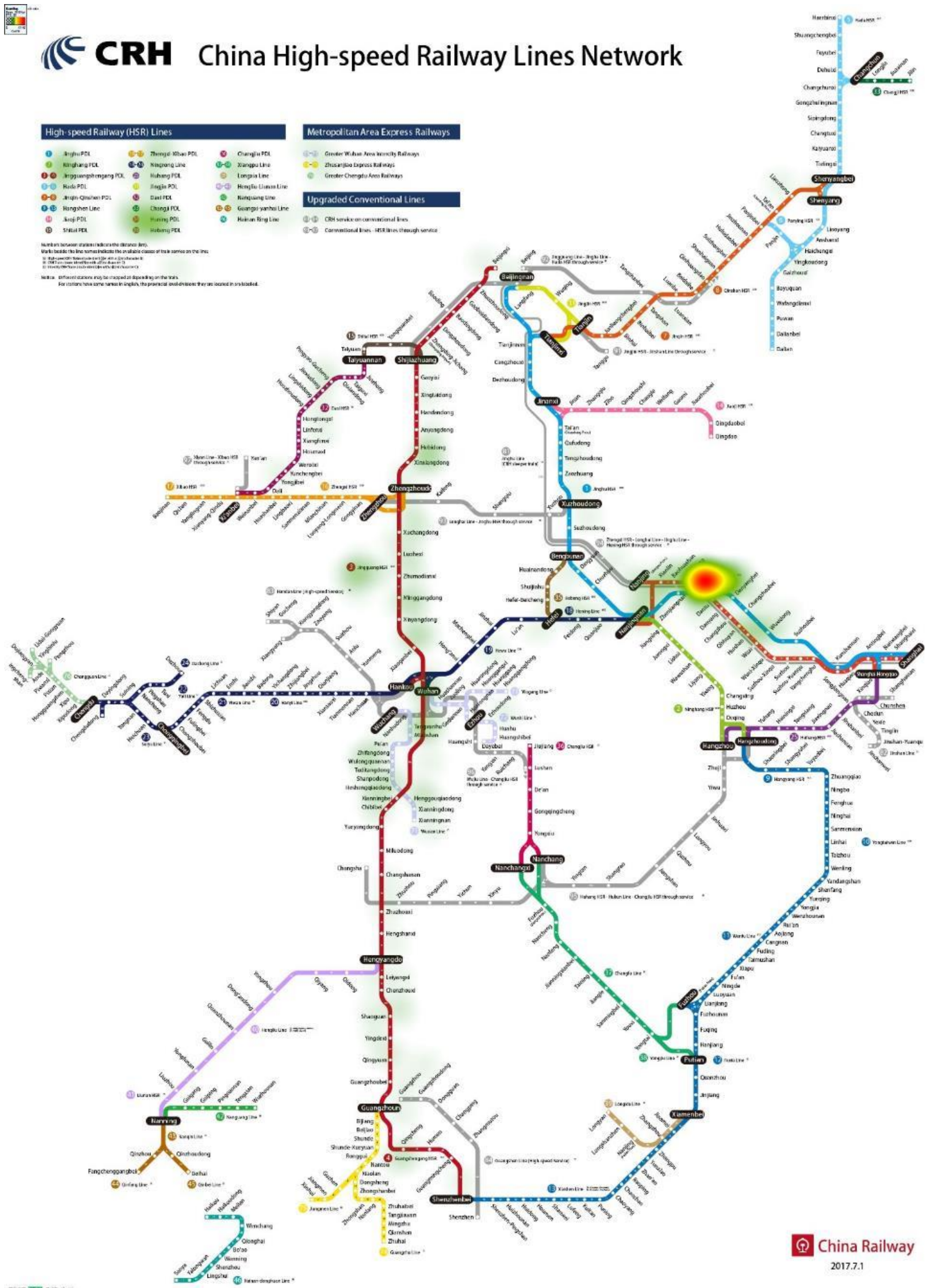
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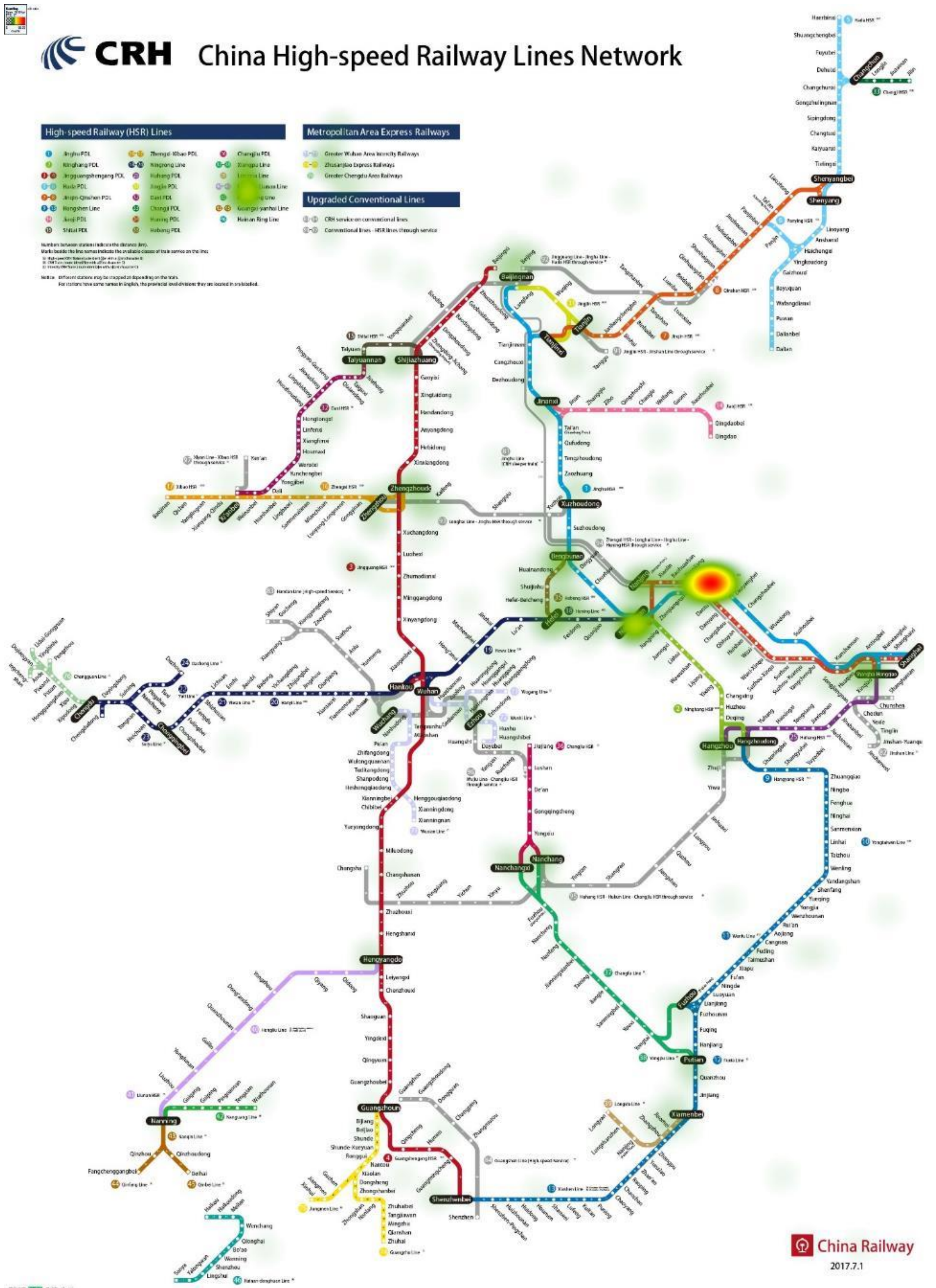
2017.7.1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Metropolitan Area Express Railways
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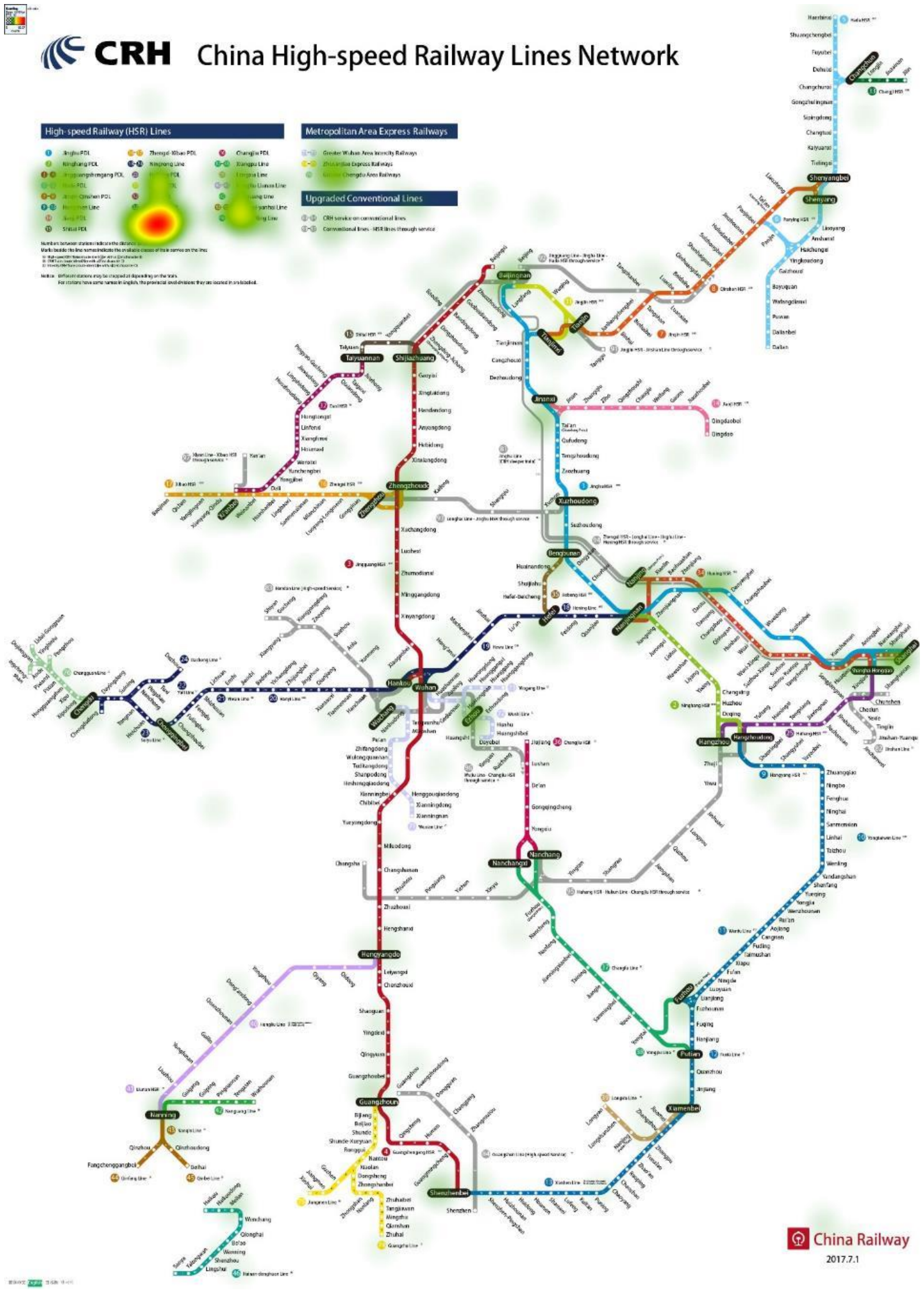
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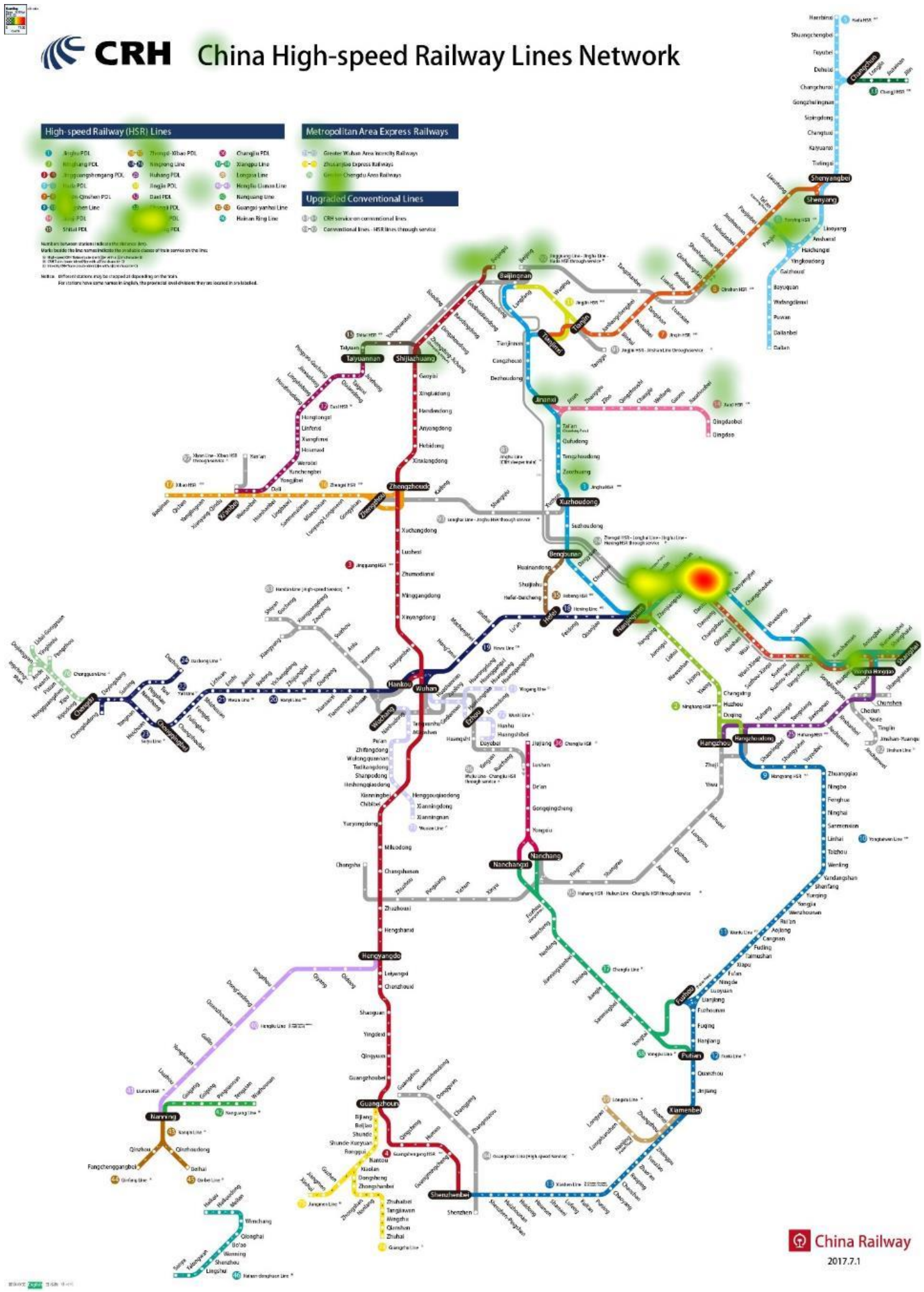
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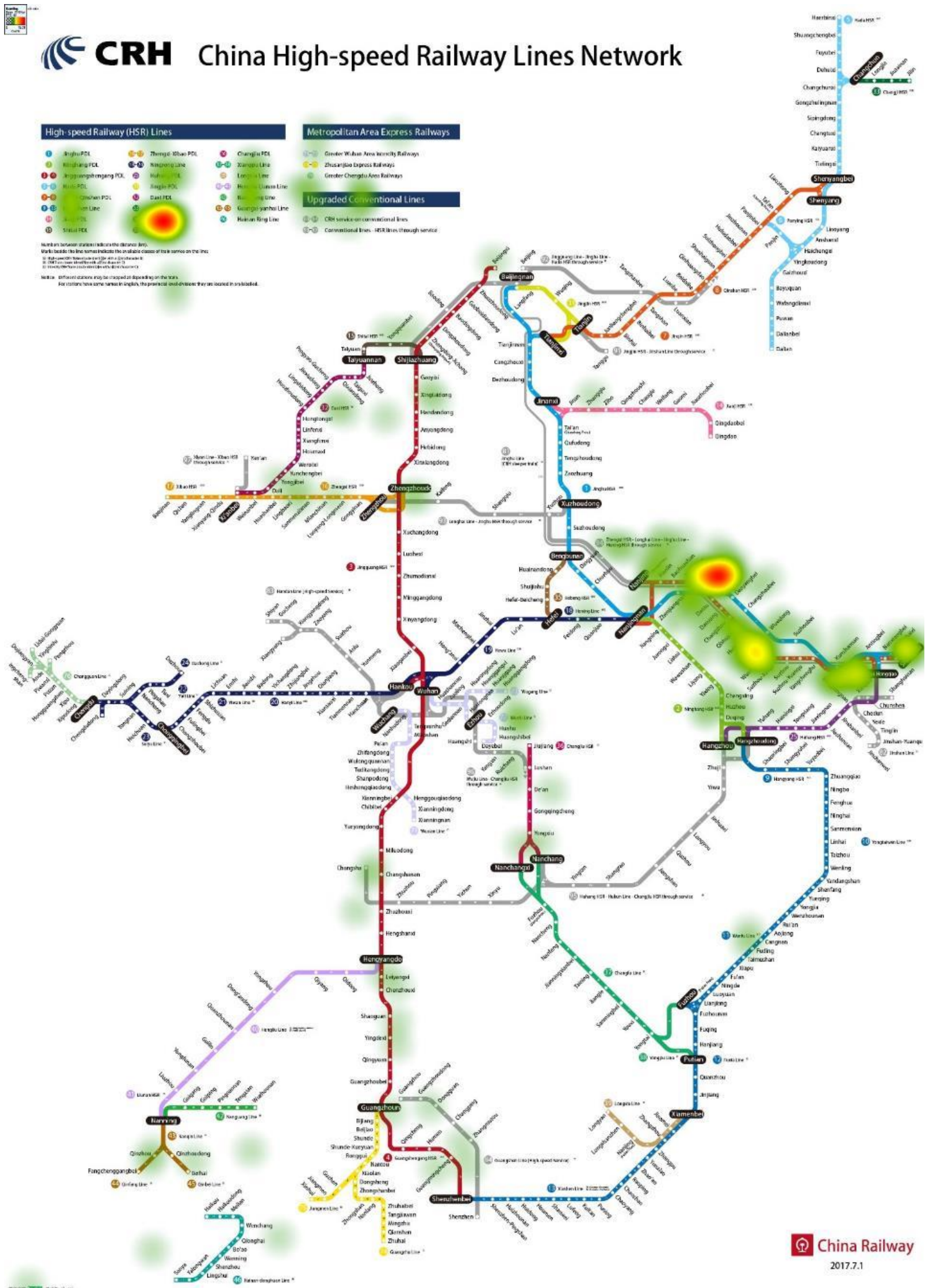
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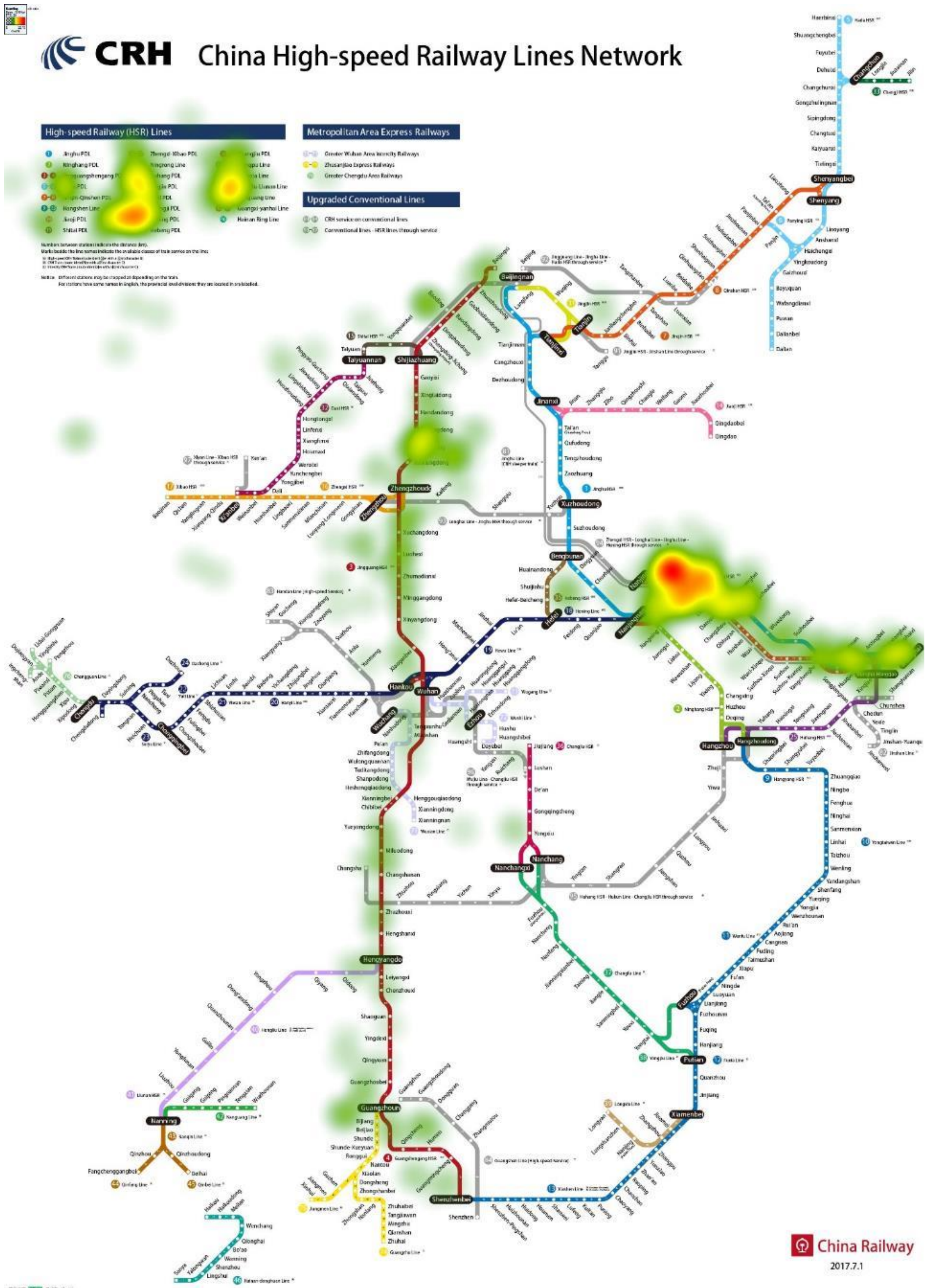
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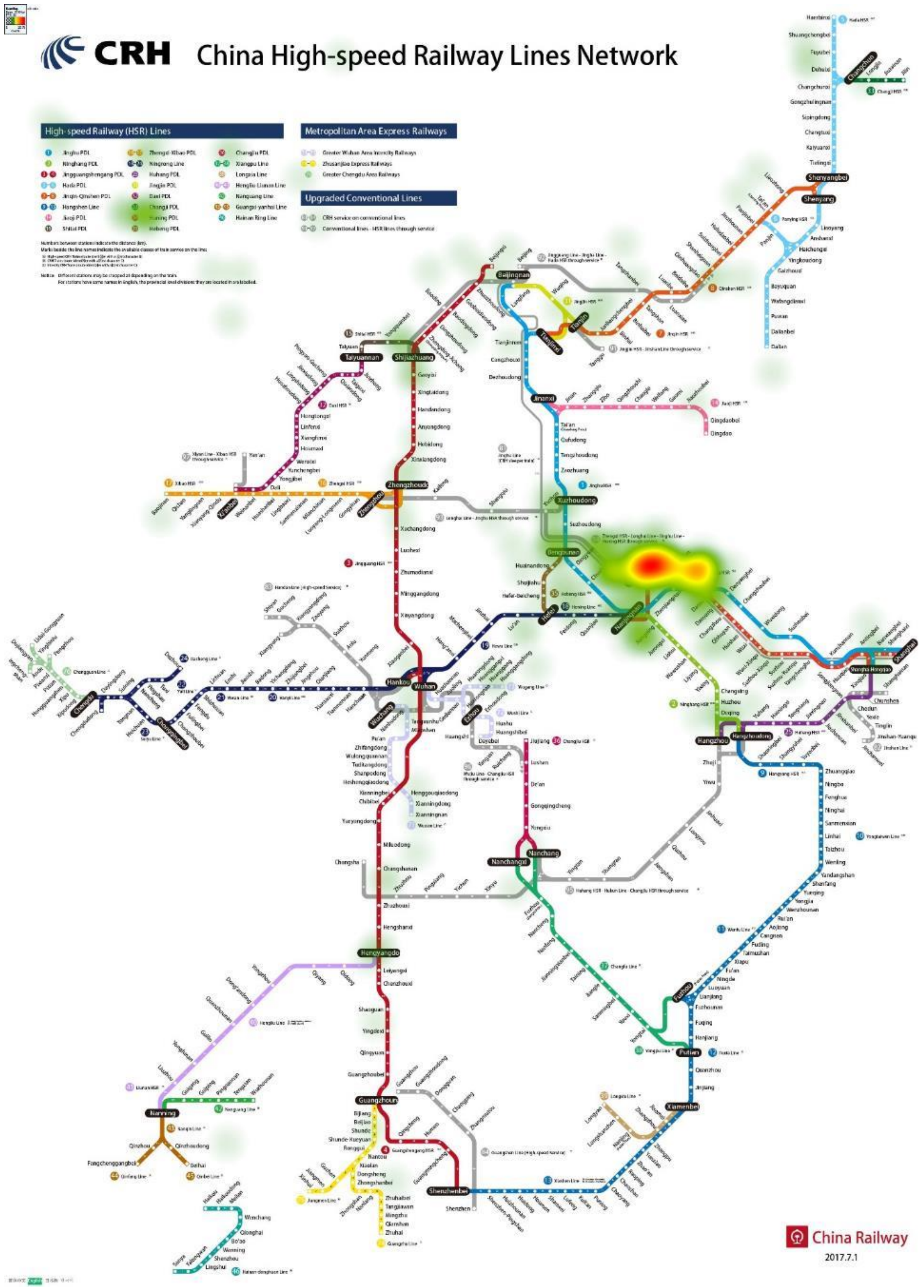
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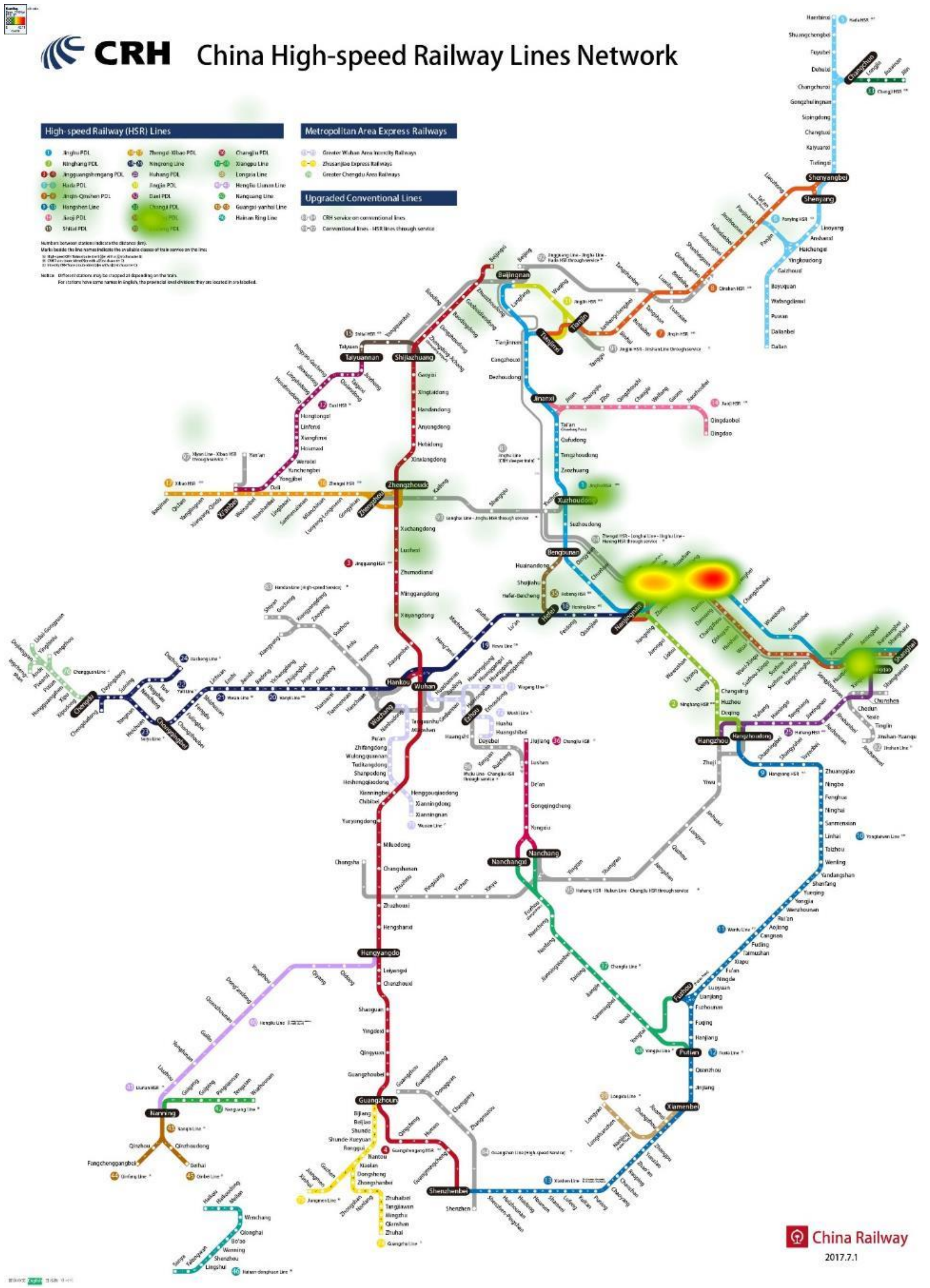
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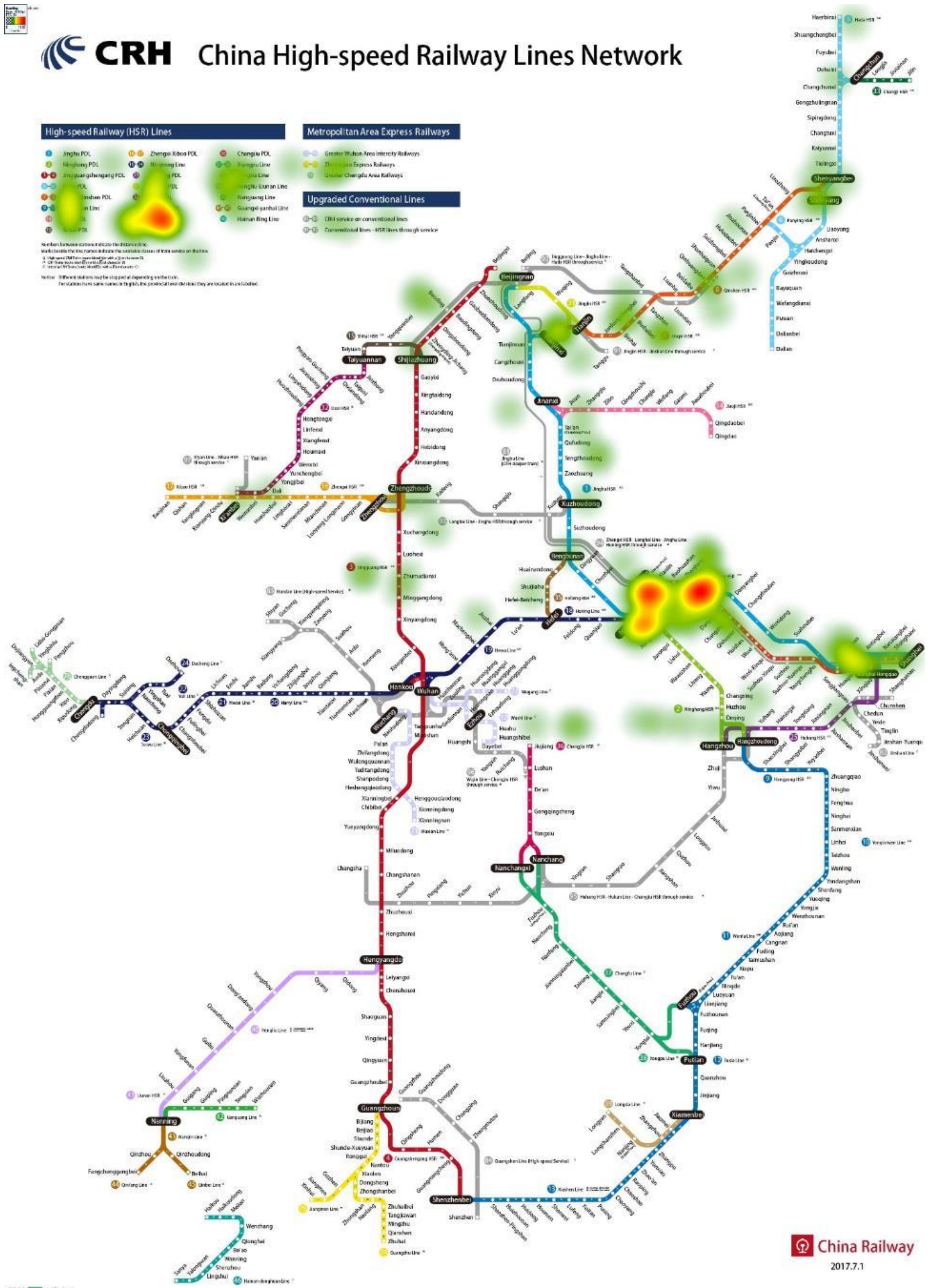
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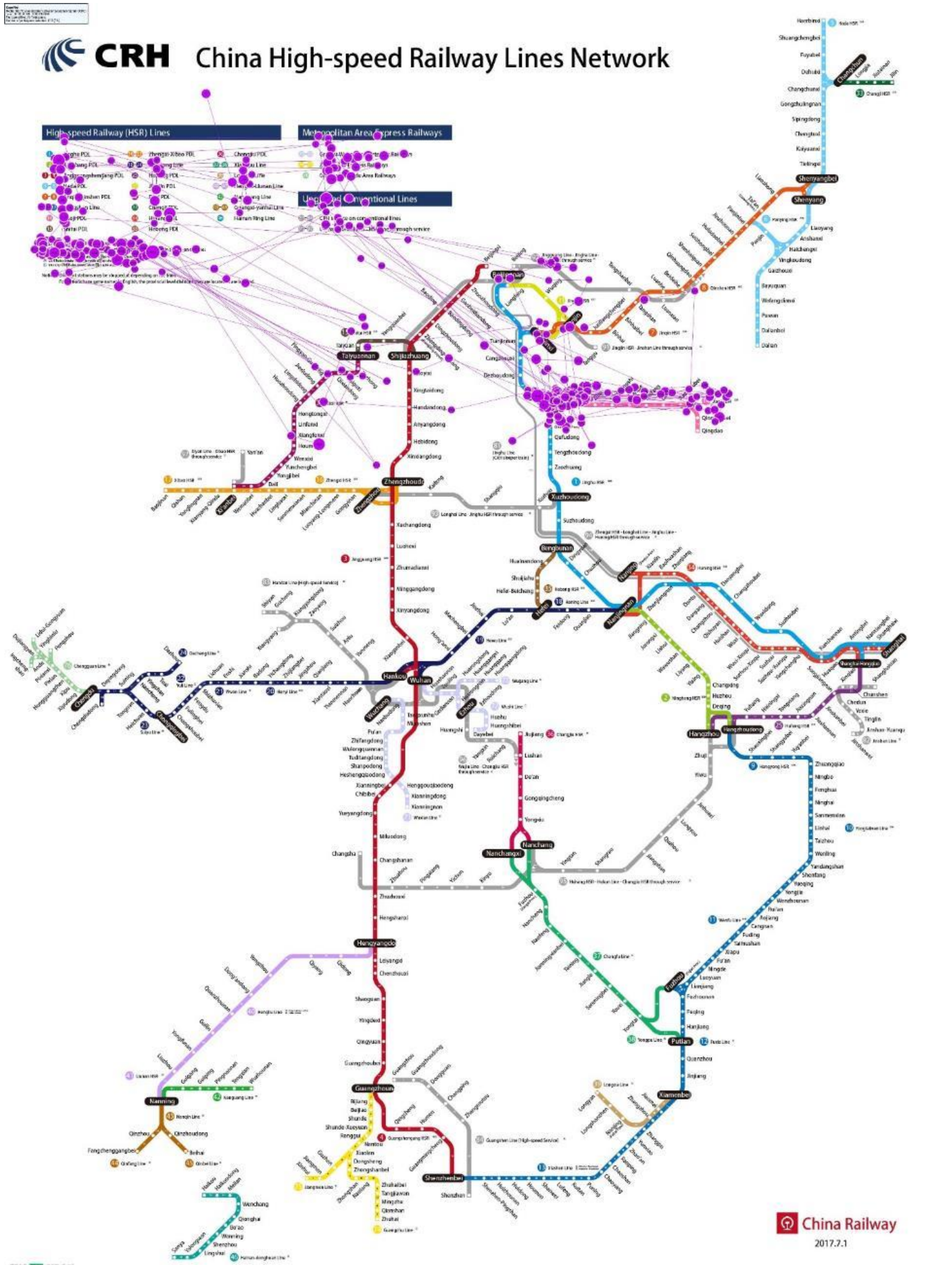
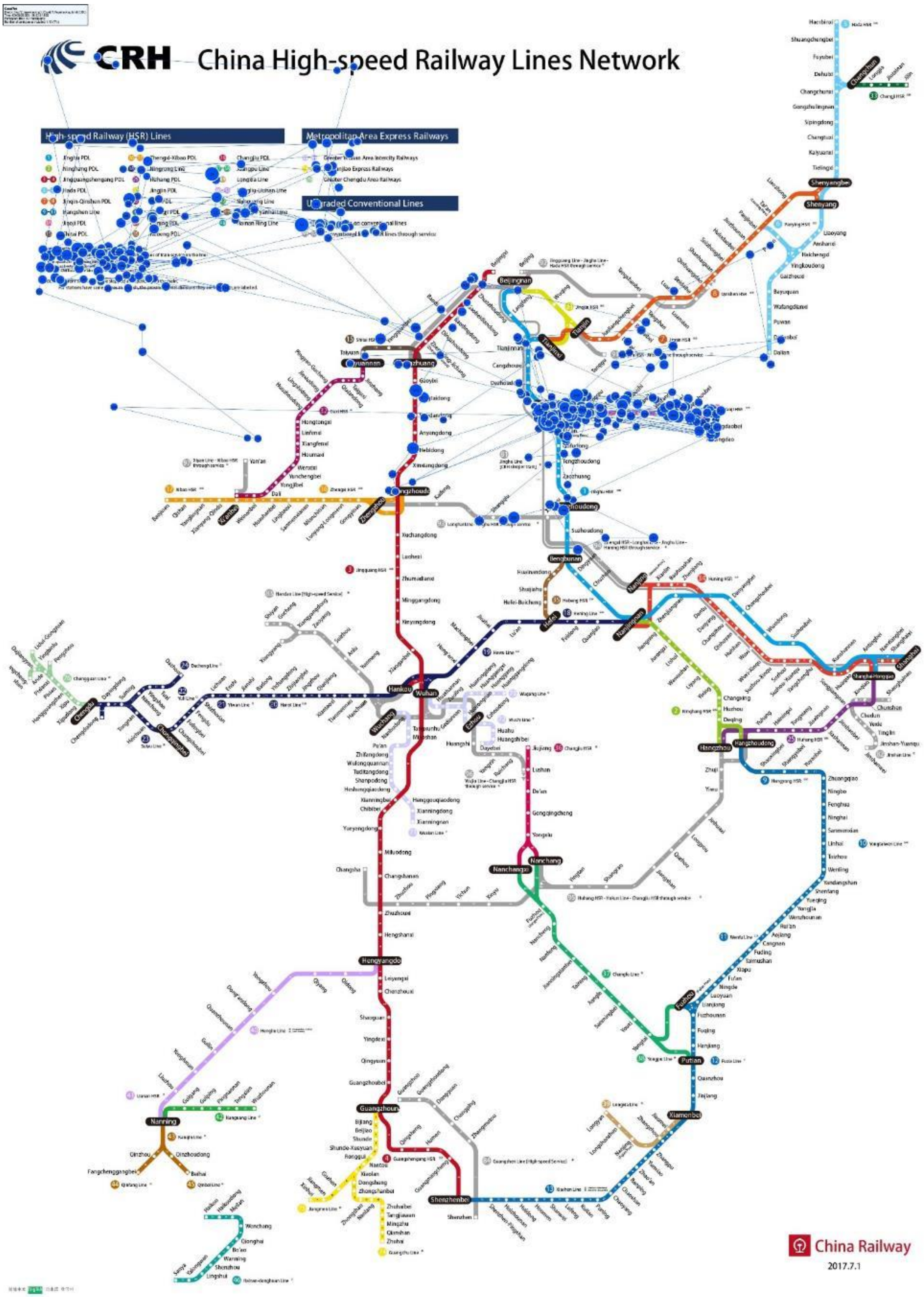
Experiment I, Task 2





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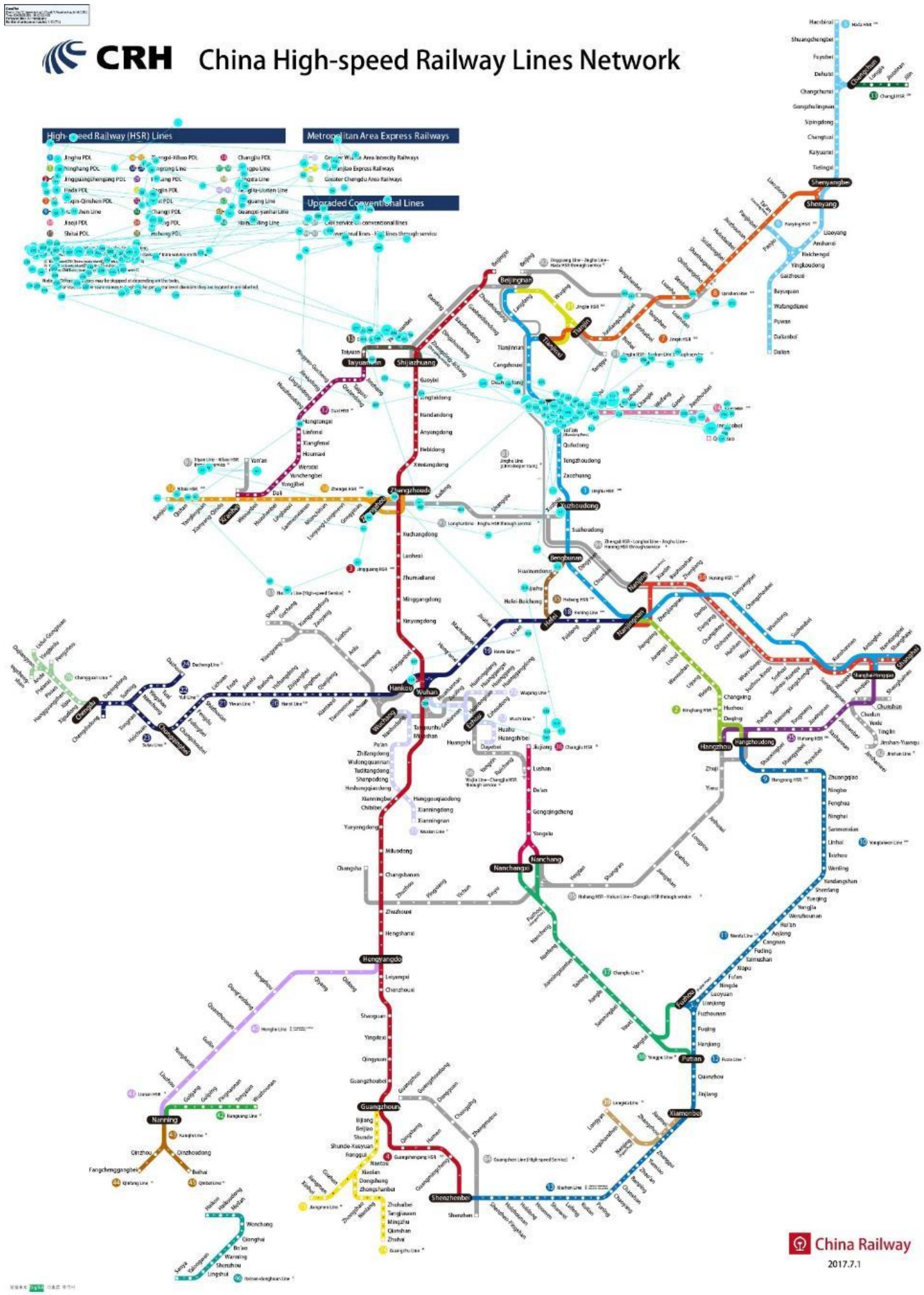

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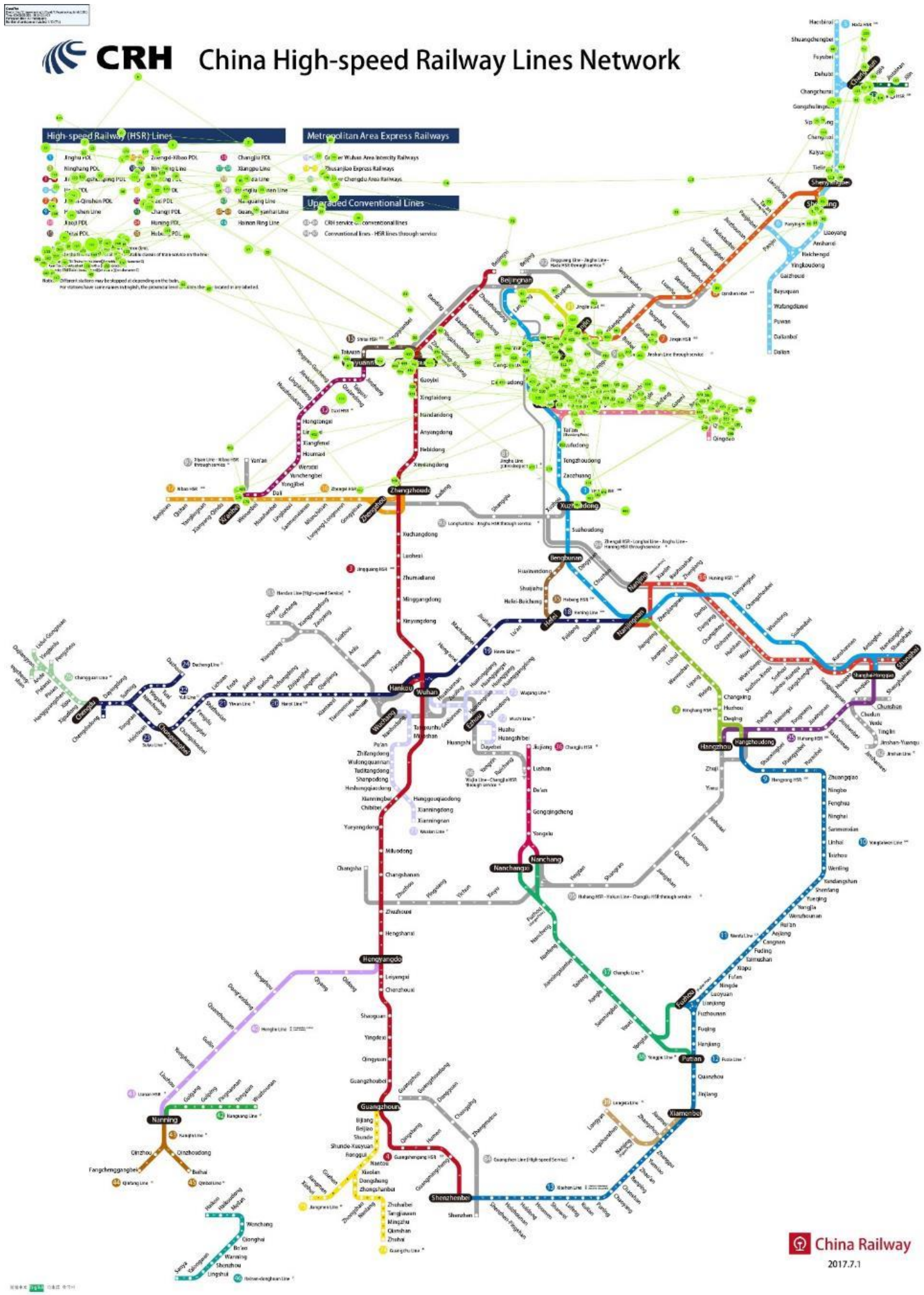
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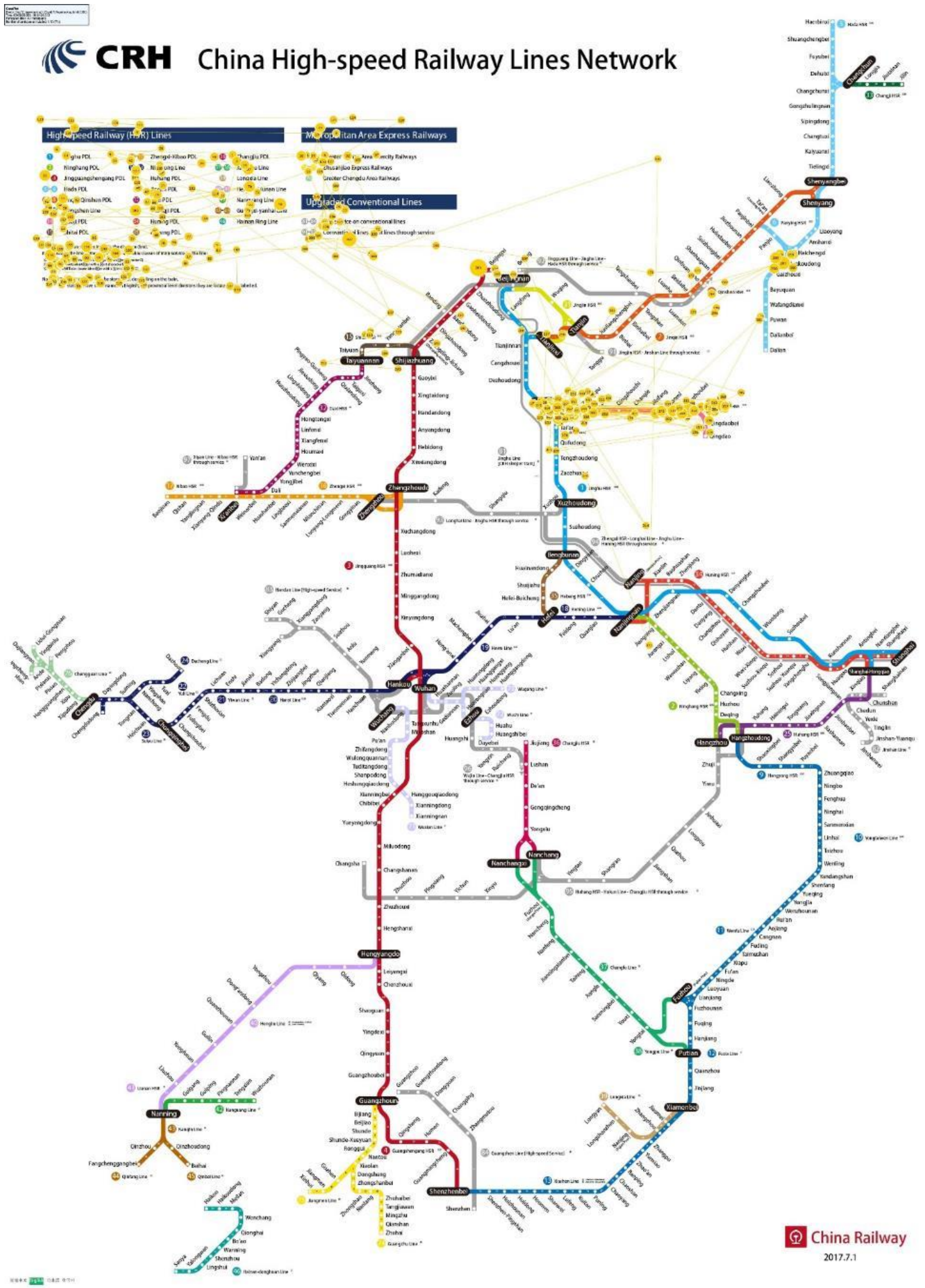

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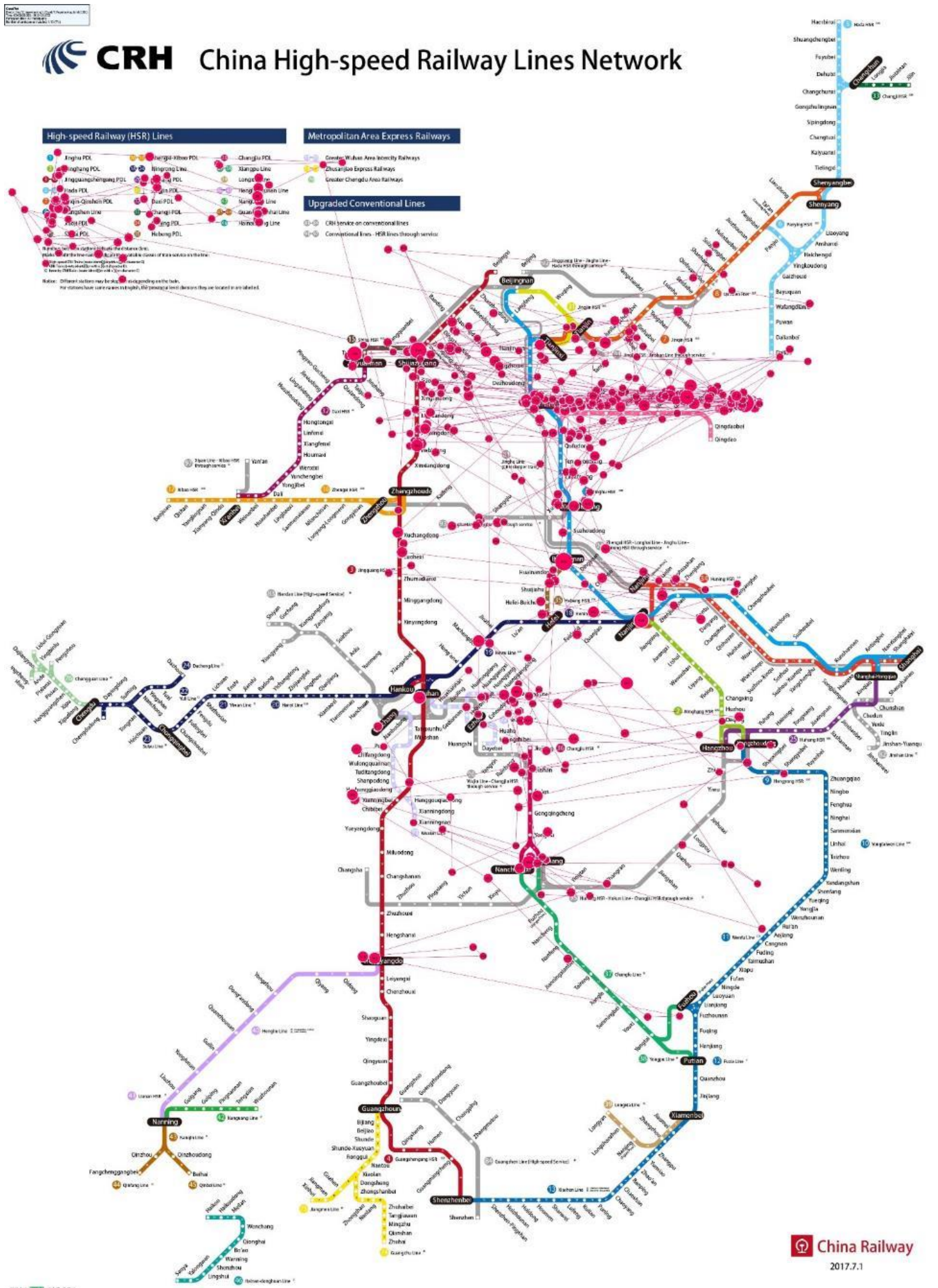

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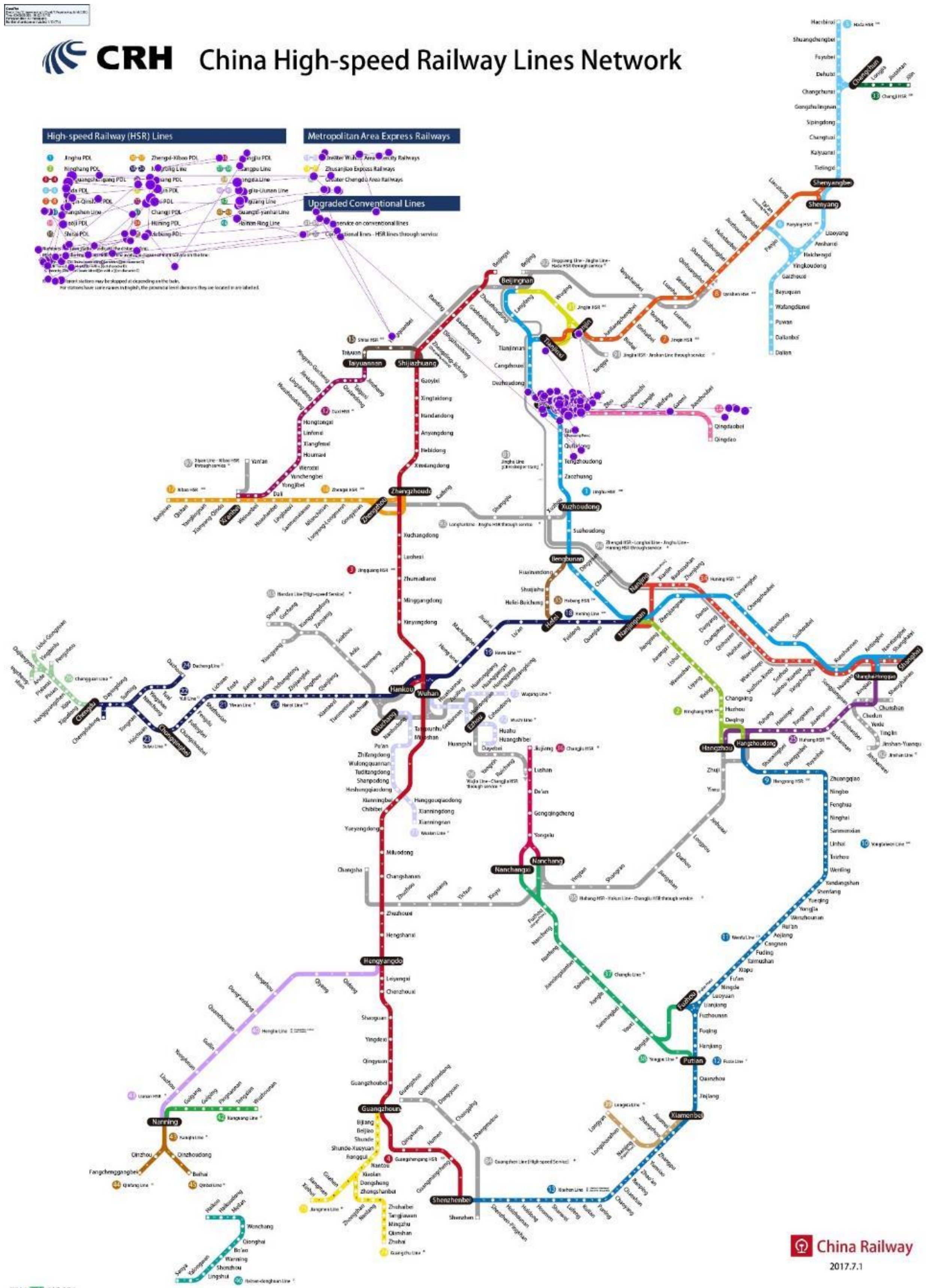
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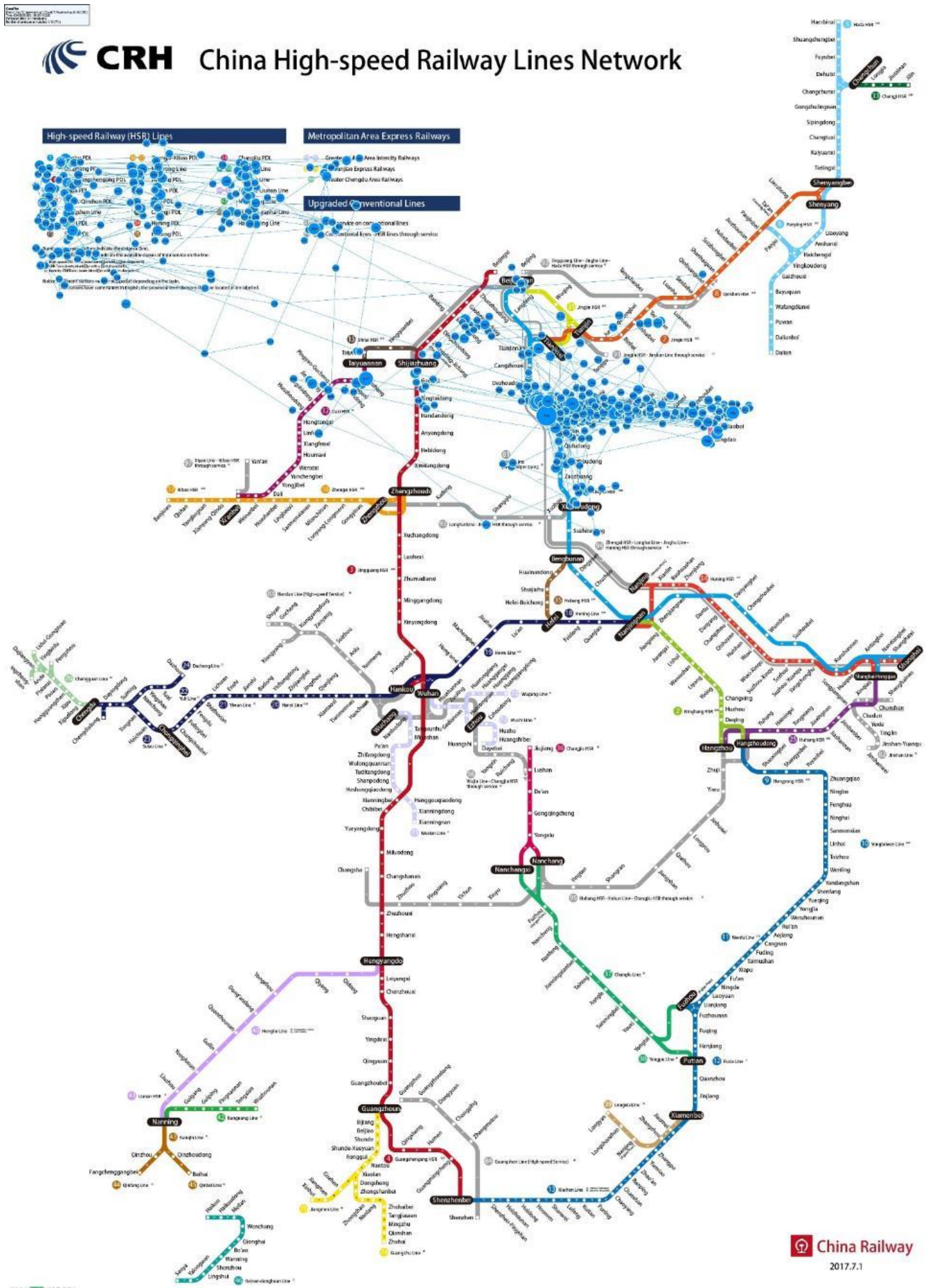
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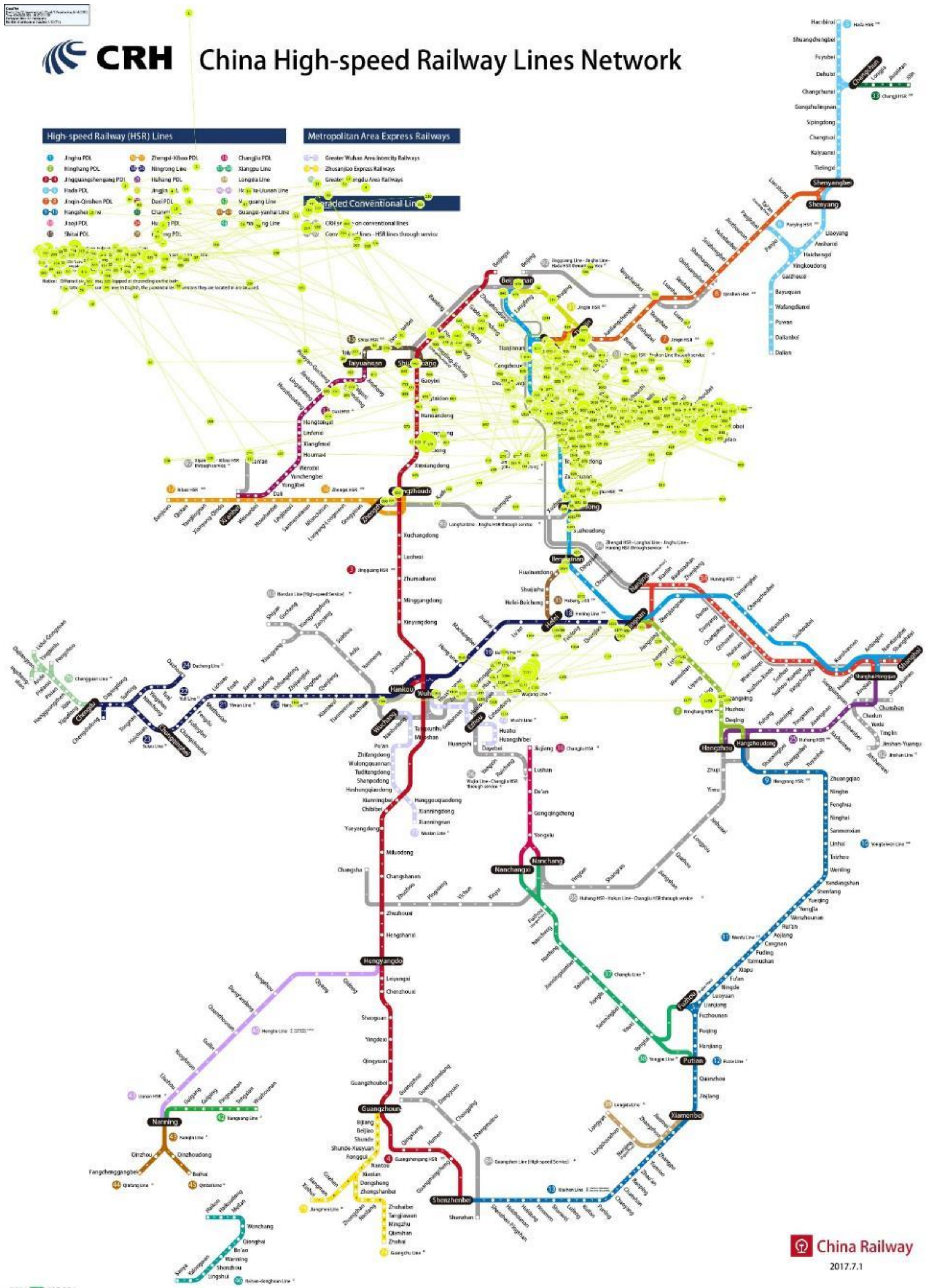
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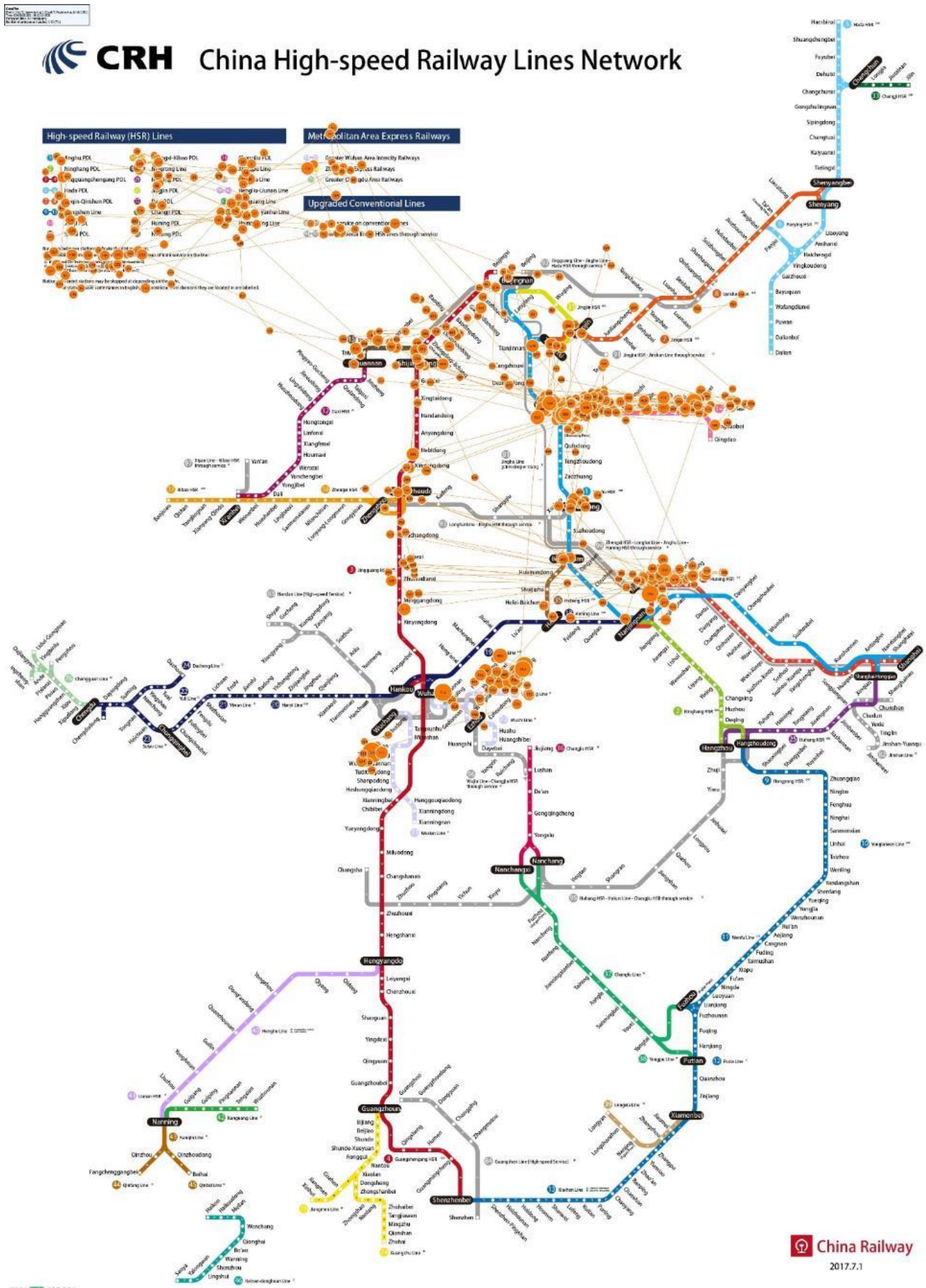

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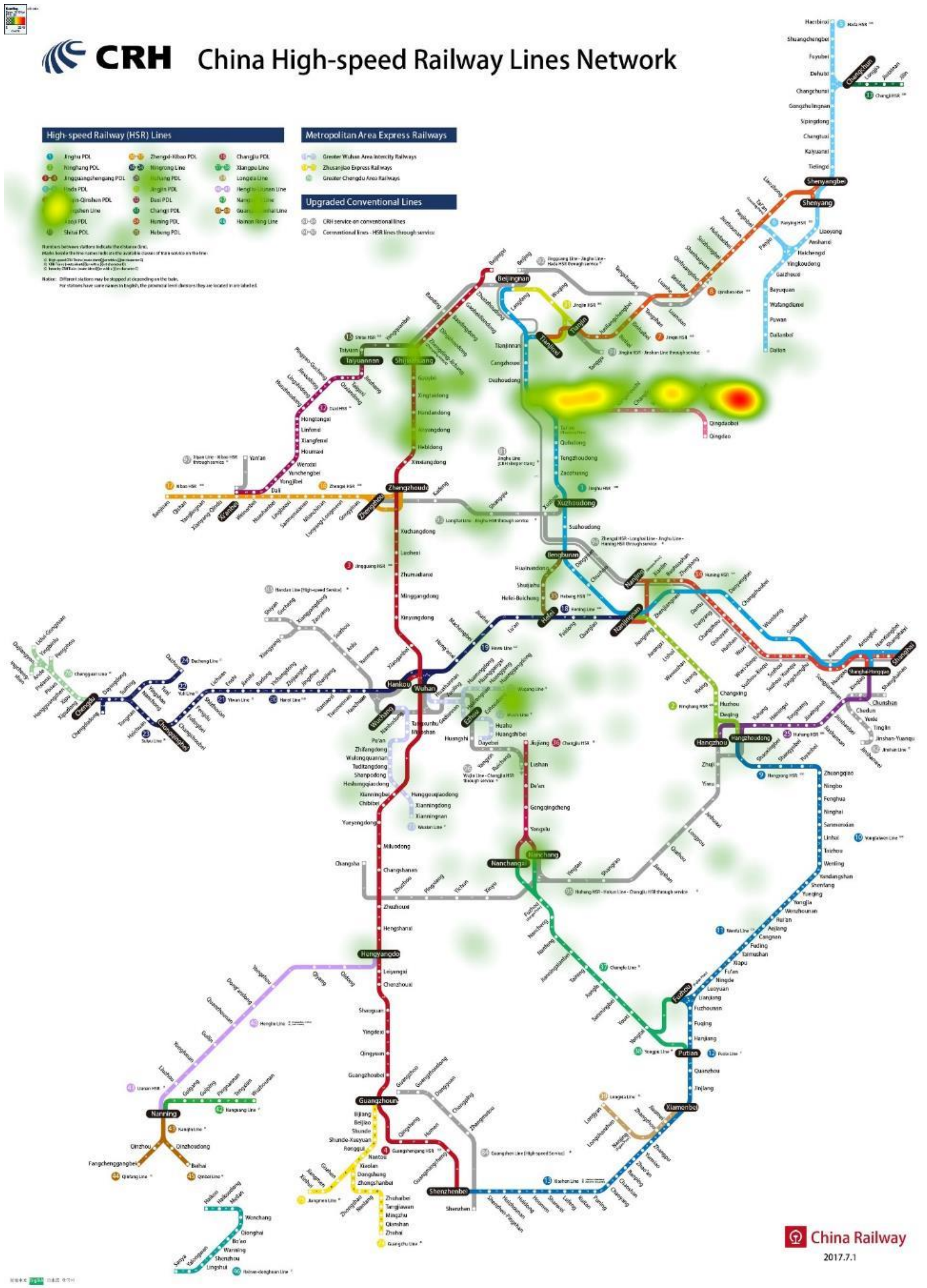

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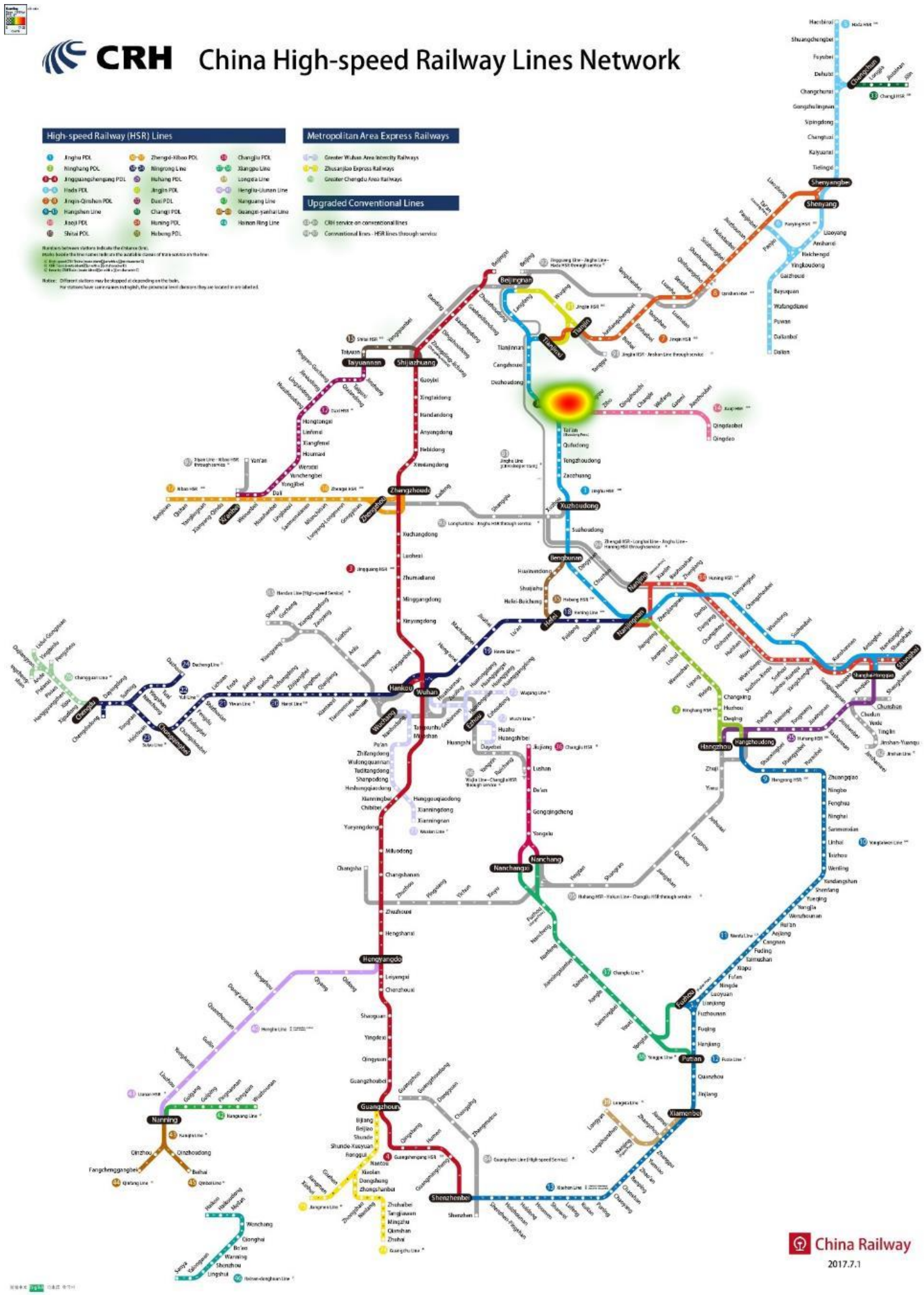
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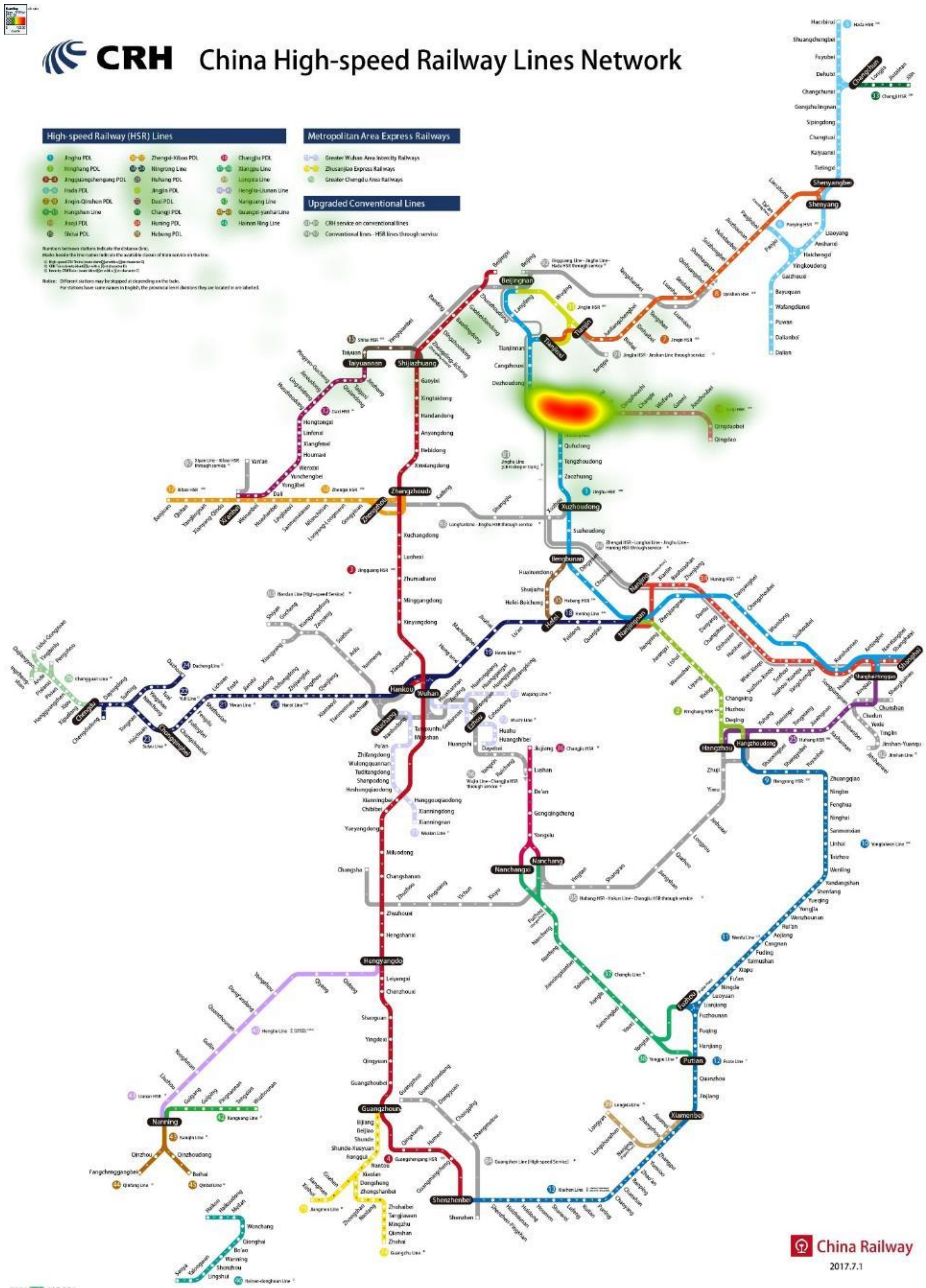
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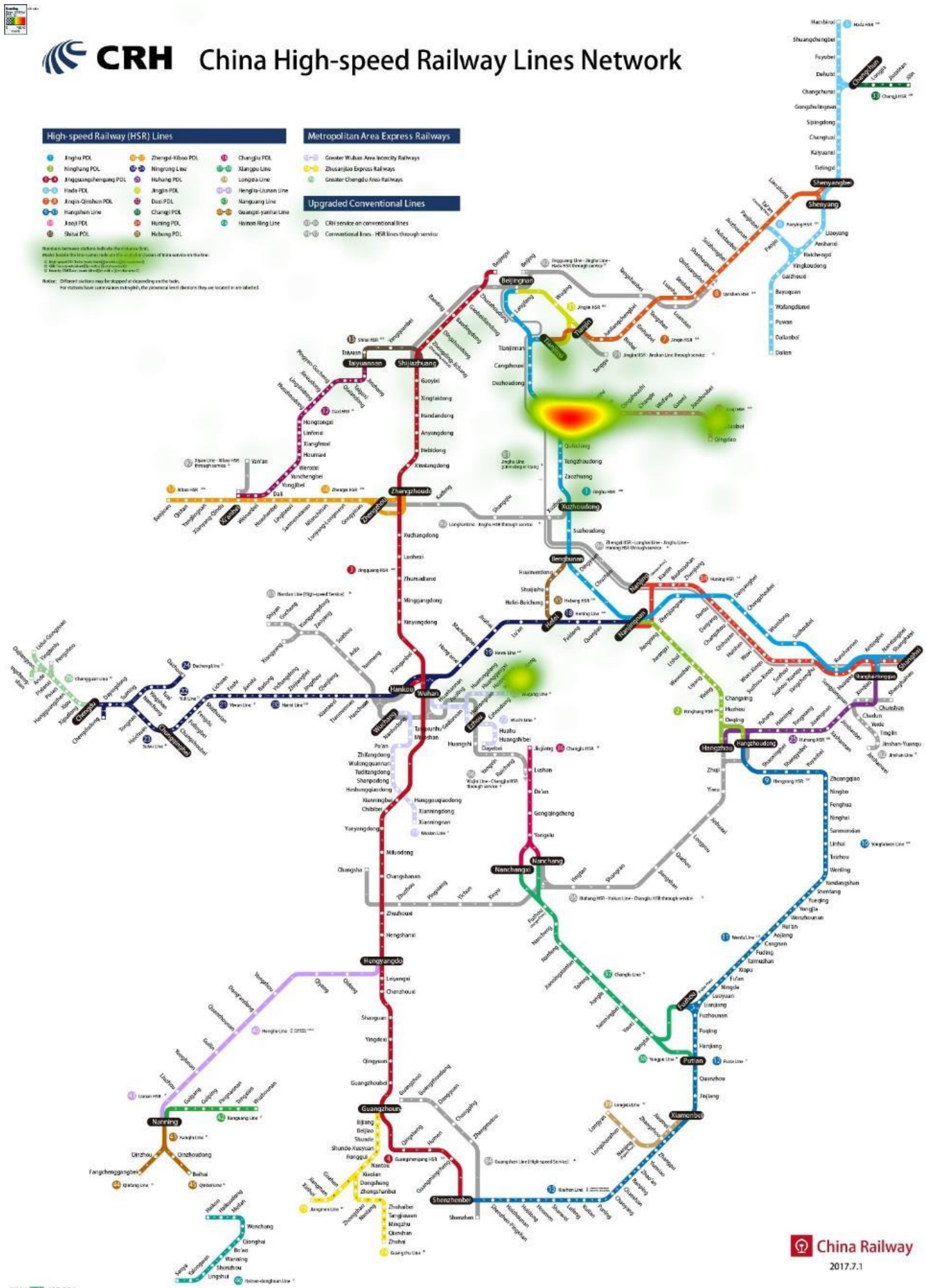
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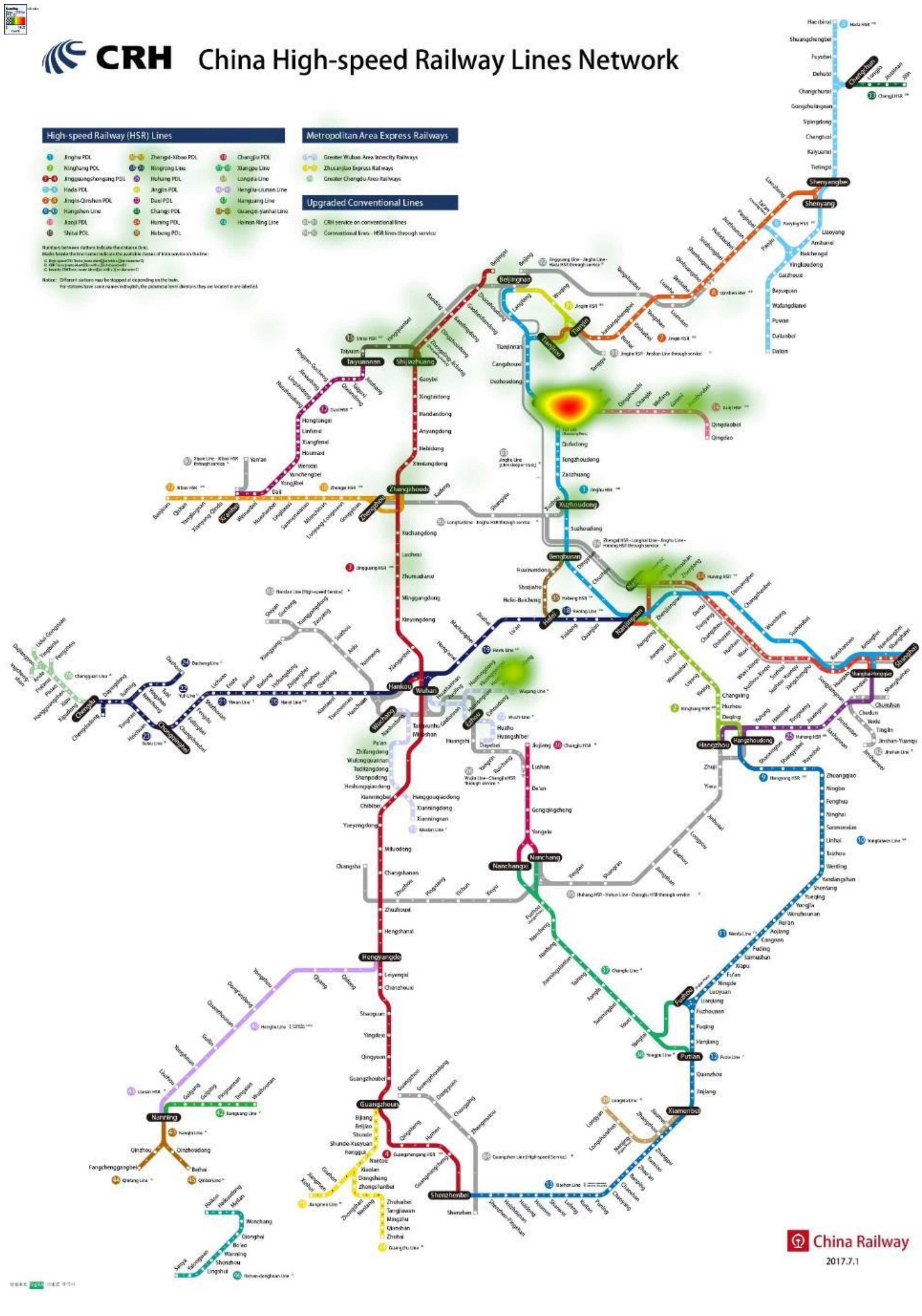
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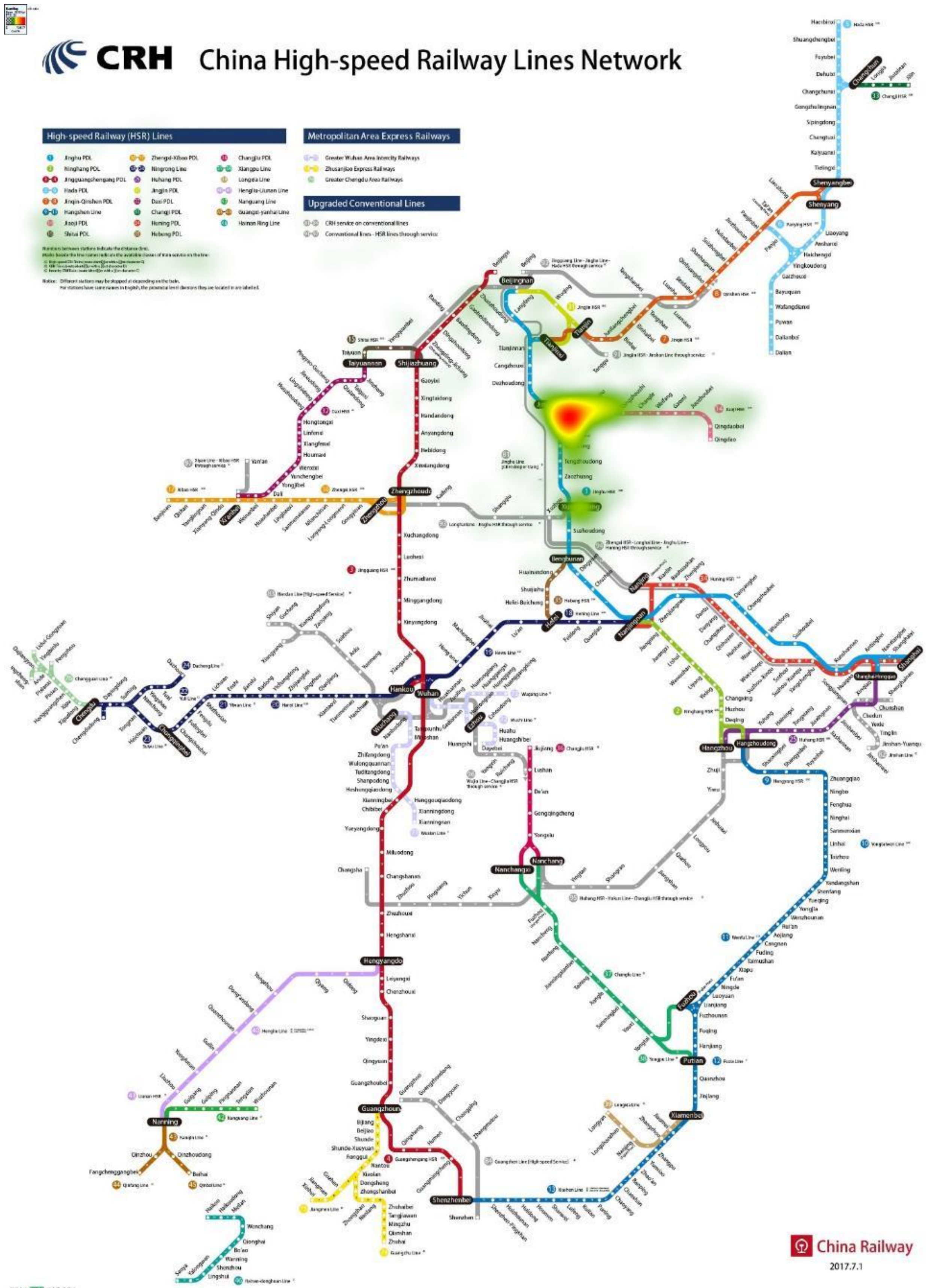
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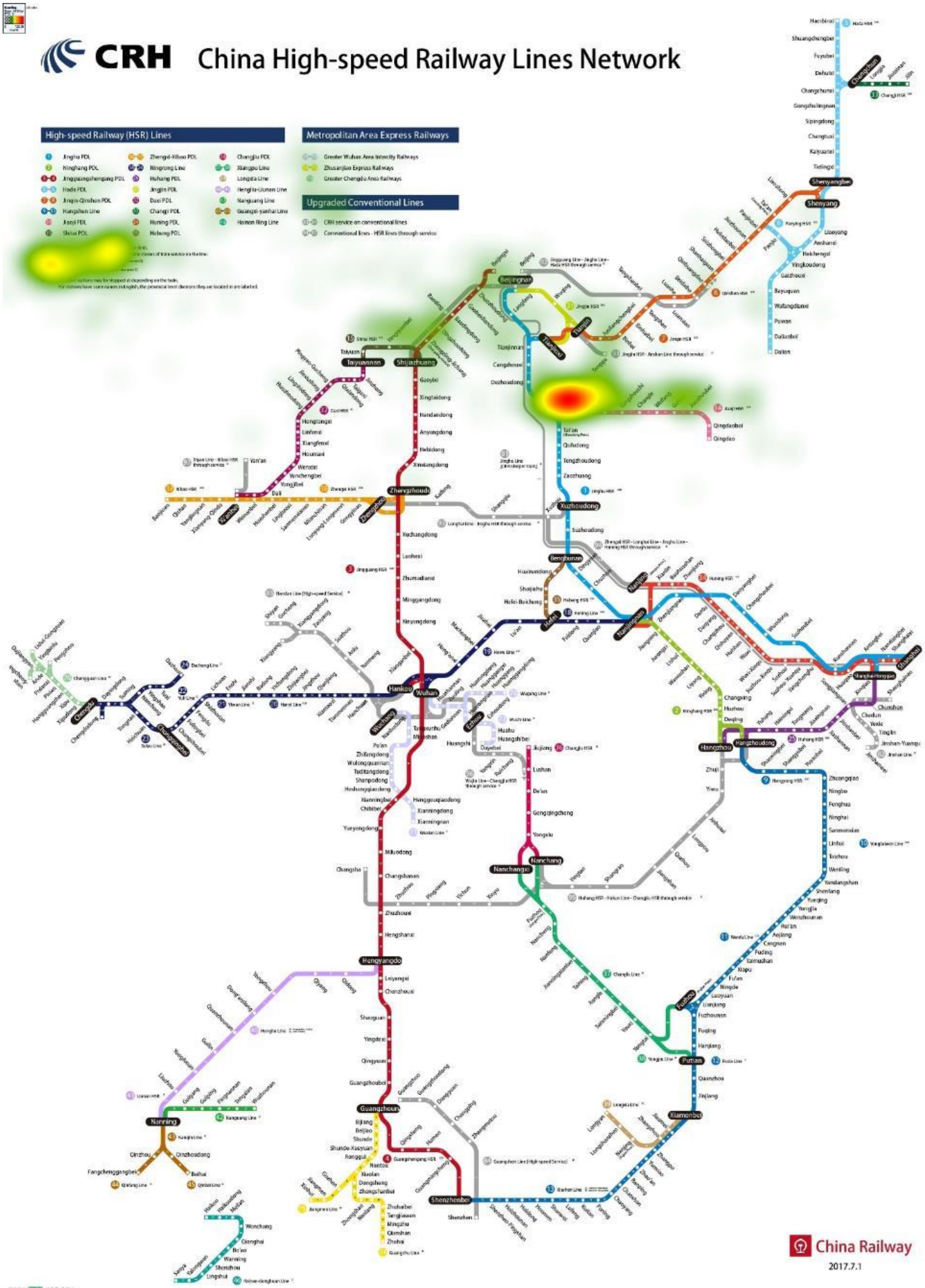
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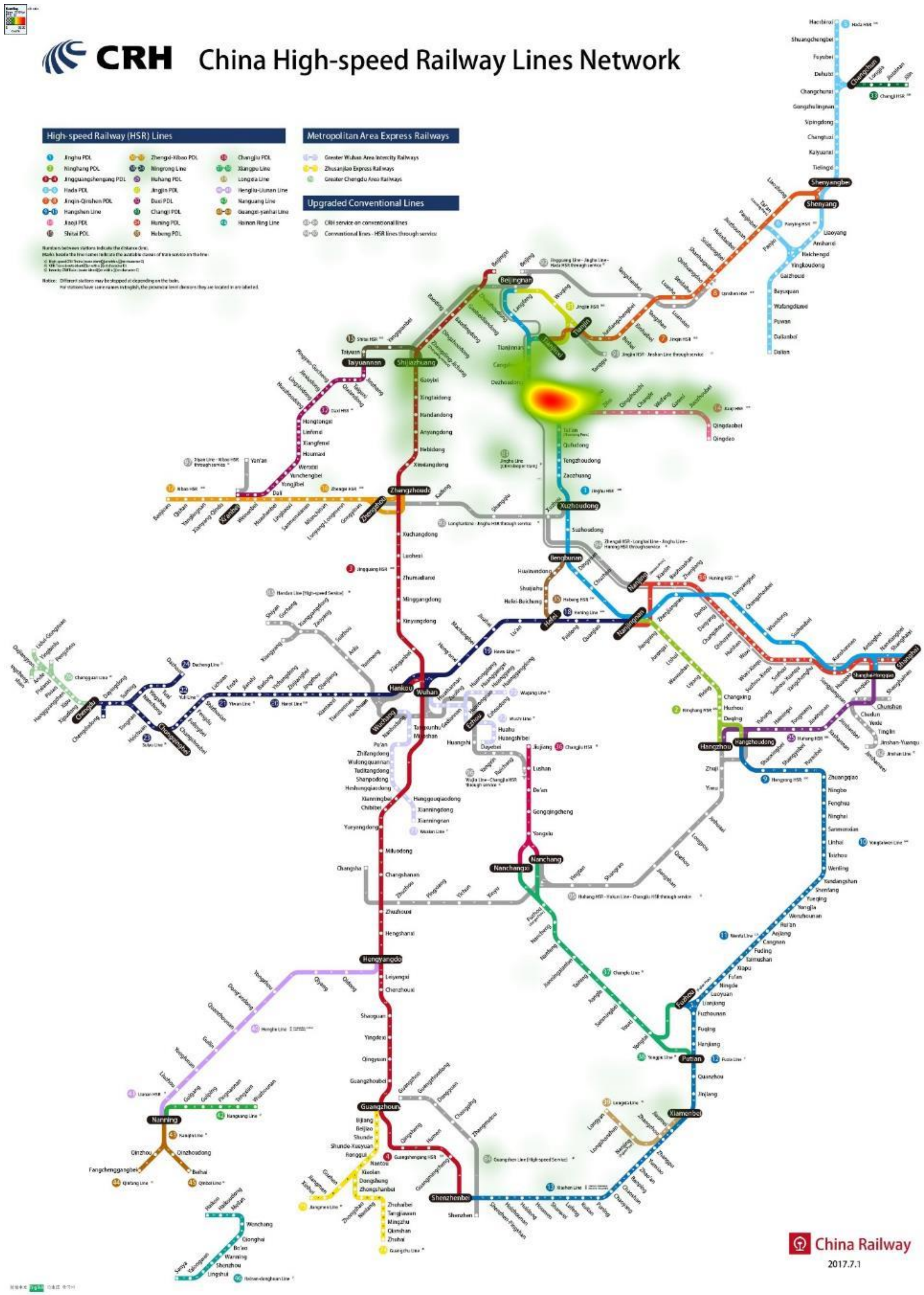
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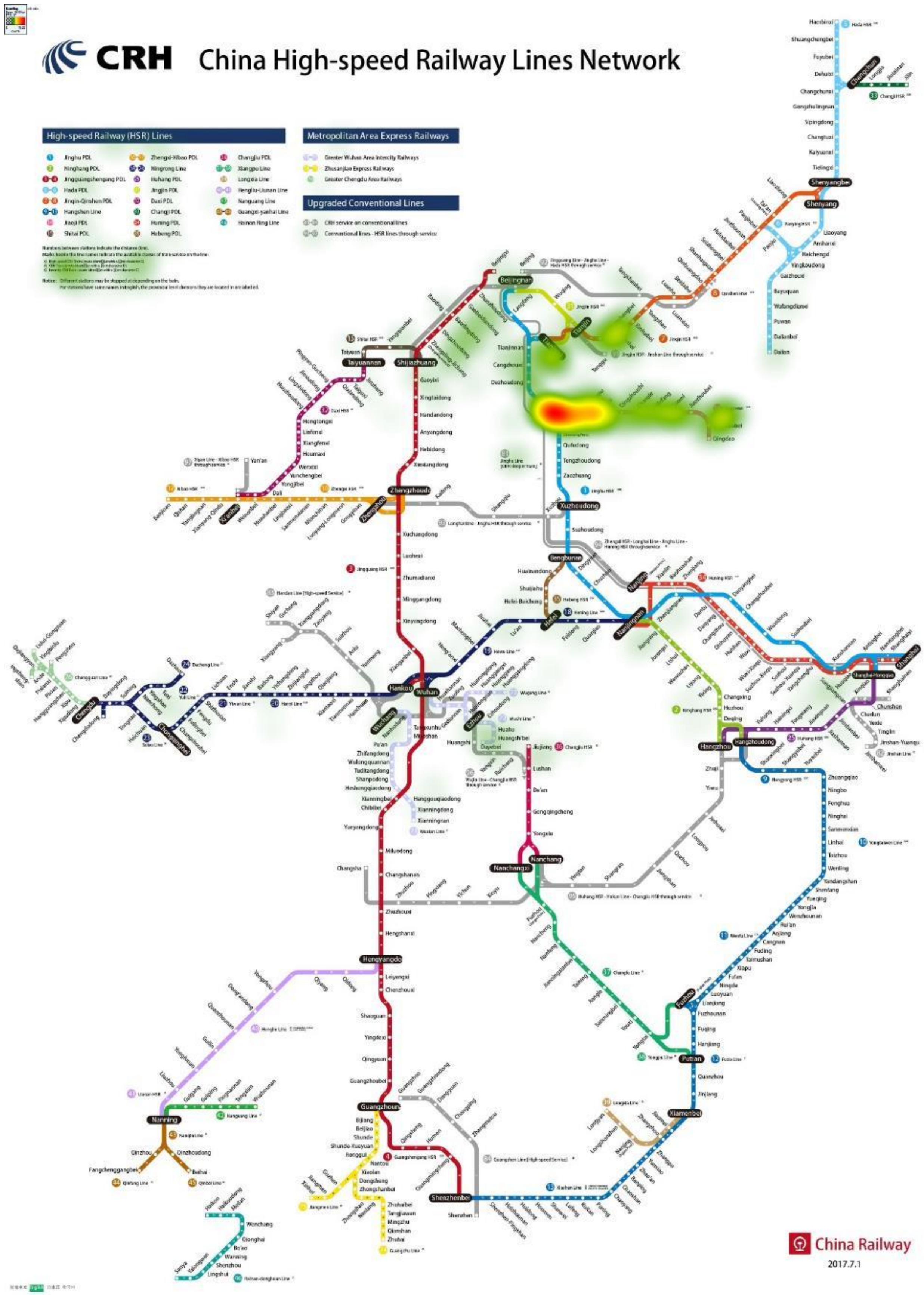
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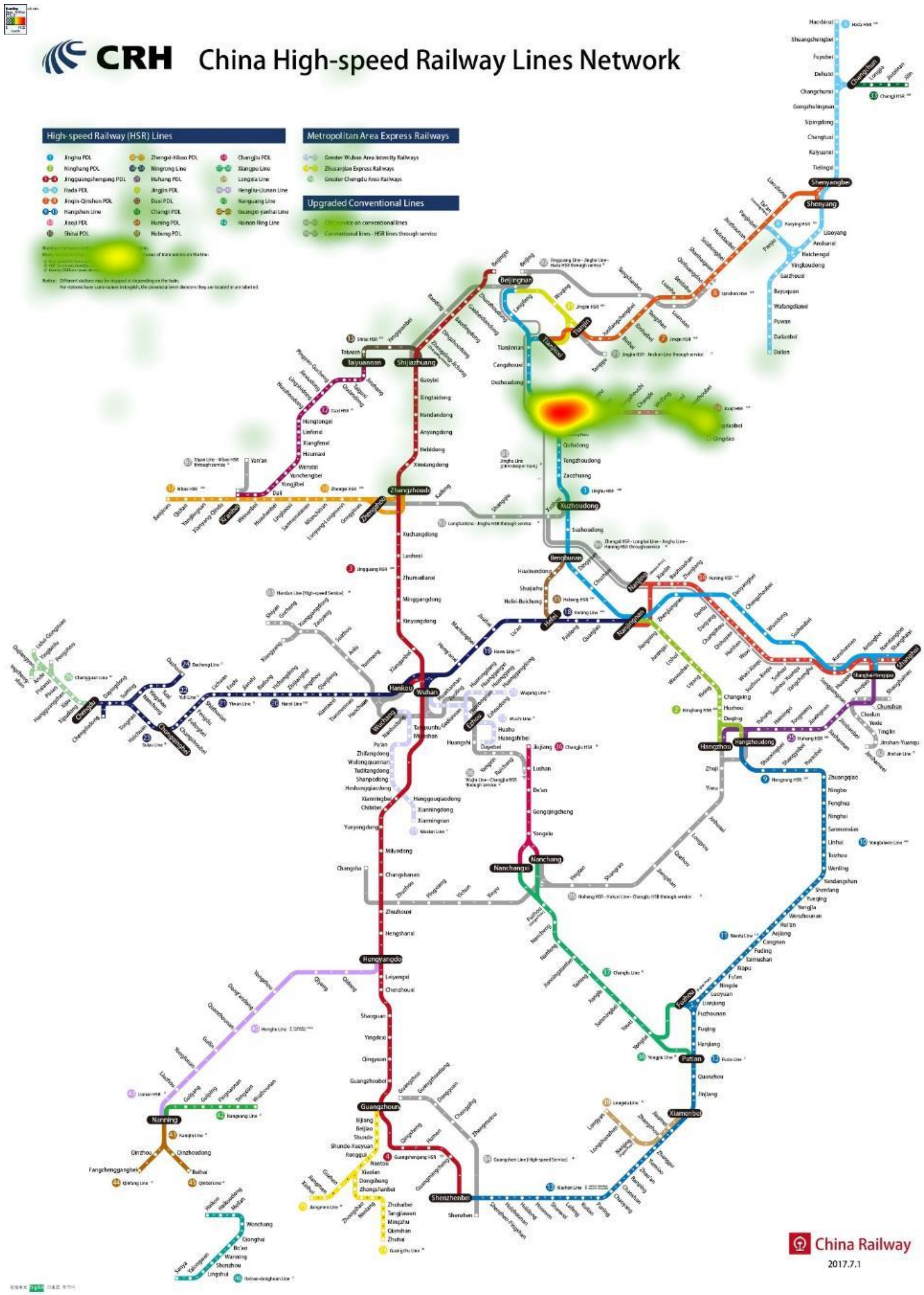
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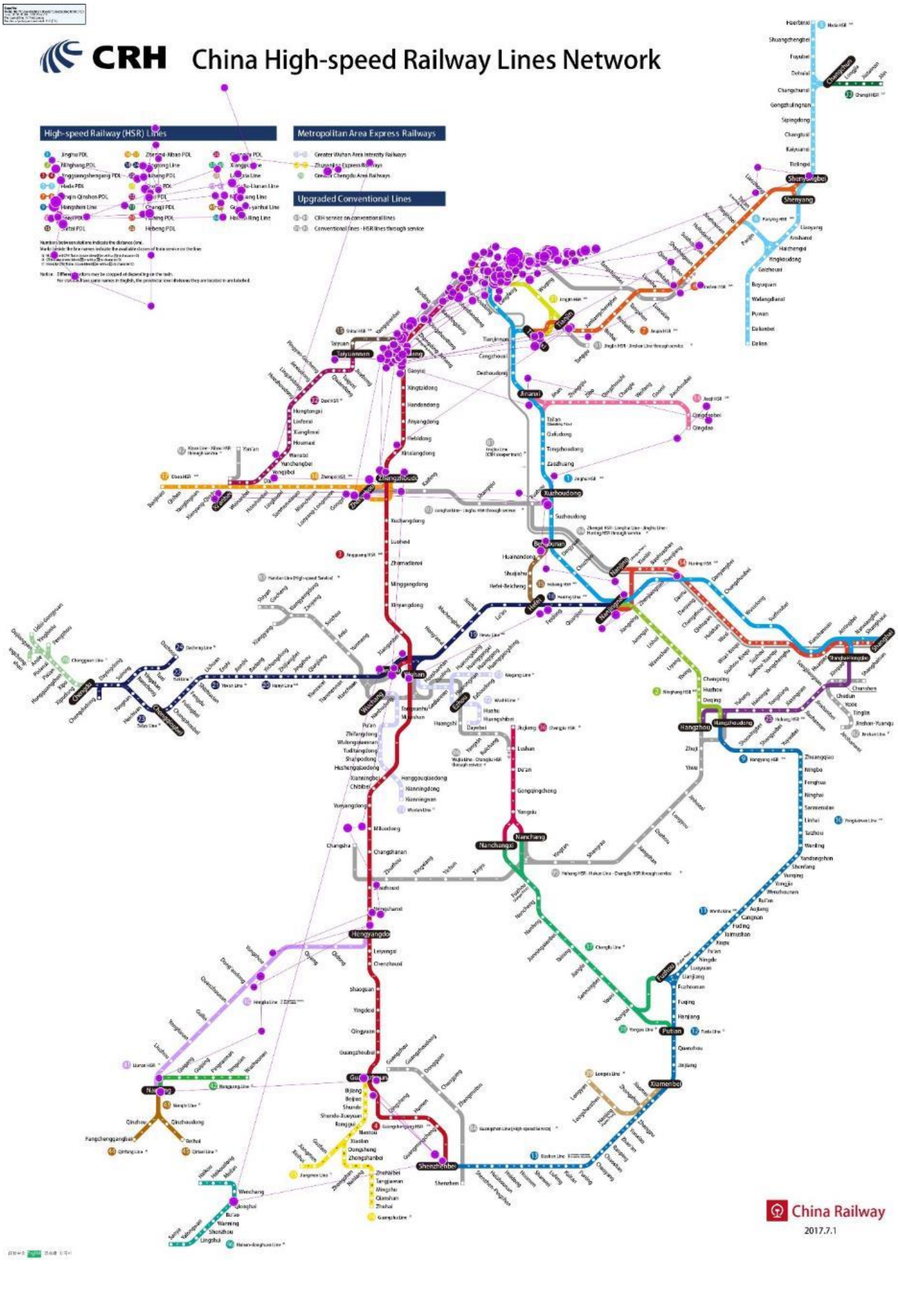
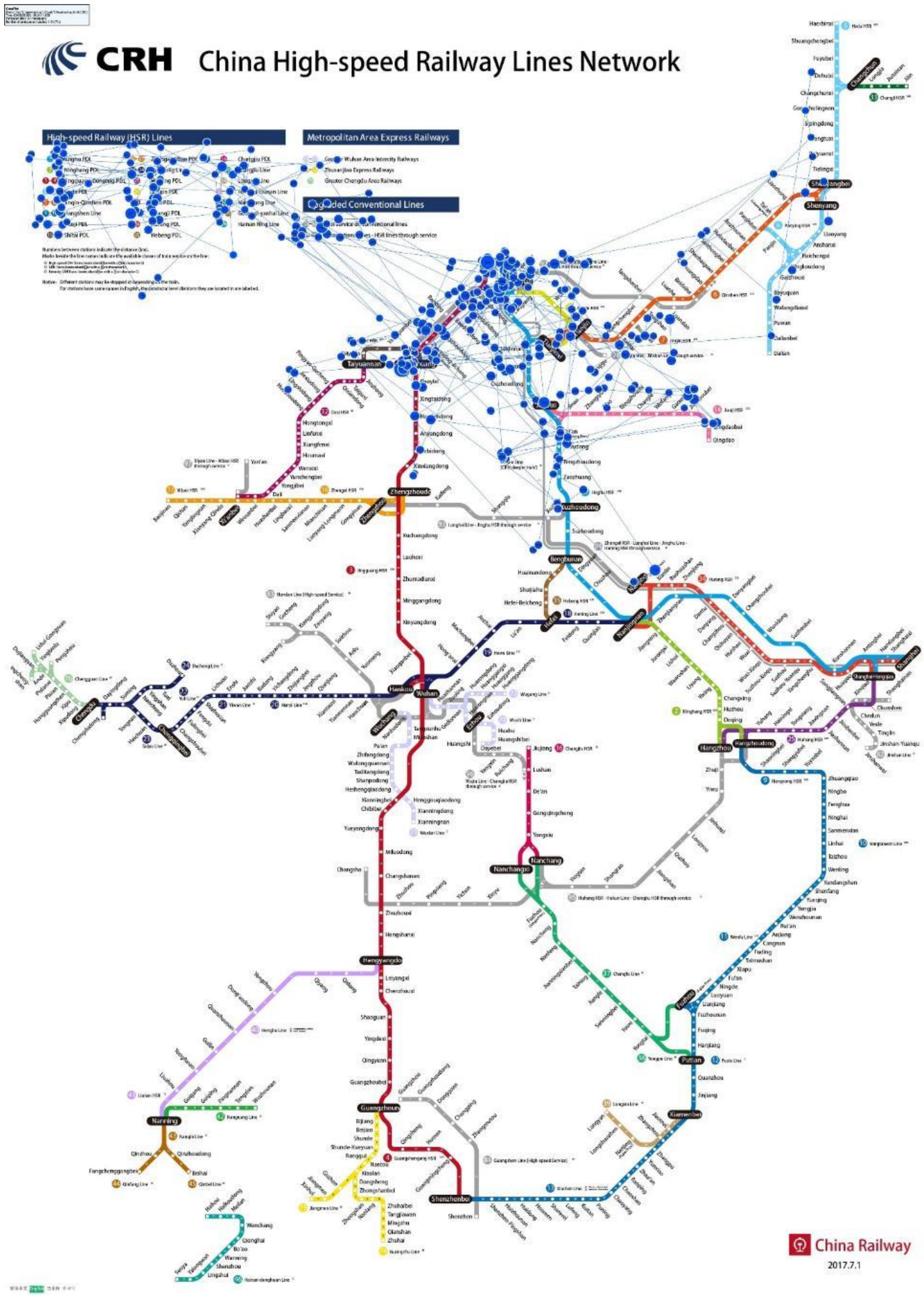
Experiment I, Task 3





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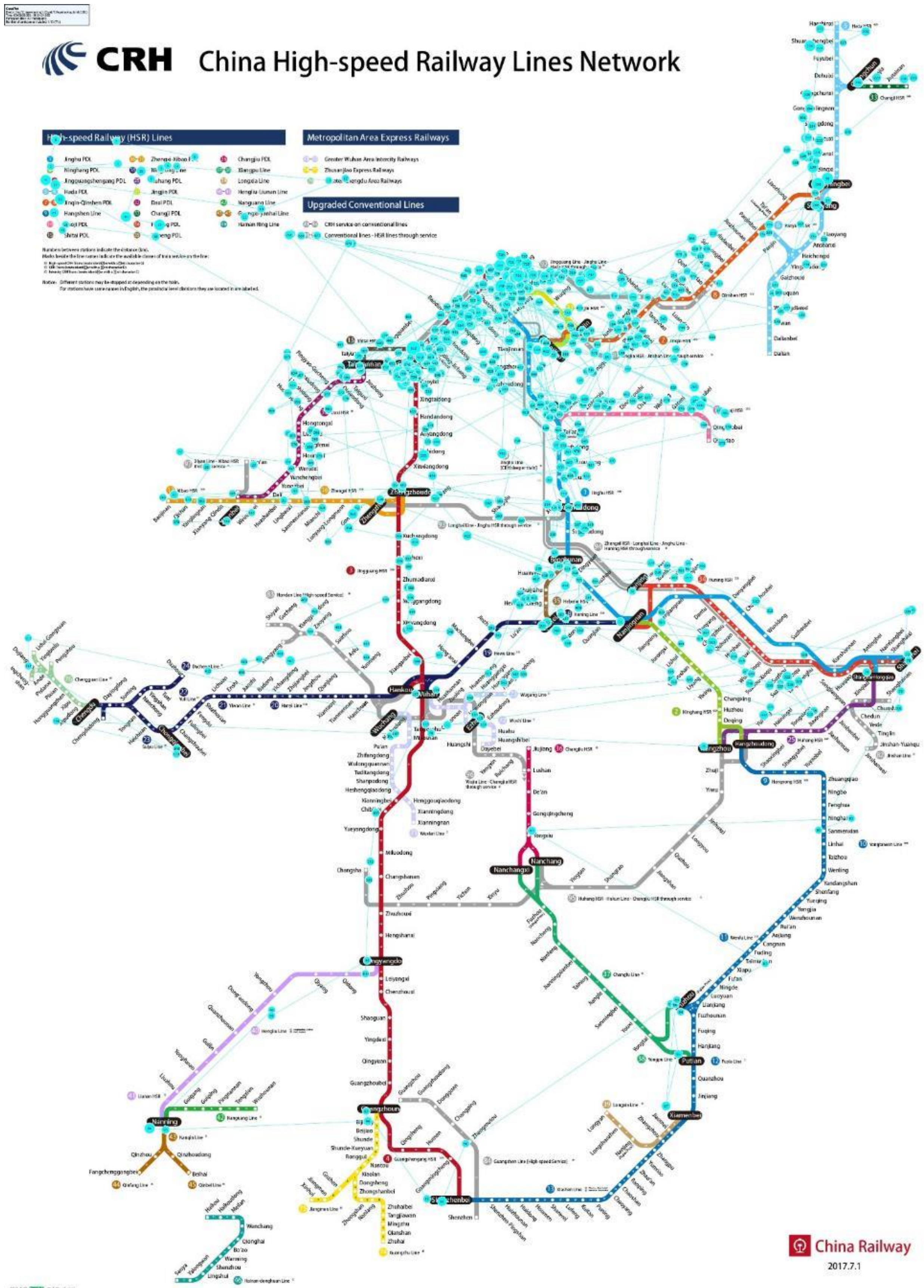
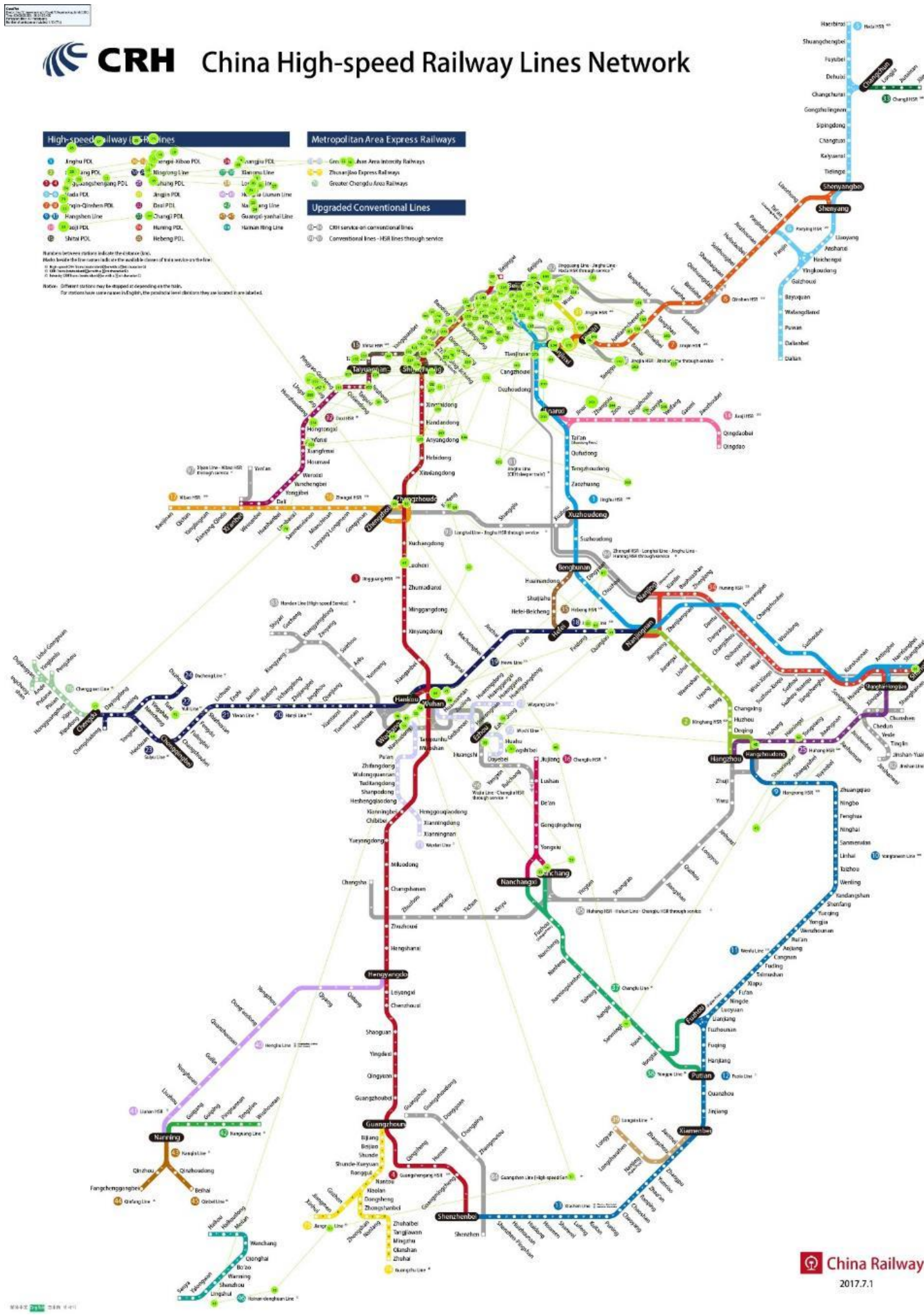
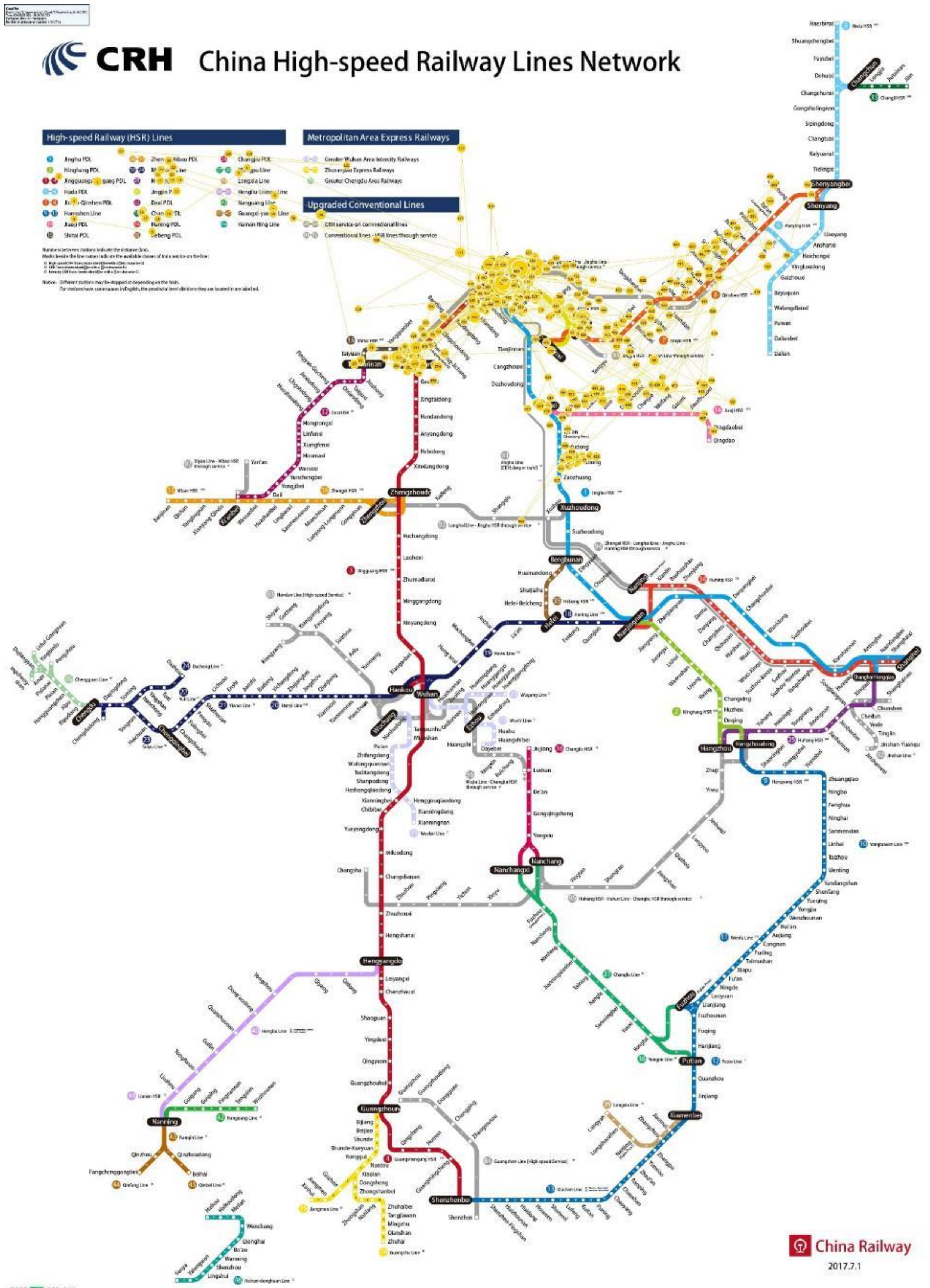
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Greater Wuhan Area Intercity Railways
Zhusanjiao Express Railways
CRH service on conventional lines
Conventional lines - HSR lines through service
Jinghu PDL
Ninghang PDL
Hada PDL
Hangshen Line
Shitai PDL
Changjiu PDL
Zhengzhoudong
Wuhan
Hankou
Wuchang
Chengdu
Chongqing
Nanjingnan
Hangzhoudong
Shanghaihongqiao
Nanchangxi
Nanchang
Changsha
Hengyangdong
Guangzhounan
Shenzhenbei
Shenzhen
Xiamenbei
Putian
Fuzhou
Nanning
Xianbei
Jinanxi
Tianjinnan
Harbinxi
Shenyang
Dalianbei
Dalian
Xingtaidong
Handandong
Anyangdong
Hebidong
Xinxiangdong
Xuchangdong
Luohe
Zhumadianxi
Xinyangdong
Shaoguan
Yingdexi
Qingyuan
Guangzhoubei
Beijiao
Shunde
Shunde-Xueyuan
Ronggui
Zhongshanbei
Zhuhaibei
Zhuhai
Wenchang
Qionghai
Bo'ao
Wanning
Sanya
Ningbo
Linhai
Taizhou
Wenling
Yueqing
Wenzhounan
Rui'an
Cangnan
Fuding
Fuqing
Quanzhou
Jinjiang
Lushan
De'an
Jiujiang
Qinzhou
Qinzhoudong
Beihai
Fangchenggangbei
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
Metropolitan Area Express Railways
Upgraded Conventional Lines
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Harbinxi
Changchun
Shenyangbei
Shenyang
Dalian
Taiyuan
Zhengzhoudong
Zhengzhou
Xuzhoudong
Bengbunan
Nanjingnan
Nanjing
Hefei
Shanghai
Shanghaihongqiao
Hangzhou
Hangzhoudong
Hankou
Wuhan
Wuchang
Chengdu
Chongqingbei
Nanchangxi
Nanchang
Changsha
Hengyangdong
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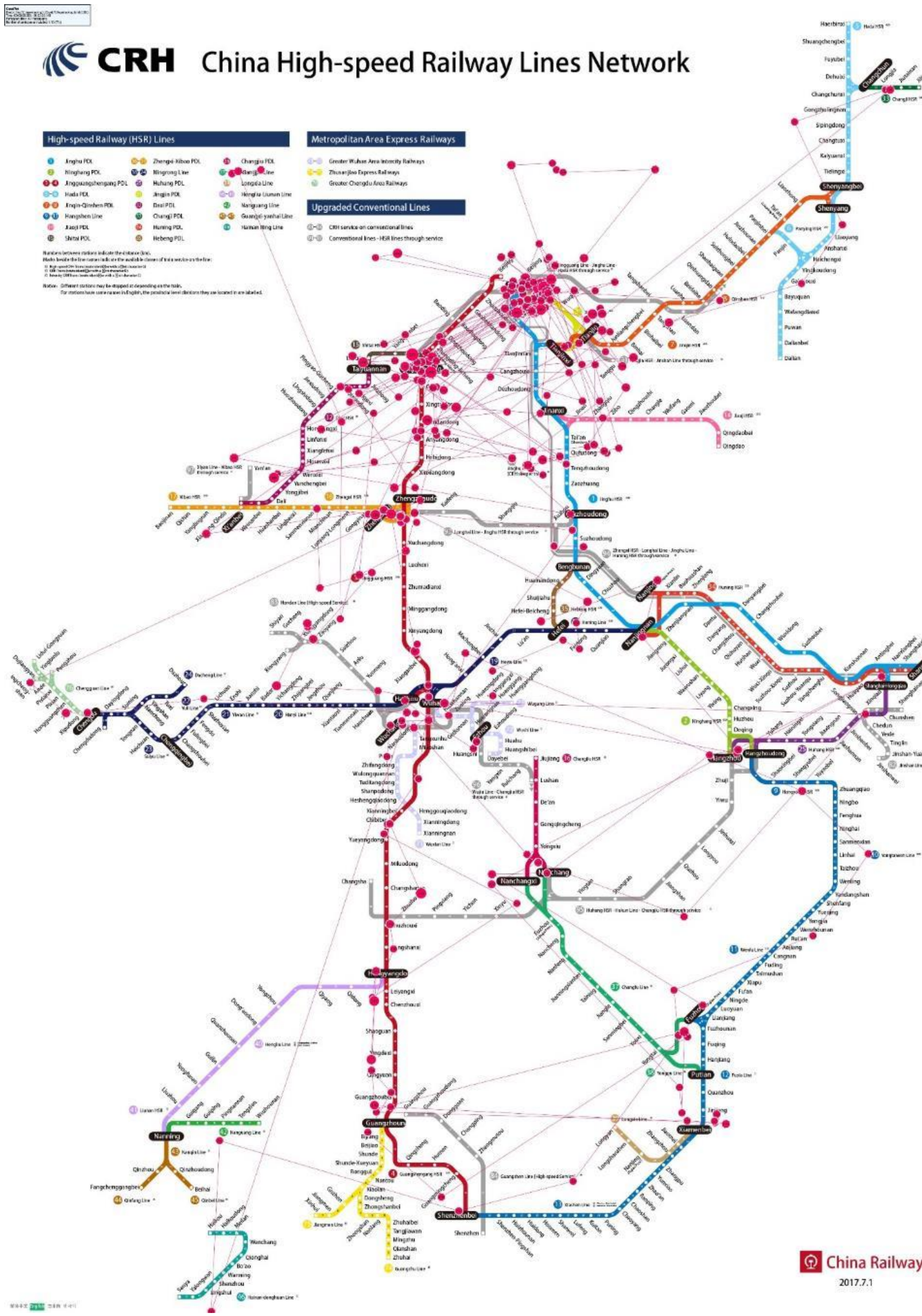
Xiamenbei
Qingdao
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Shenyangbei
Shenyang
Taiyuannan
Jinan
Zhengzhoudong
Xuzhoudong
Bengbunan
Nanjingnan
Hefei
Shanghai
Hangzhoudong
Wuhan
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Nanchang
Guangzhounan
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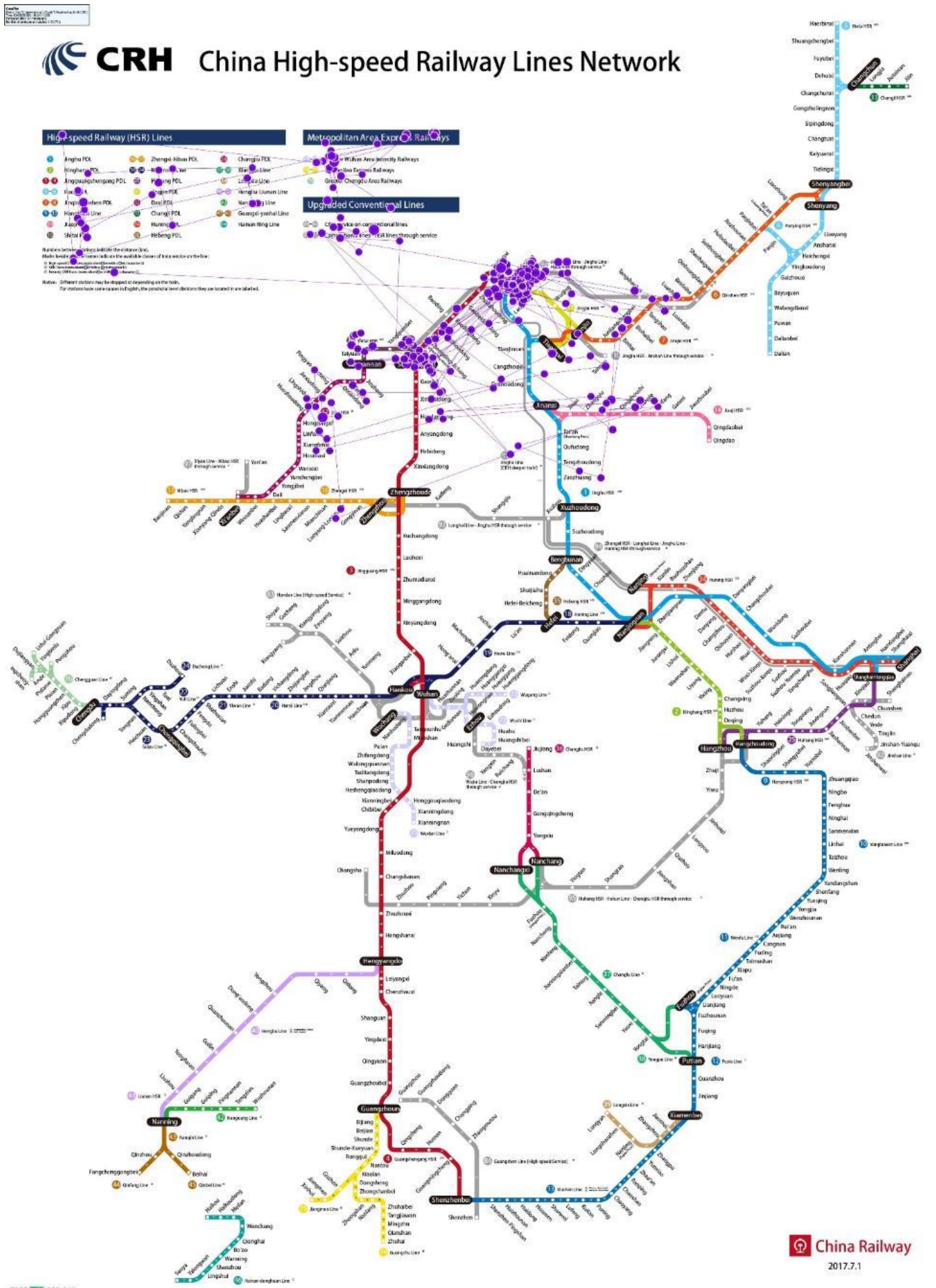
Xiamenbei
Putian
Nanning
Chongqingbei
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Haerbinxi
Shenyangbei
Shenyang
Dalian
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Jinan
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Bengbunan
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Hefei
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Ningbo
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Hankou
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Chengdu
Chongqingbei
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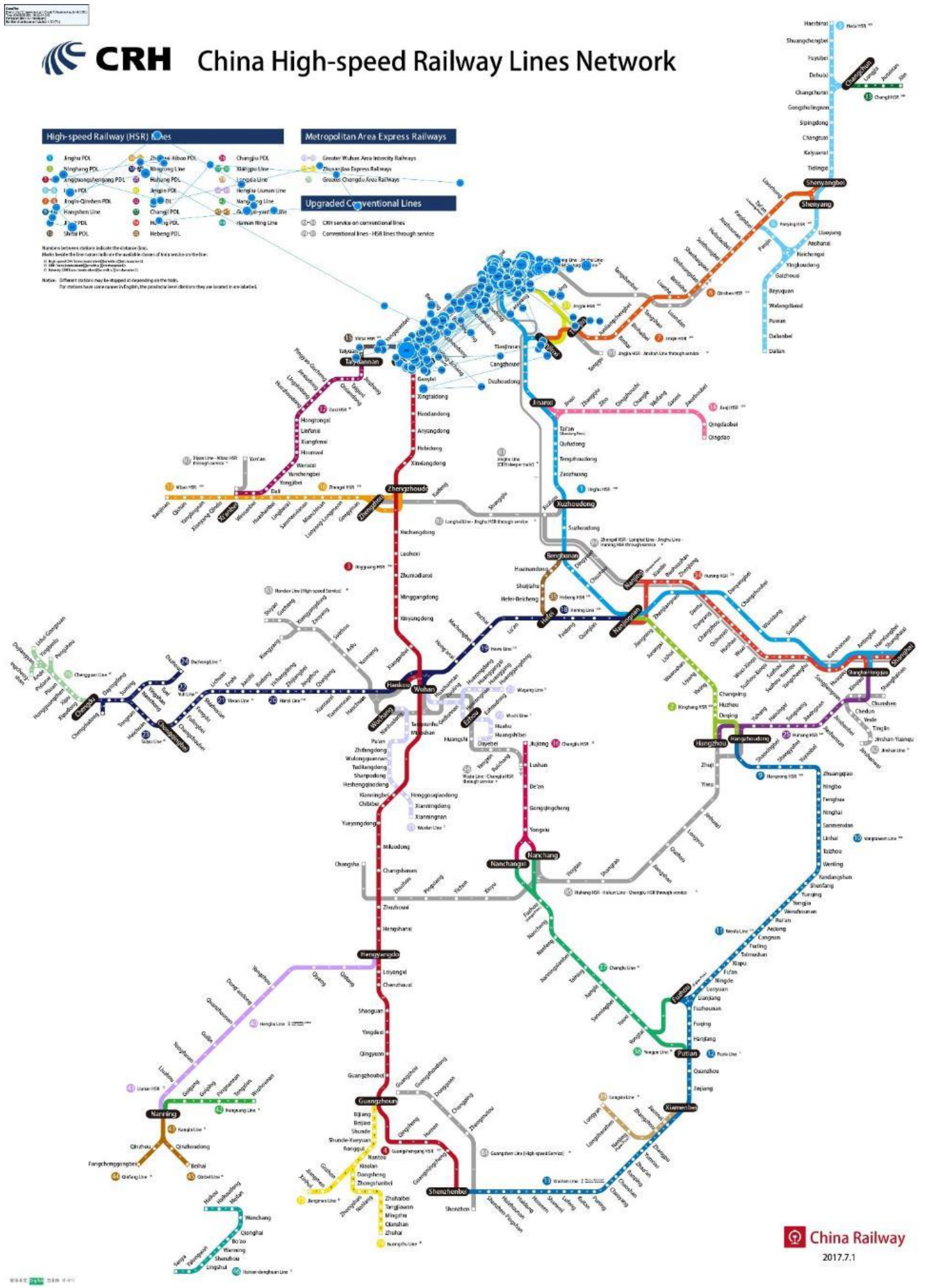
Xiamenbei
Putian
Fuzhou
Nanning
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Greater Wuhan Area Intercity Railways
Greater Chengdu Area Railways
CRH service on conventional lines
Conventional lines - HSR lines through service
Haerbinxi
Shenyangbei
Shenyang
Dalianbei
Dalian
Taiyuannan
Zhengzhoudong
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Hangzhoudong
Hefei
Hankou
Wuhan
Wuchang
Chengdu
Chongqingbei
Nanchang
Nanchangxi
Hengyangdong
Guangzhounan
Shenzhenbei
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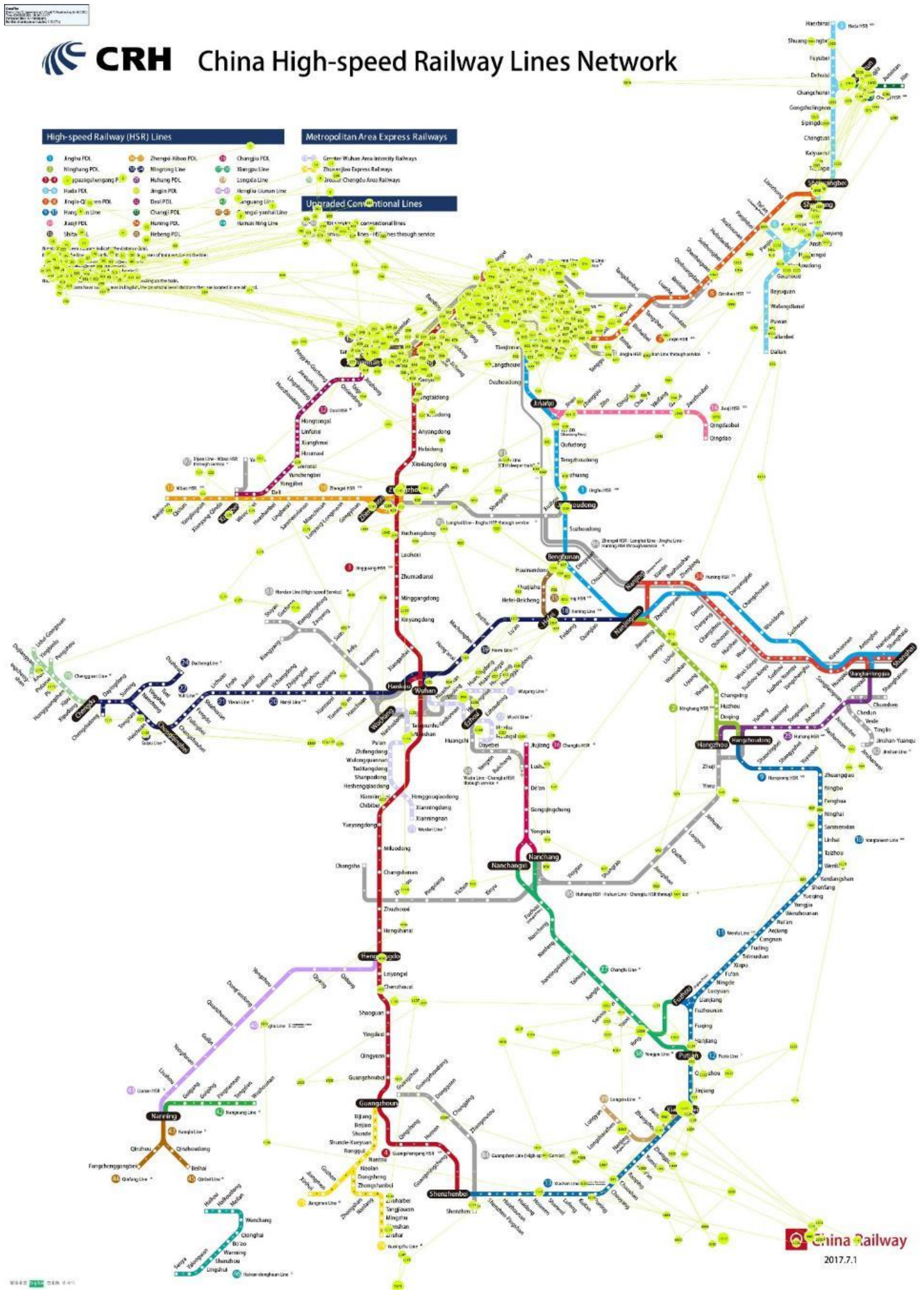
Putian
Fuzhou
Nanning
Xi'anbei
Jinanxi
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Harbin
Changchun
Shenyang
Dalian
Tianjin
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Bengbunan
Hefei
Nanjingnan
Shanghai
Hangzhou
Hangzhoudong
Wuhan
Hankou
Chengdu
Chongqing
Nanchang
Nanchangxi
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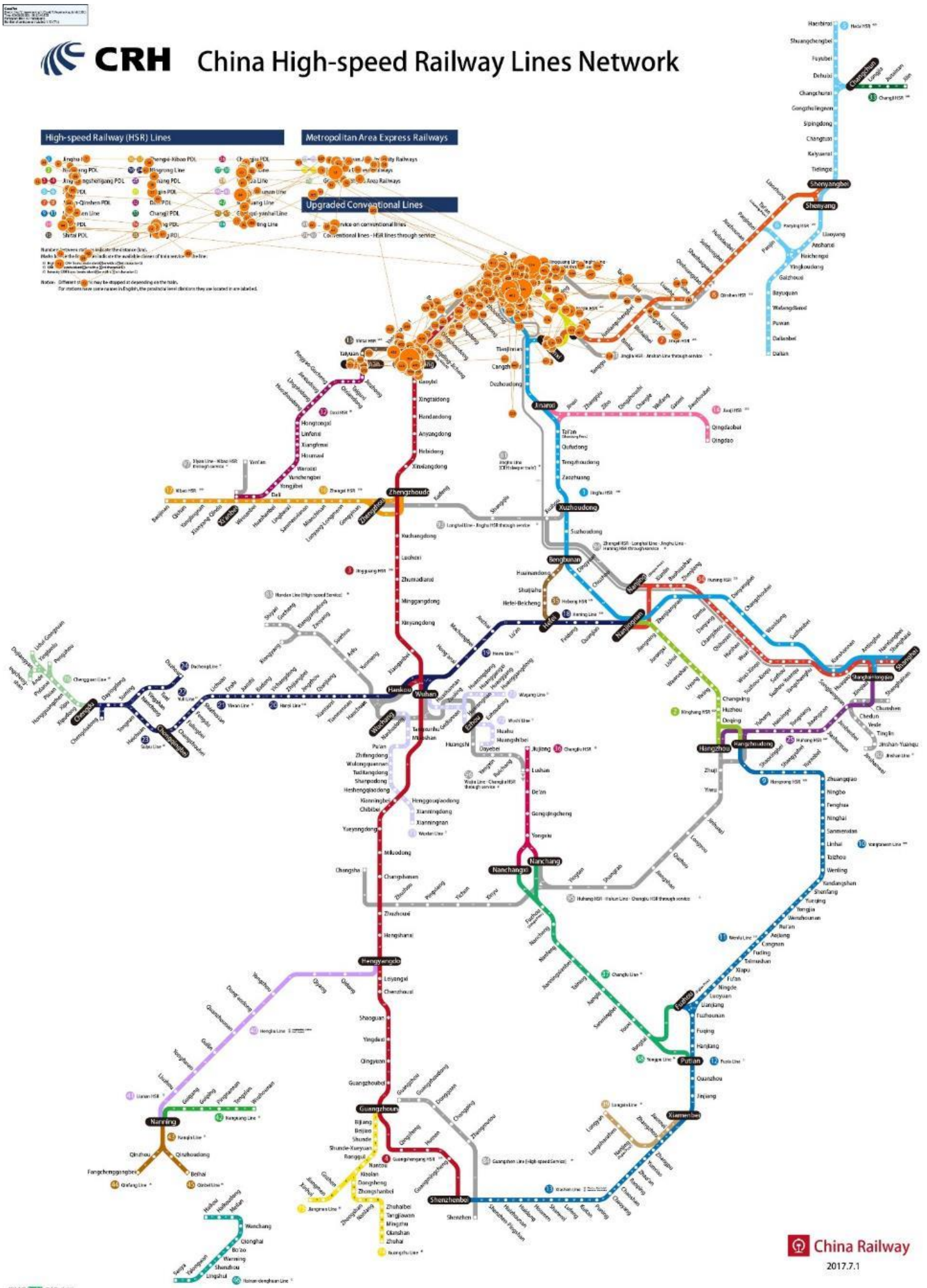
Guangzhou
Shenzhenbei
Fuzhou
Putian
Xiamen
Nanning
Haikou
Sanya
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Haerbinxi
Changchunxi
Shenyangbei
Shenyang
Dalianbei
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Shijiazhuang
Taiyuan
Jinanxi
Qingdaobei
Qingdao
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Hefei
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Wuchang
Chengdudong
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Hangzhou
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Guangzhounan
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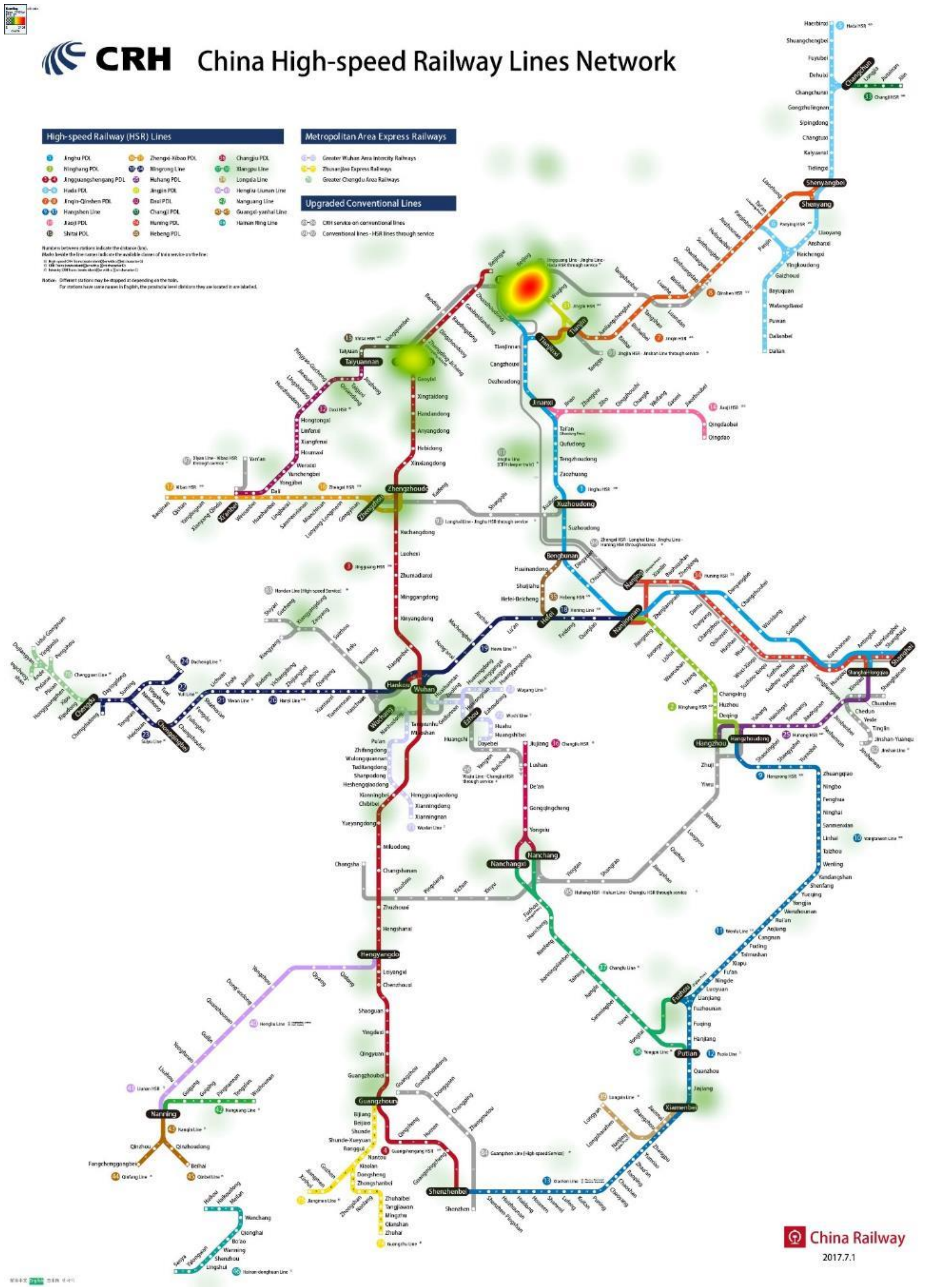
Putian
Xiamenbei
Nanning
China Railway
2017.7.1



CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Shenyangbei
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Zhengzhoudong
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Hankou
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Hangzhoudong
Nanchang
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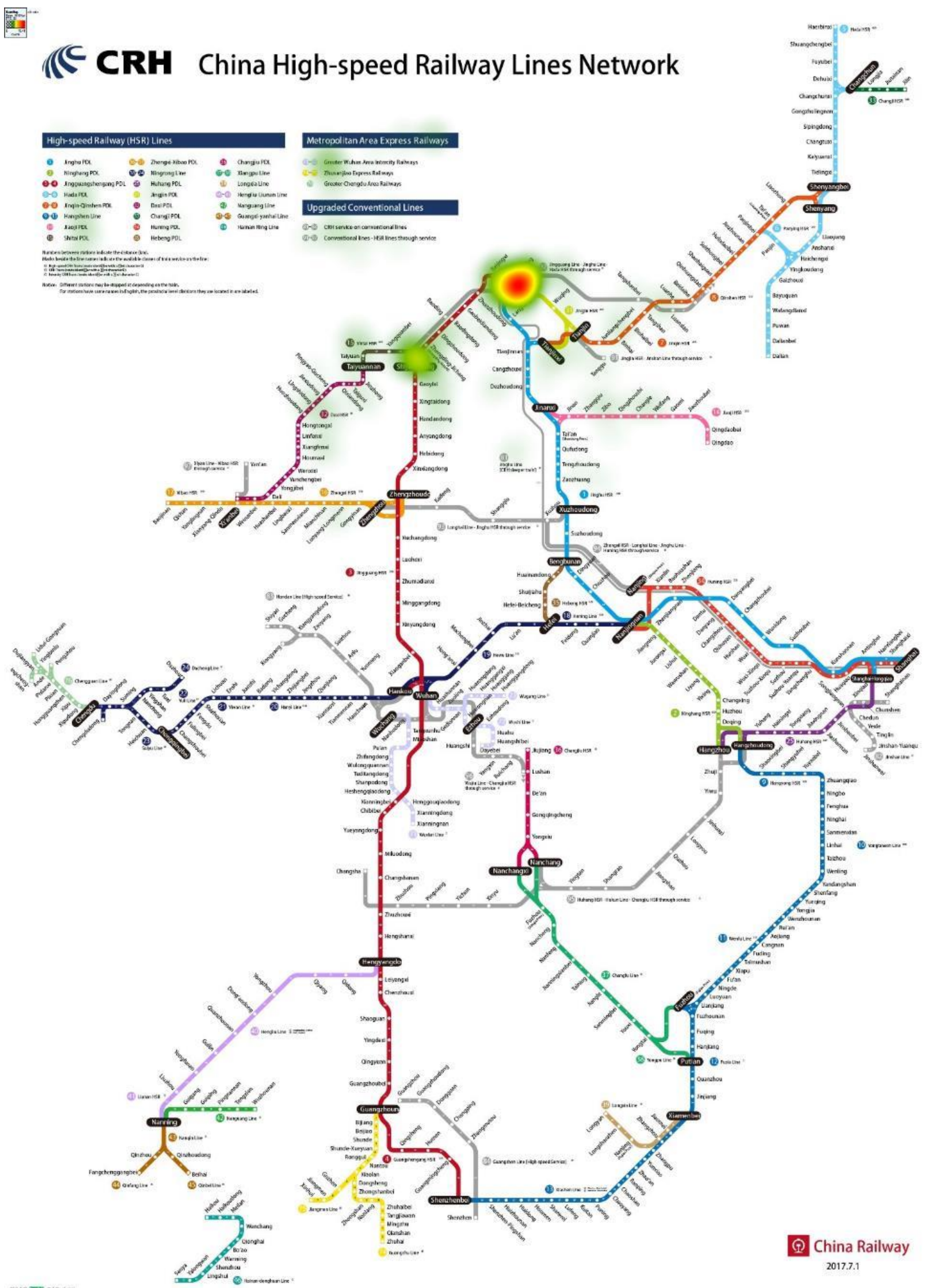
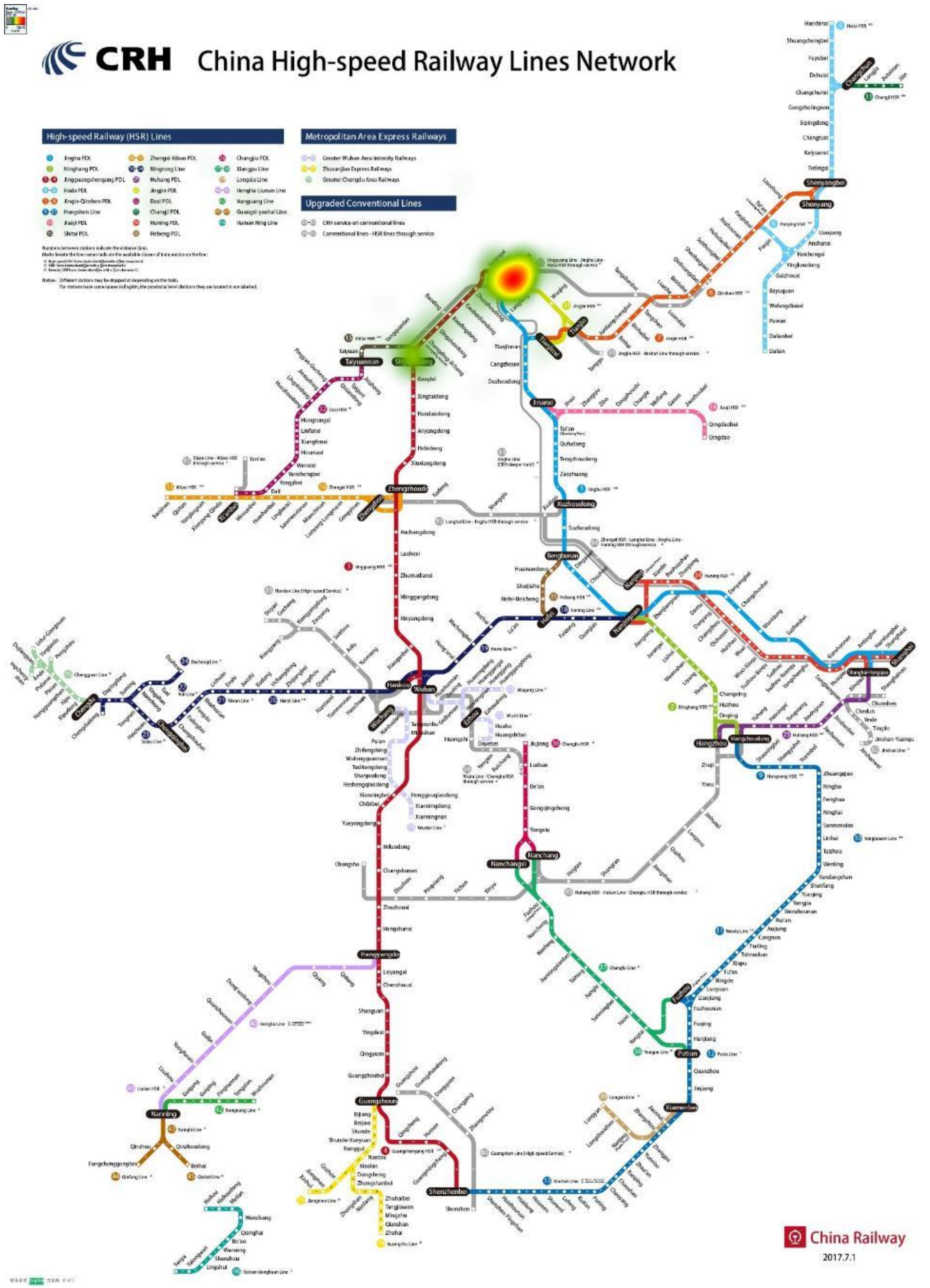
Guangzhounan
Shenzhenbei
Xiamenbei
Putian
Nanning
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
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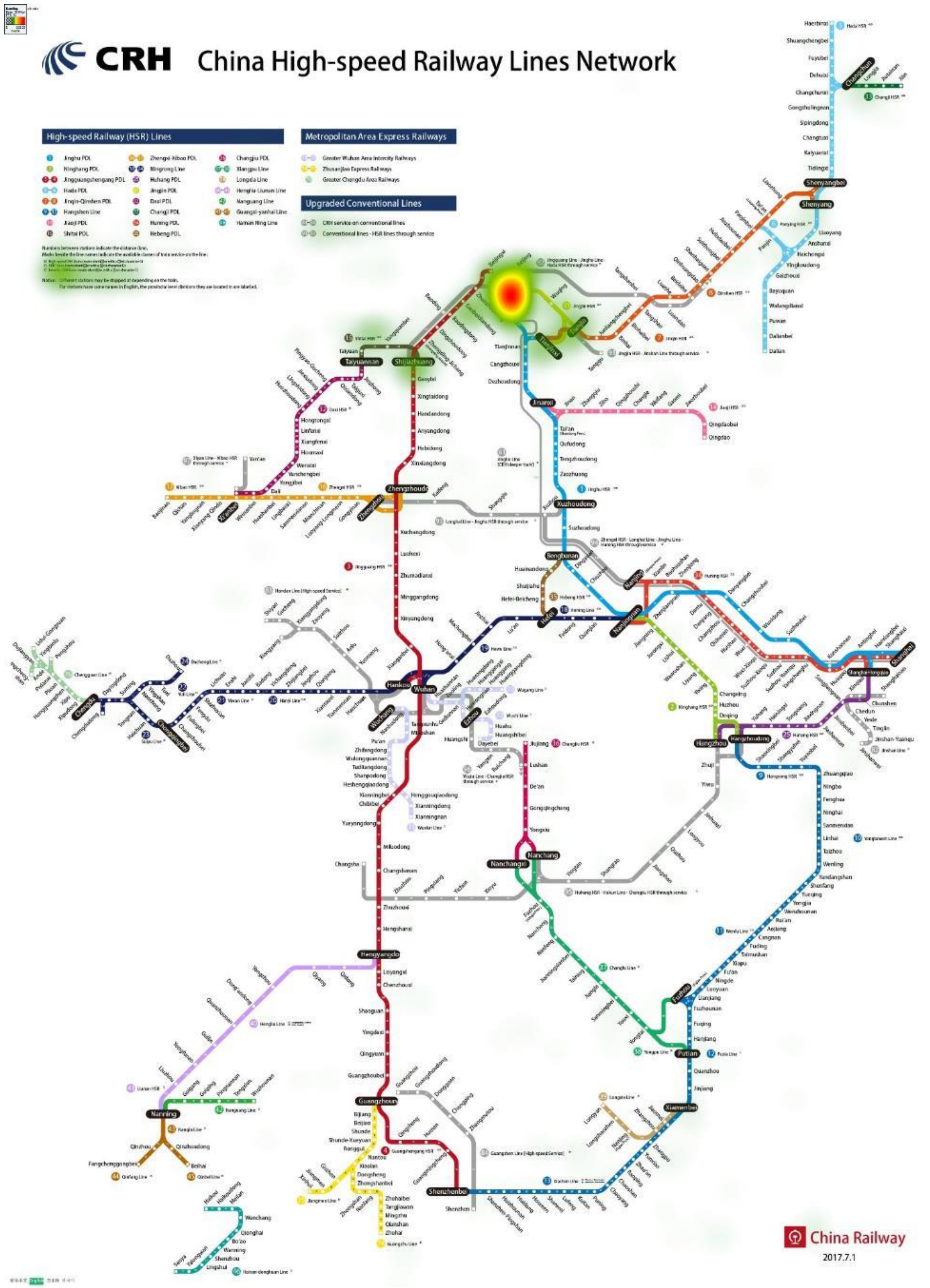
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China Railway
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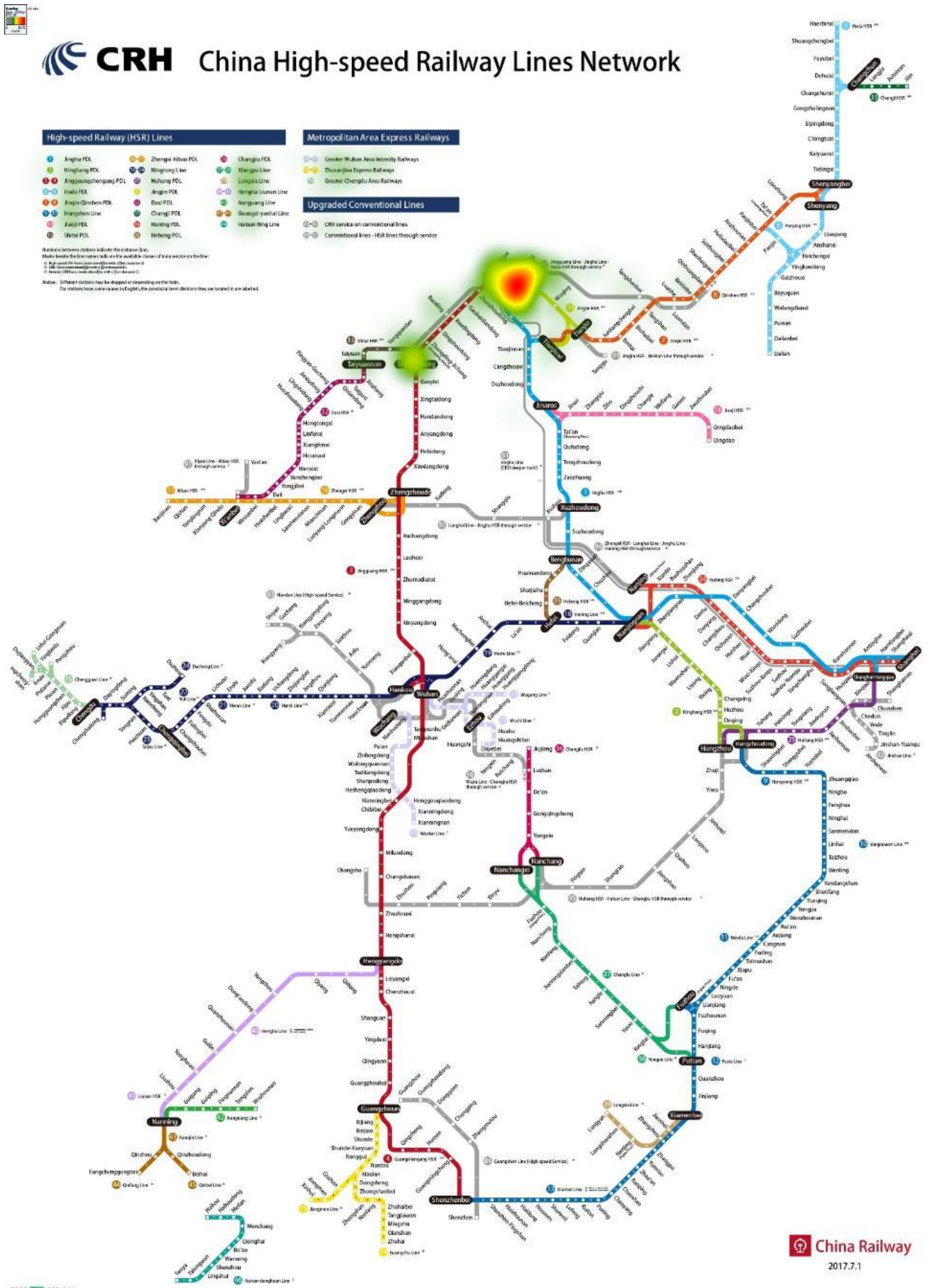
CRH China High-speed Railway Lines Network
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Metropolitan Area Express Railways
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CRH service on conventional lines
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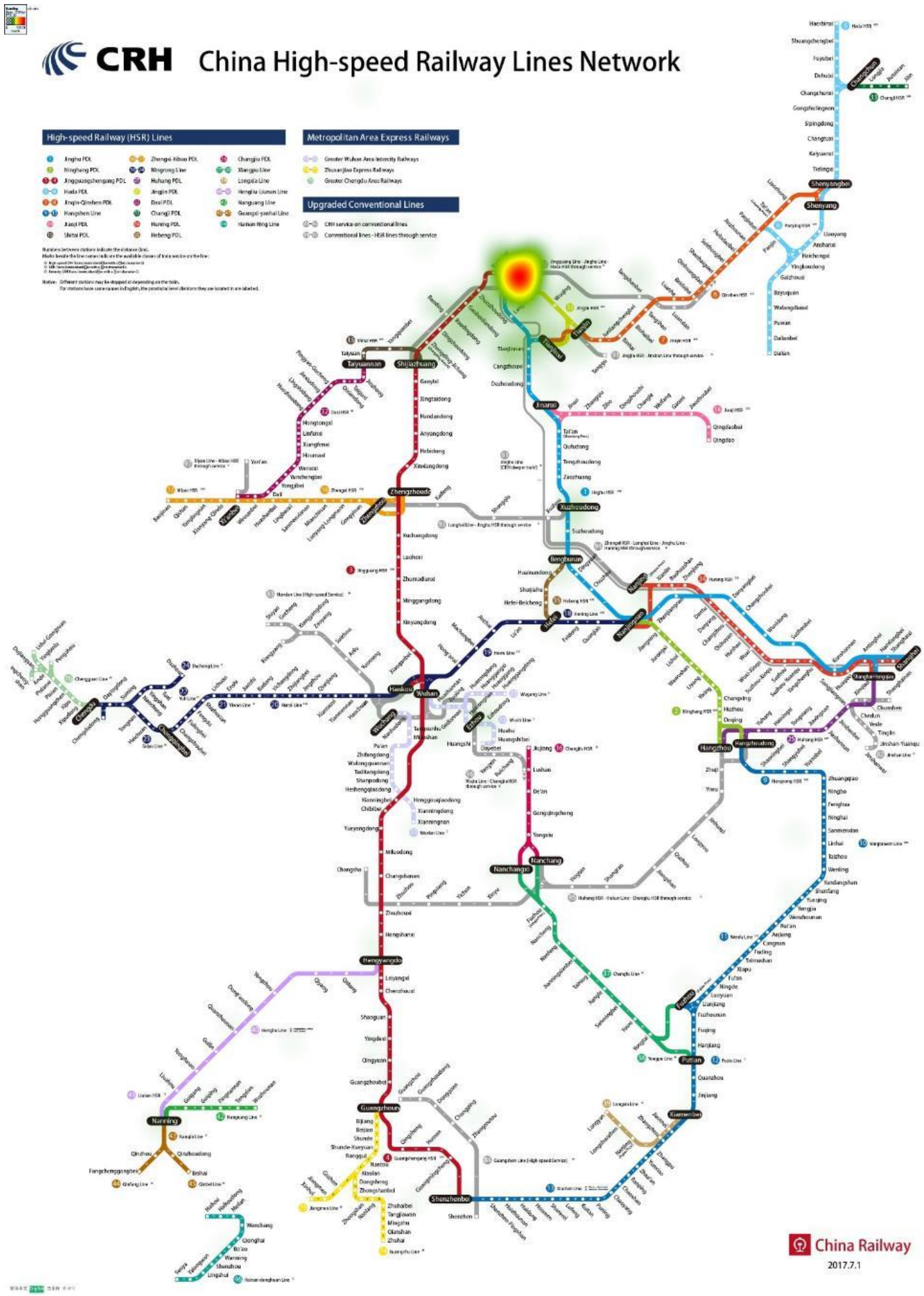
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
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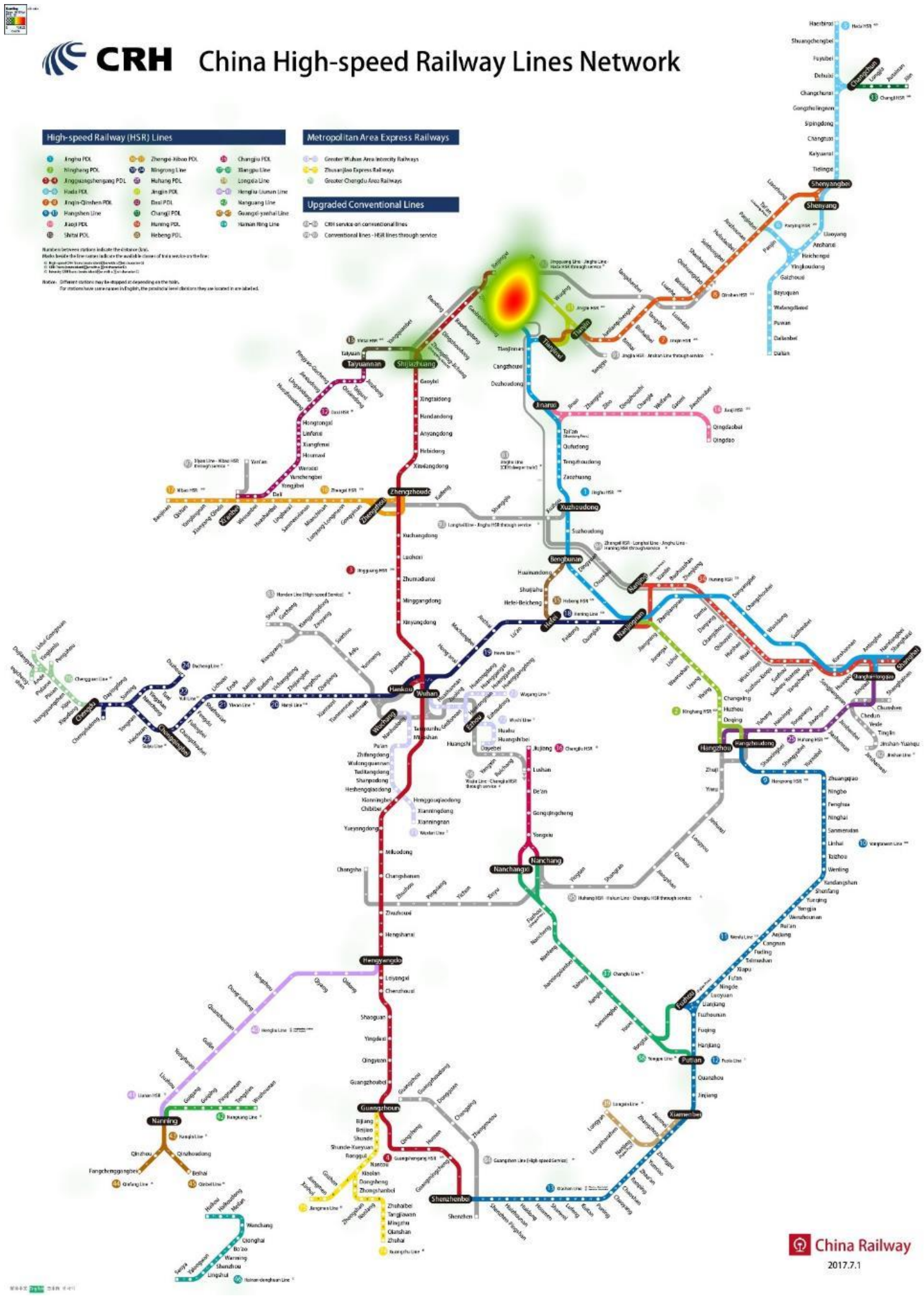
Metropolitan Area Express Railways
Upgraded Conventional Lines
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
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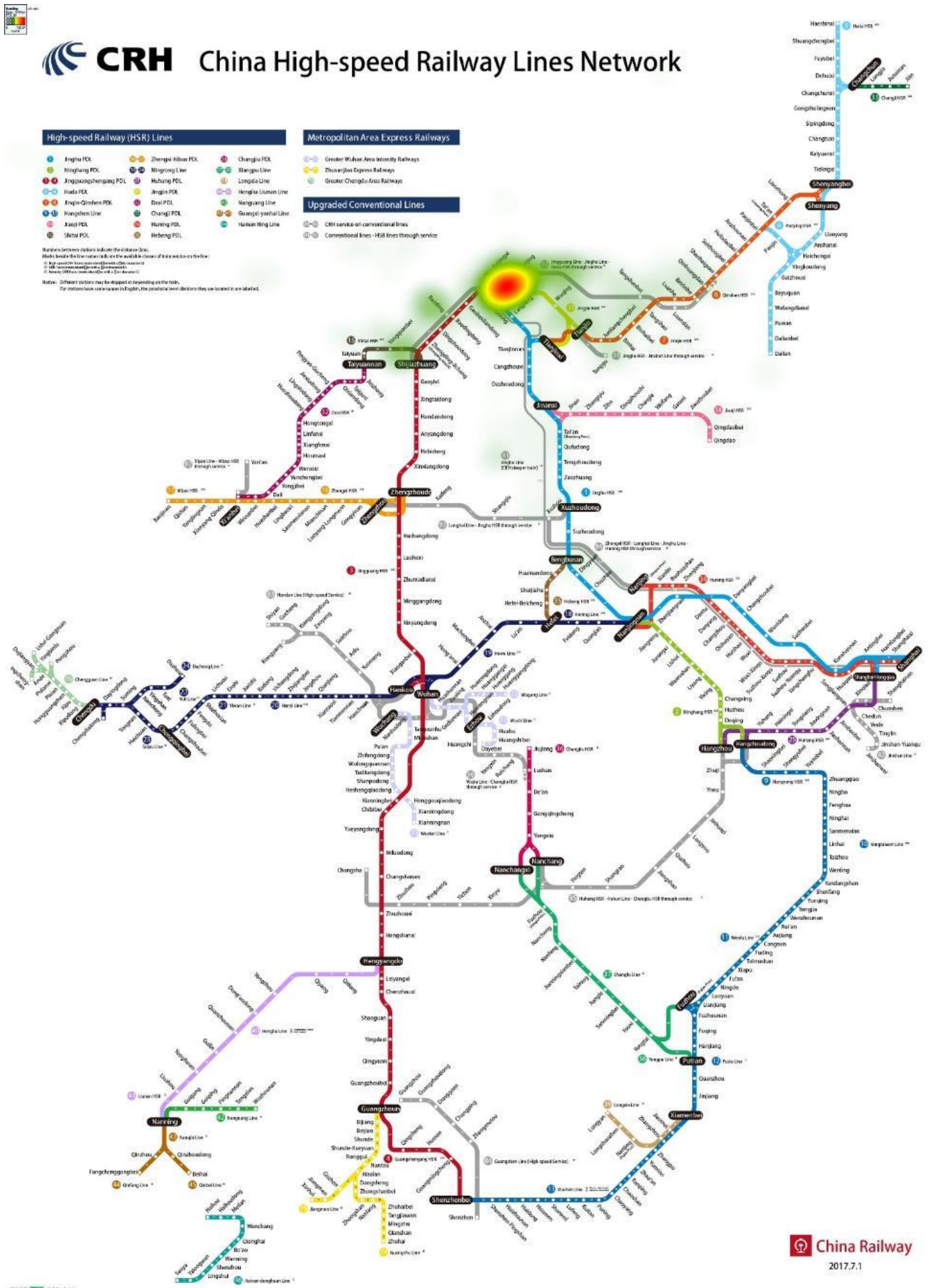
China Railway
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Harbinxi
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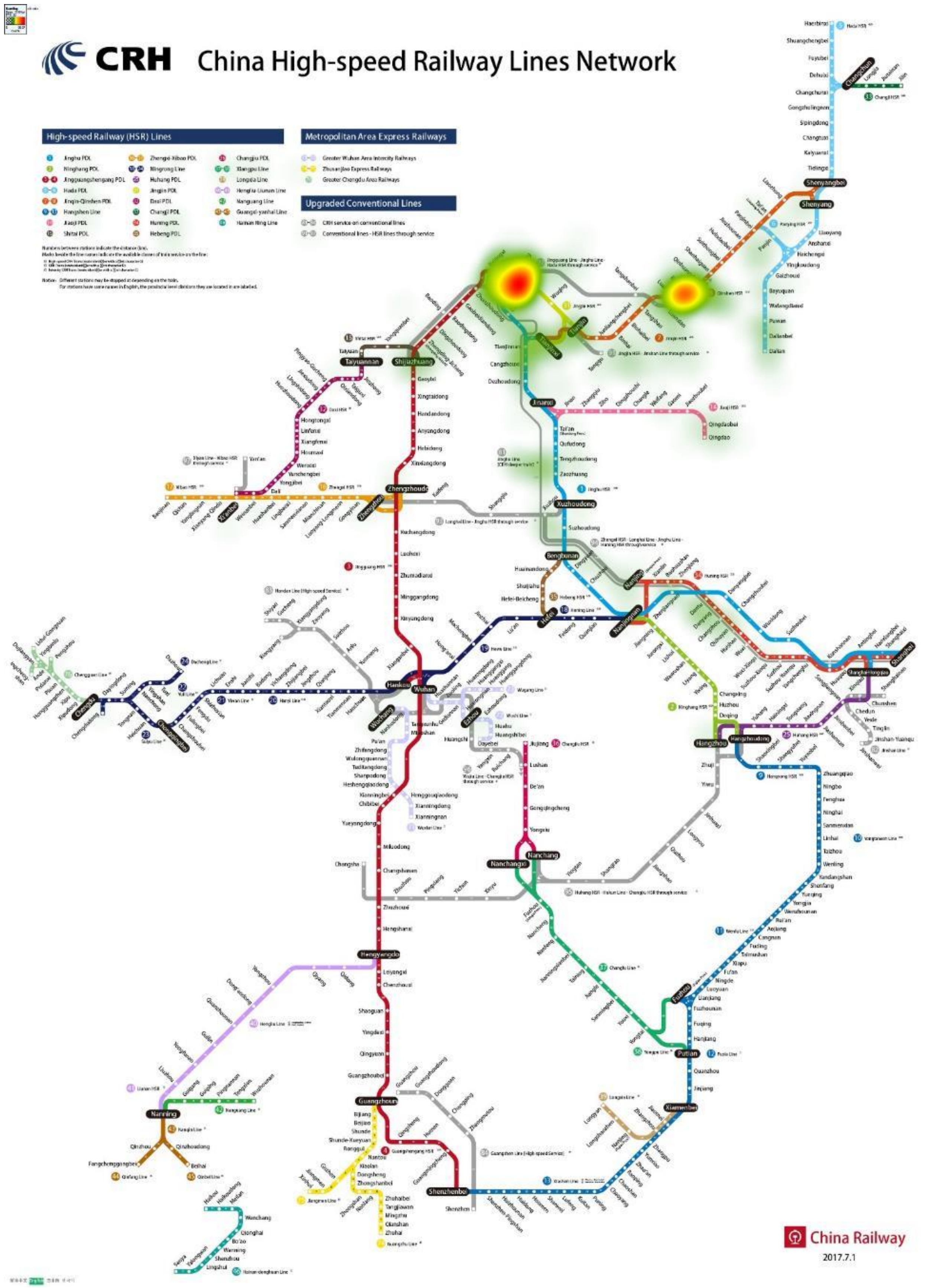
CRH China High-speed Railway Lines Network
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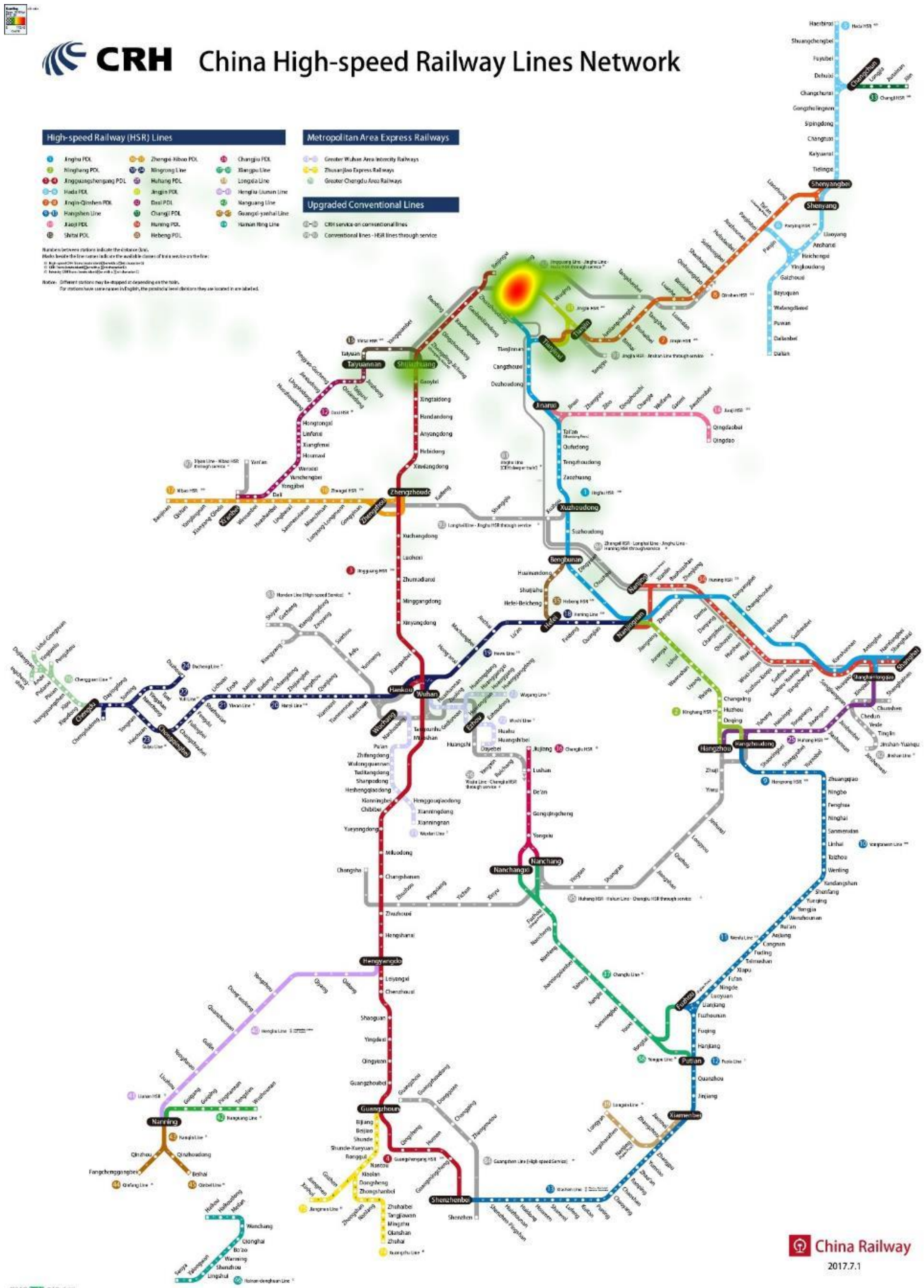
2017.7.1


CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Metropolitan Area Express Railways
Upgraded Conventional Lines
Harbinxi
Changchunxi
Shenyangbei
Shenyang
Dalian
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Tianjin
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Chengdu
Chongqingbei
Nanchangxi
Nanchang
Changsha
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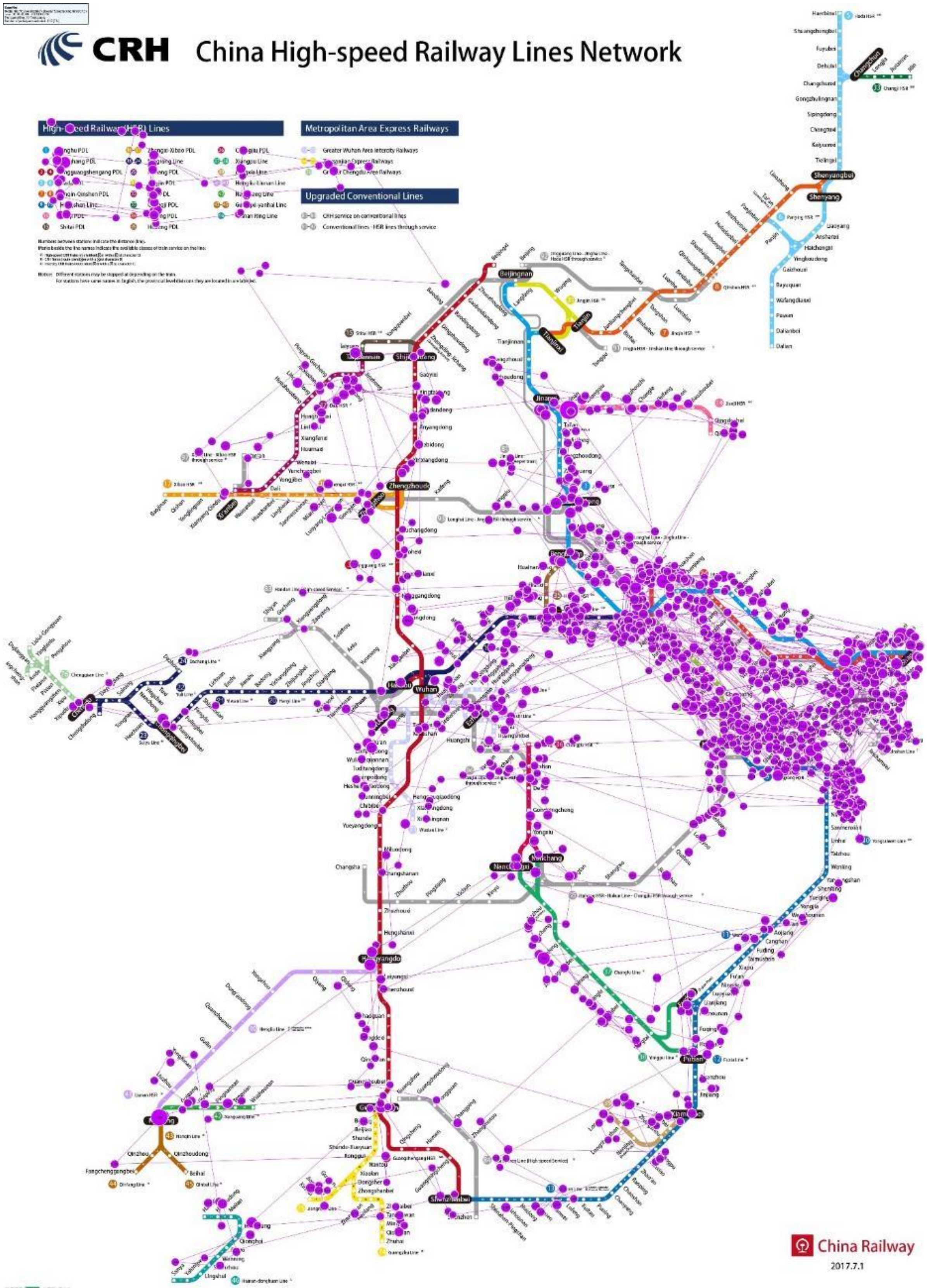
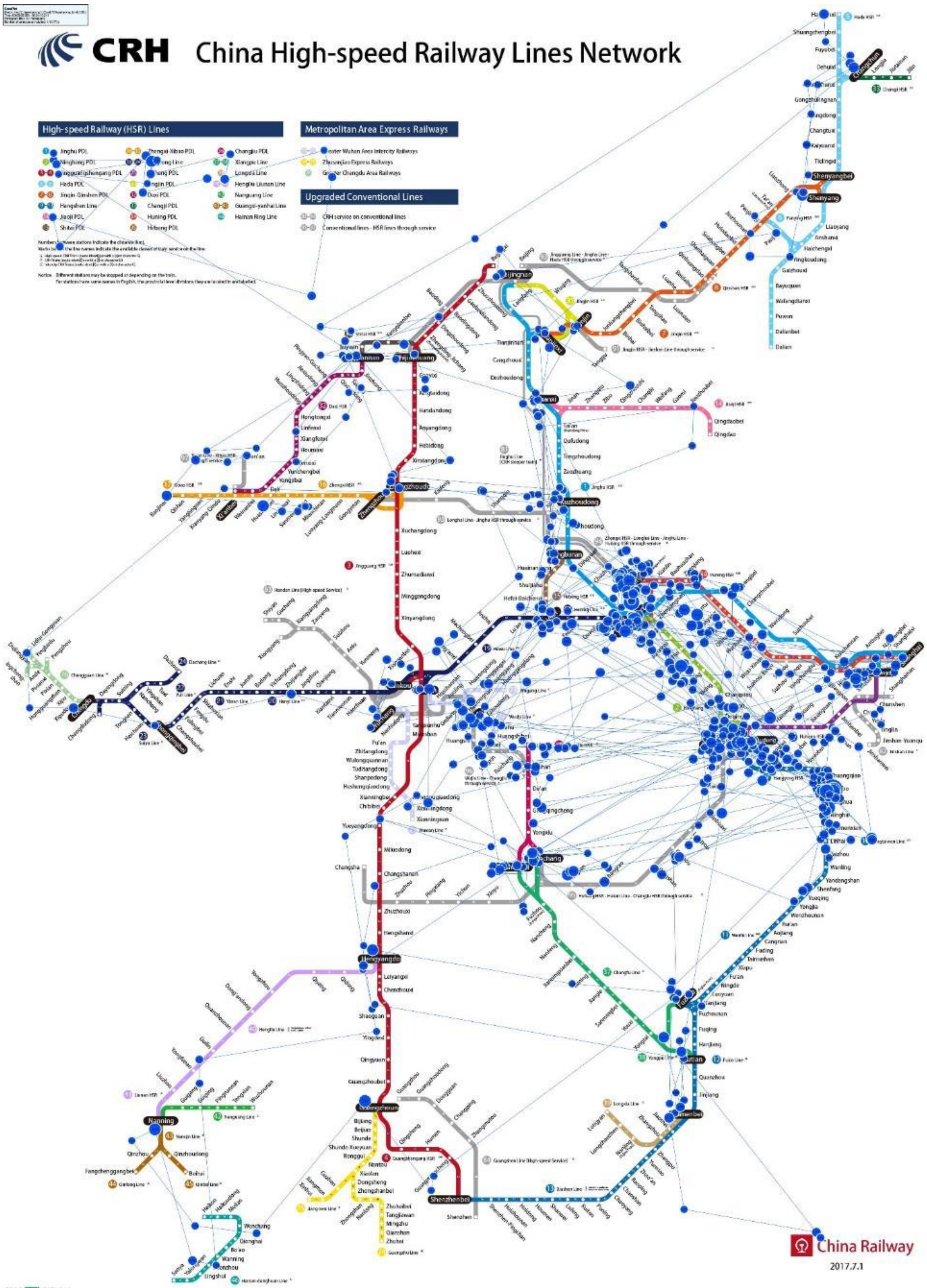
Putian
Xiamenbei
Guangzhounan
Shenzhenbei
Nanning
China Railway
2017.7.1

Experiment I, Task 4




CRH China High-speed Railway Lines Network
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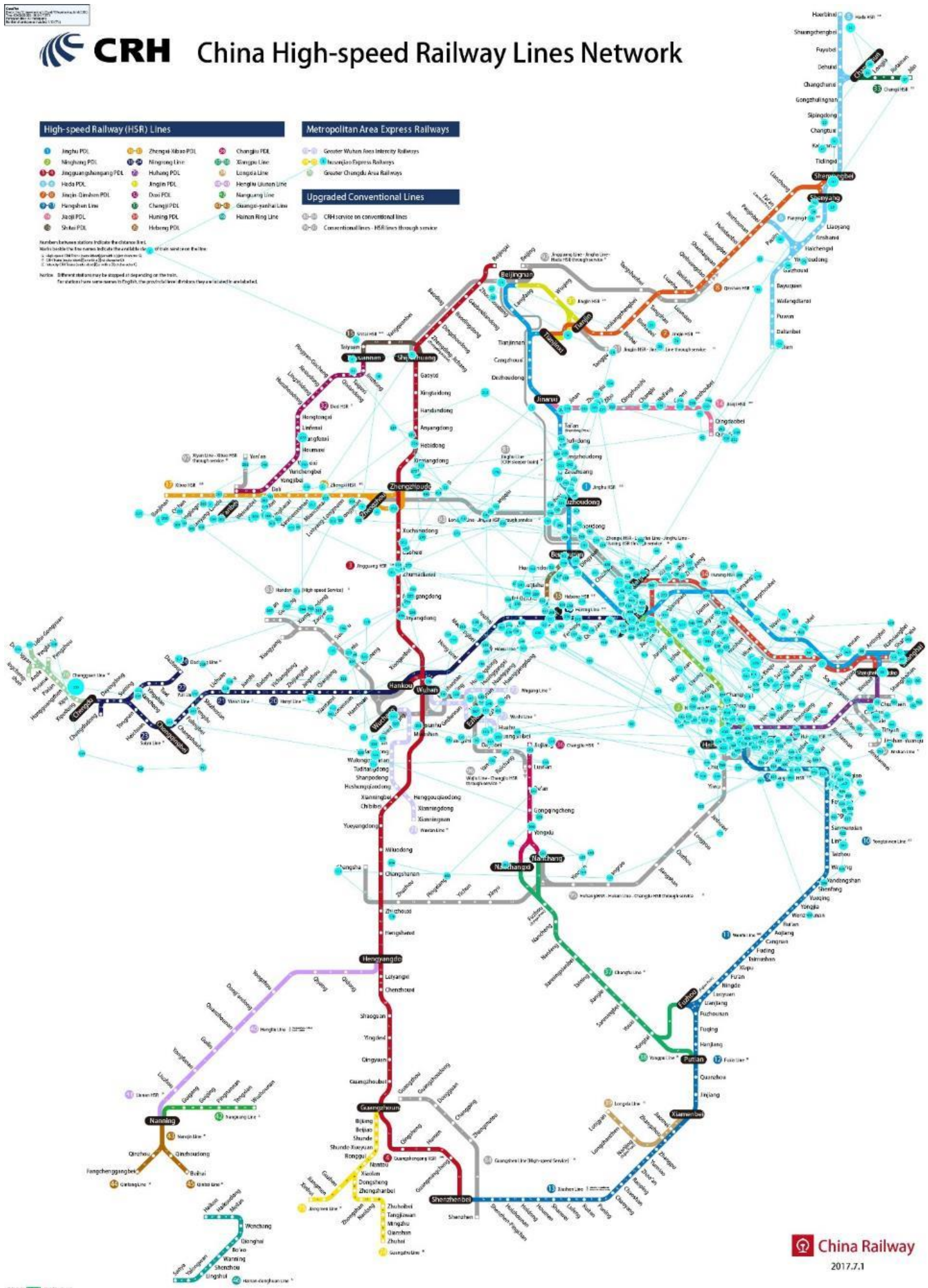

CRH China High-speed Railway Lines Network
High-speed Railway (HSR) Lines
Jinghu PDL
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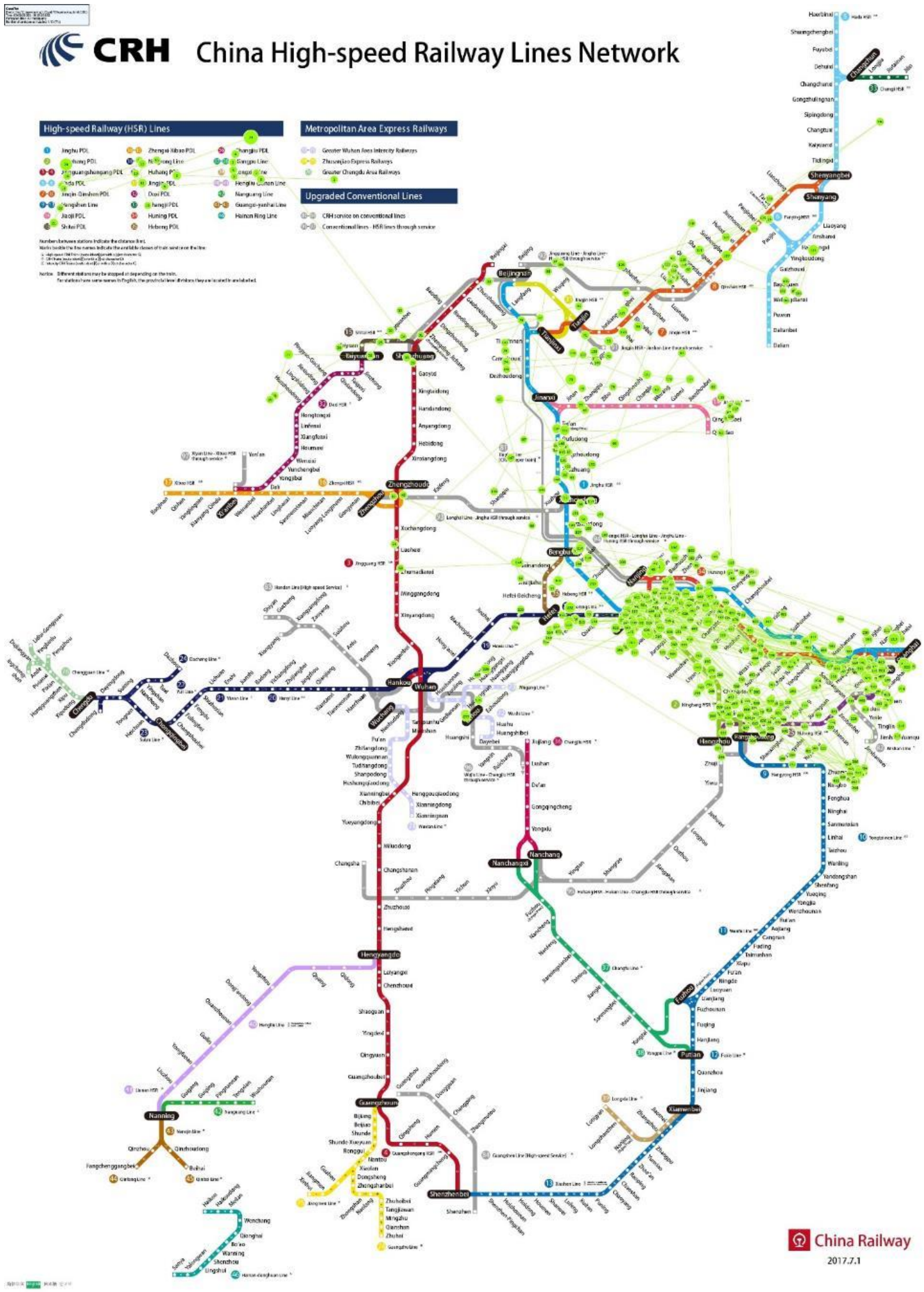
Hangshen Line
Jiaoji PDL
Shitai PDL
Zhengxi-Xibao PDL
Ningrong Line
Huhang PDL
Jingjin PDL
Daxi PDL
Changji PDL
Huning PDL
Hebeng PDL
Changjiu PDL
Xiangpu Line
Longxia Line
Hengliu-Liunan Line
Nanguang Line
Guangxi-yanhai Line
Hainan Ring Line
Metropolitan Area Express Railways
Greater Wuhan Area Intercity Railways
Greater Chengdu Area Railways
Upgraded Conventional Lines
CRH service on conventional lines
Conventional lines - HSR lines through service
Numbers between stations indicate the distance (km).
Notice: Different stations may be stopped at depending on the train.
For stations have same names in English, the provincial level divisions they are located in are labeled.
China Railway
2017.7.1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China Railway
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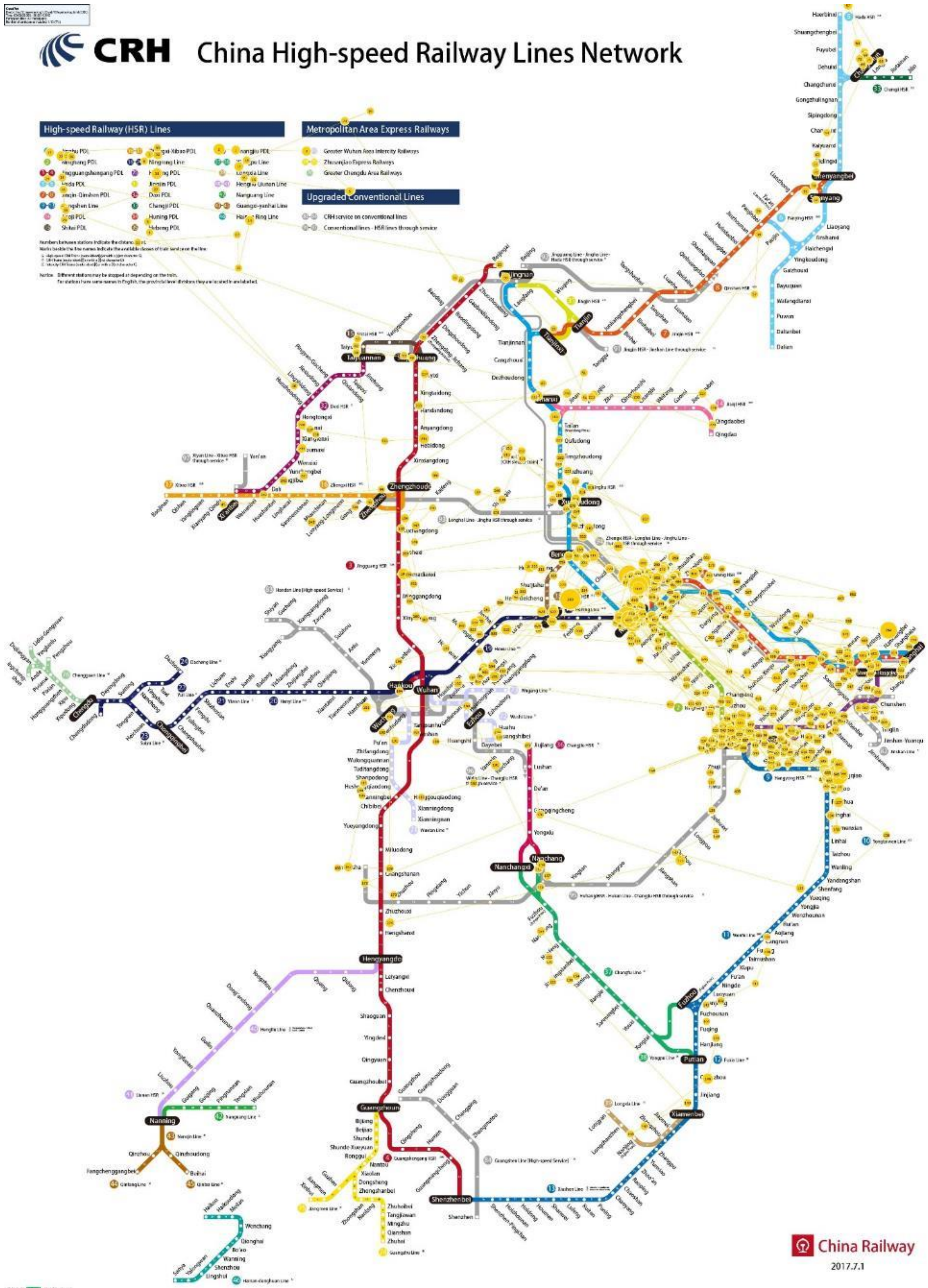
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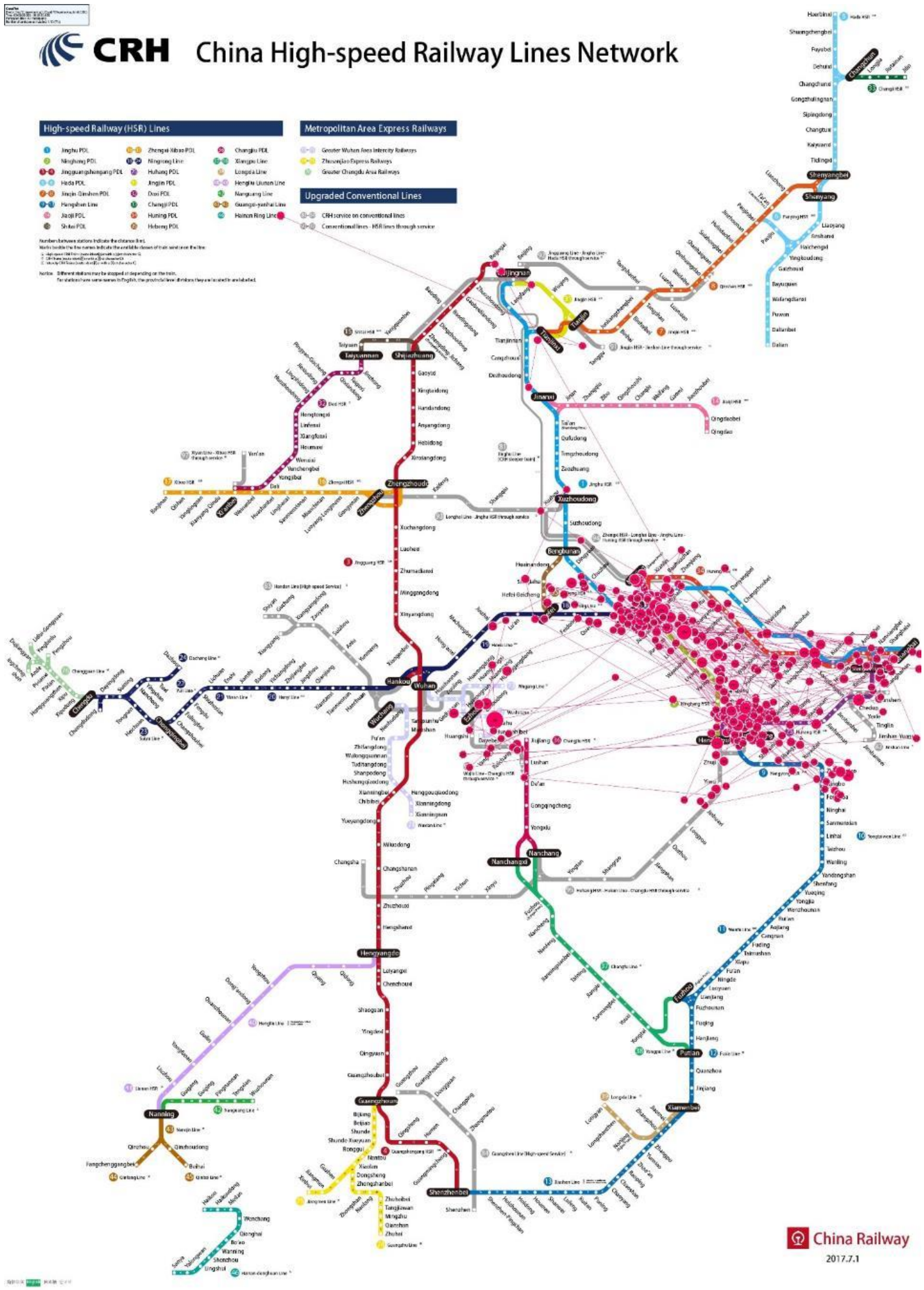
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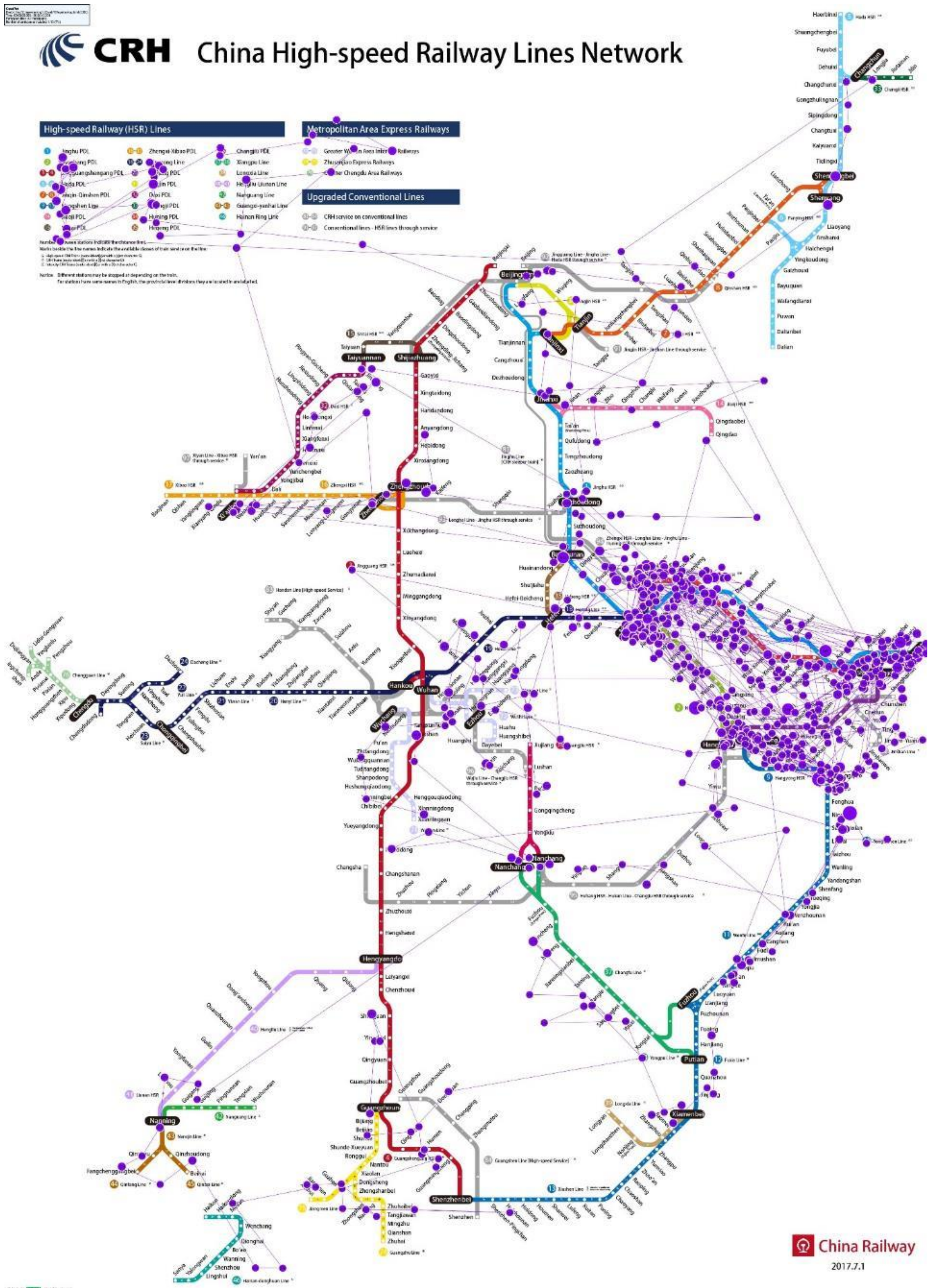
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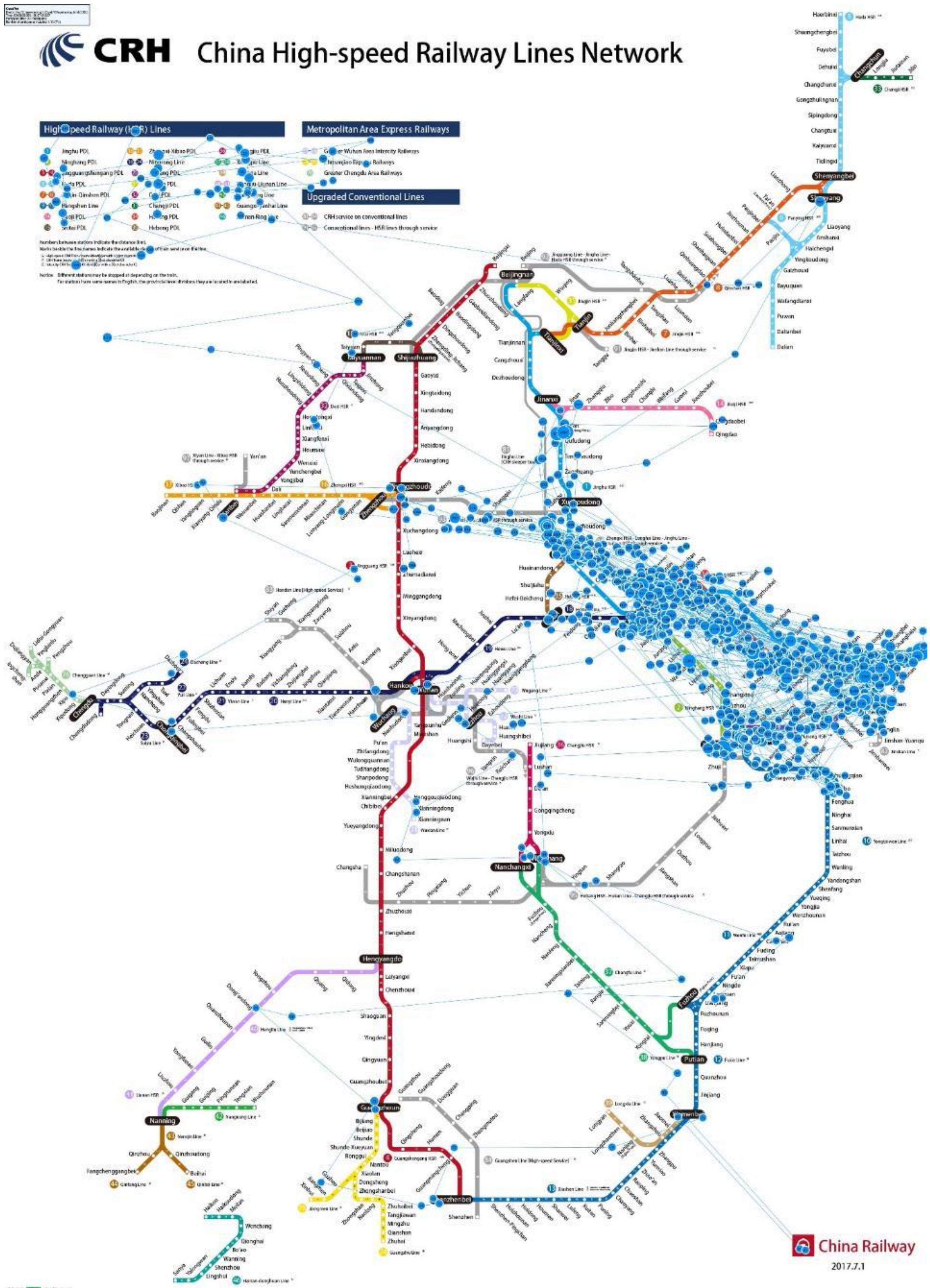
China Railway
2017.7.1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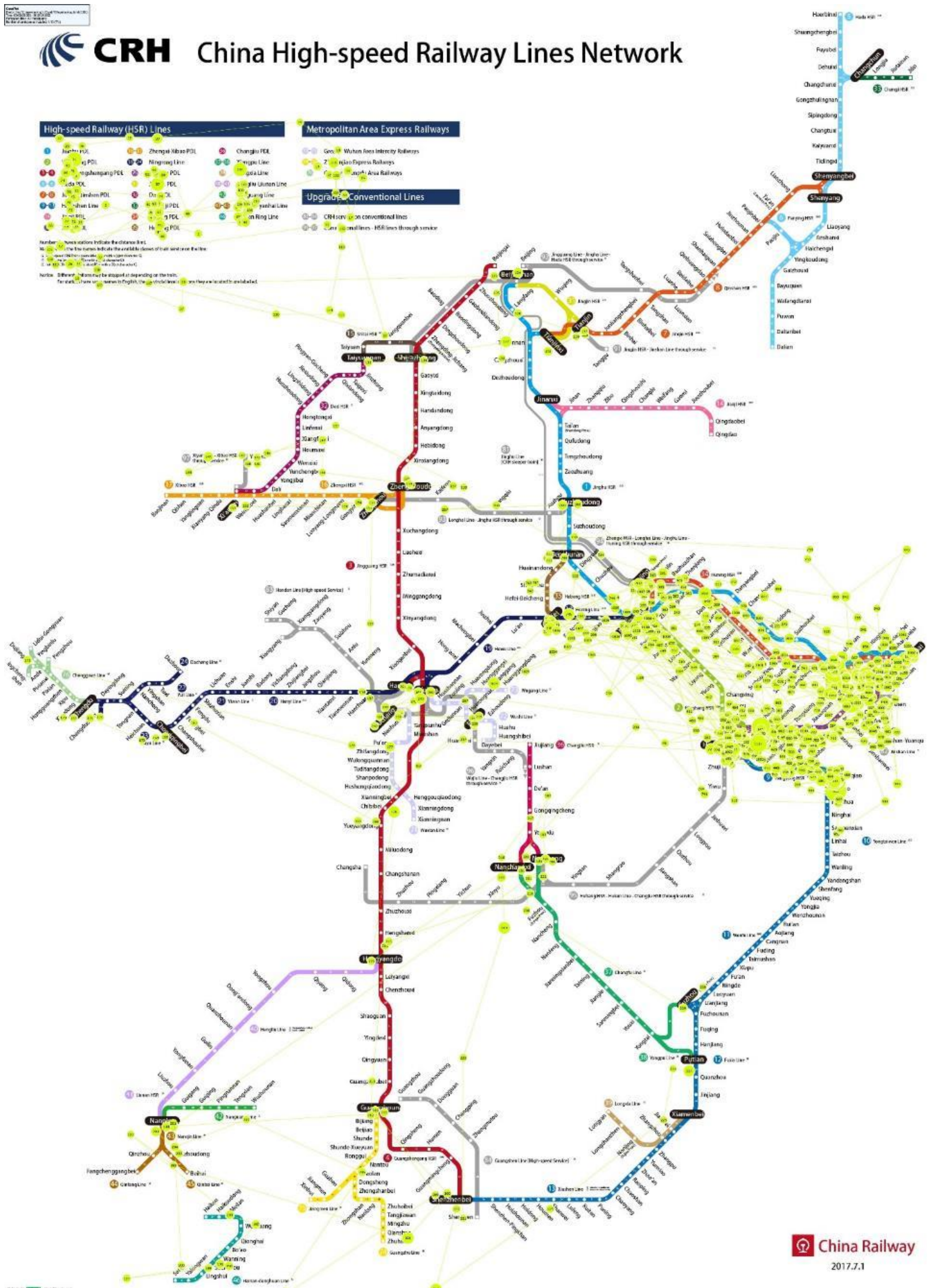
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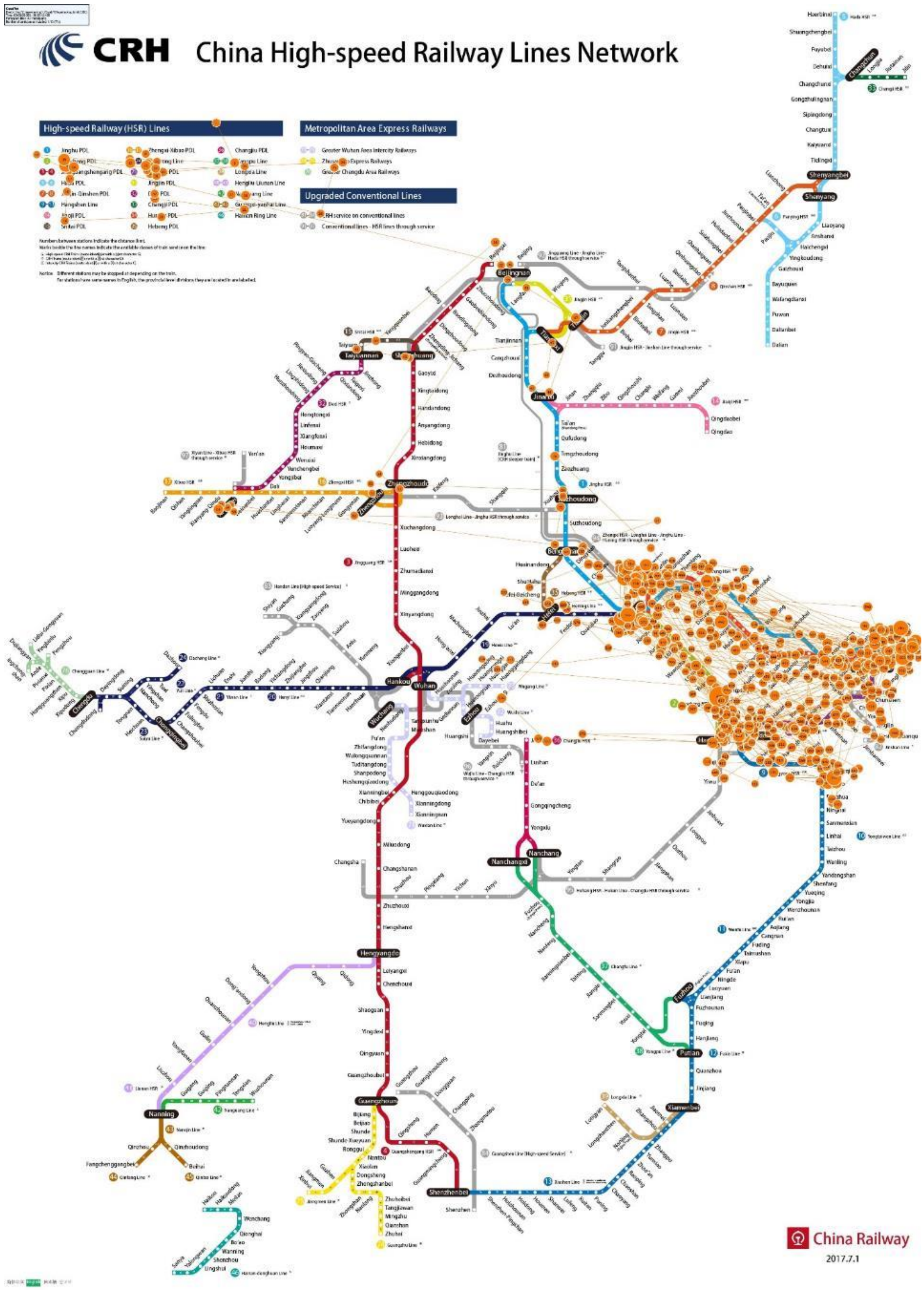
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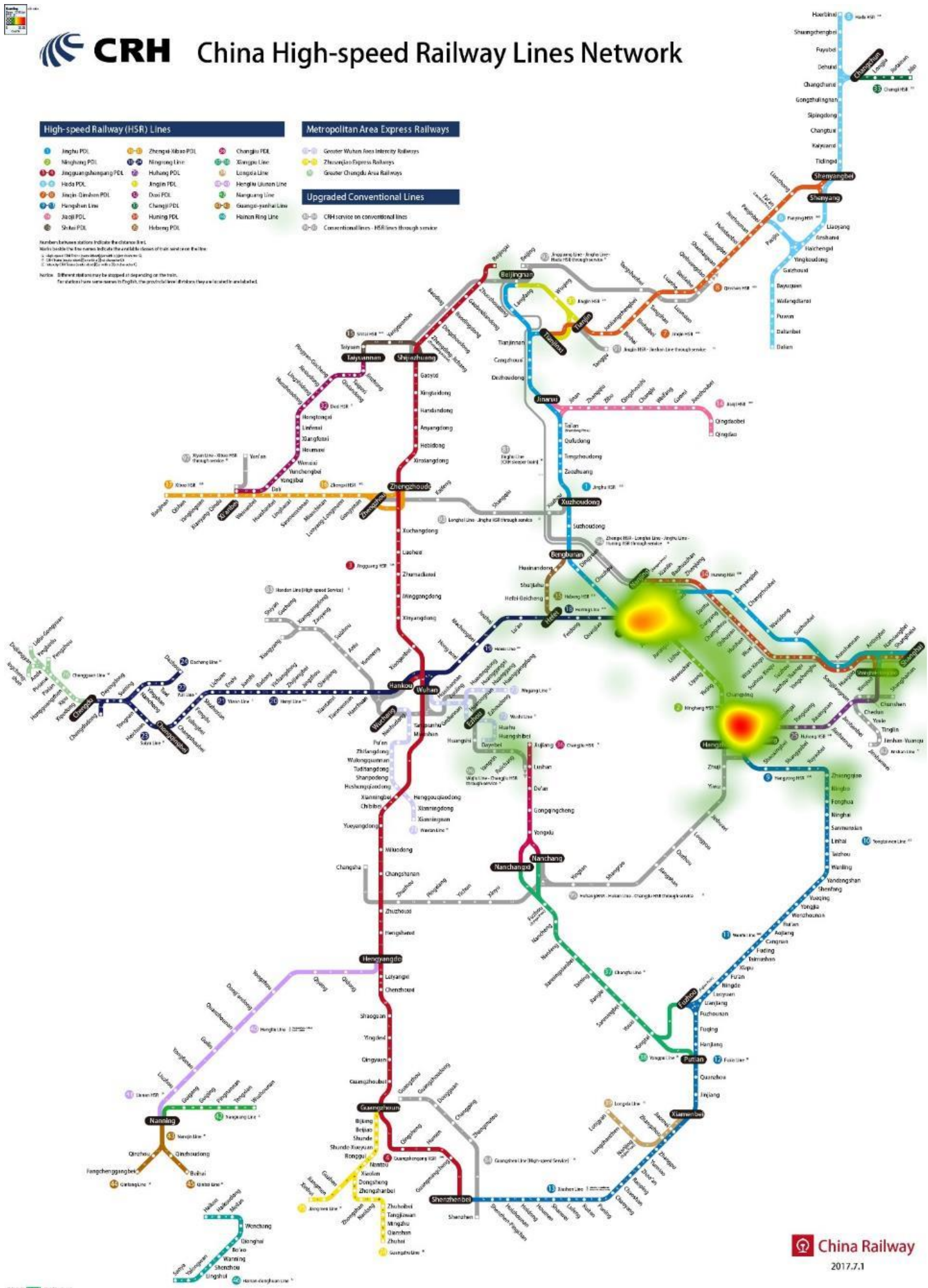
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Beijingnan
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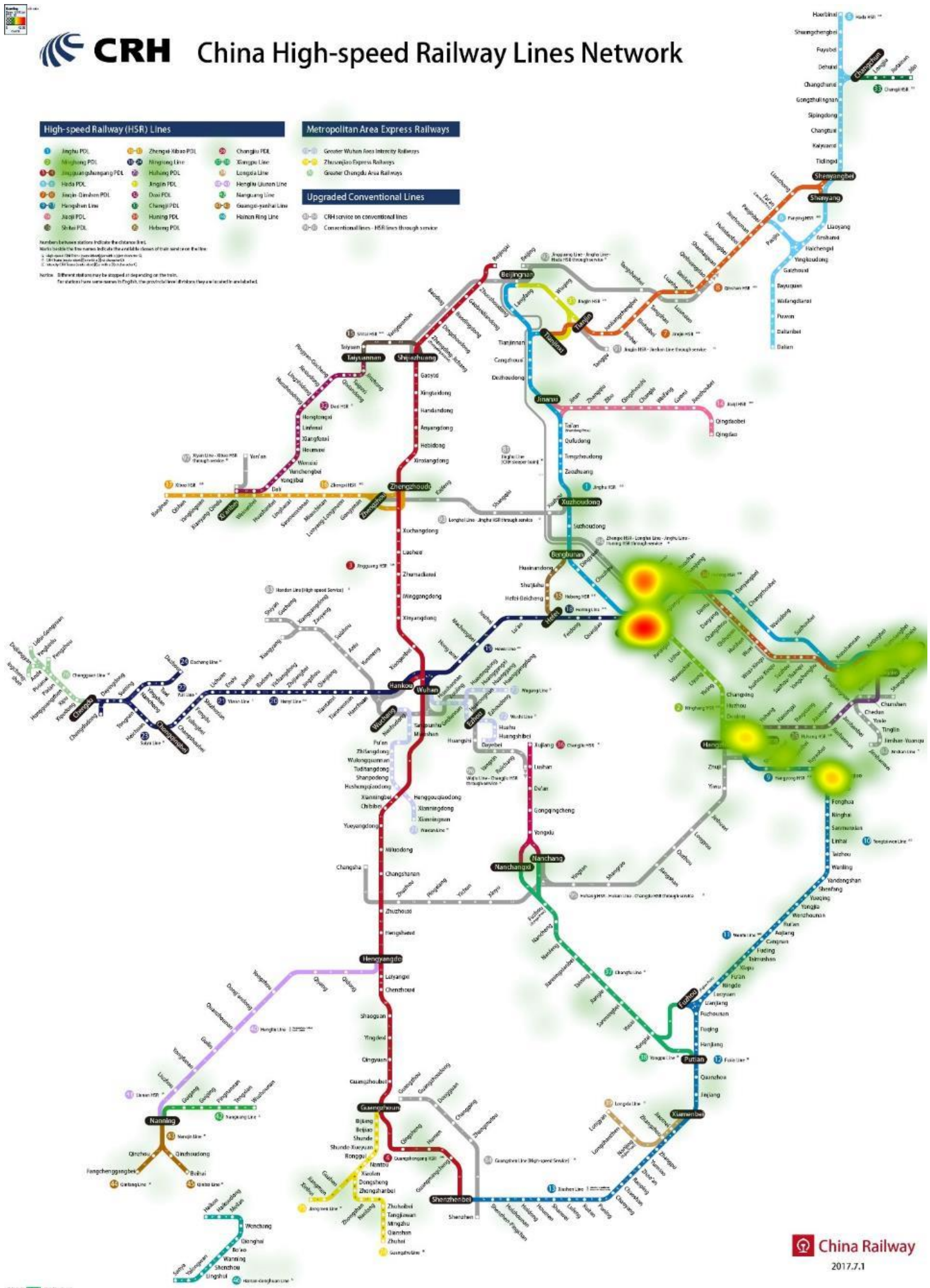
Shenyangbei
Shenyang
Changchun
China Railway
2017.7.1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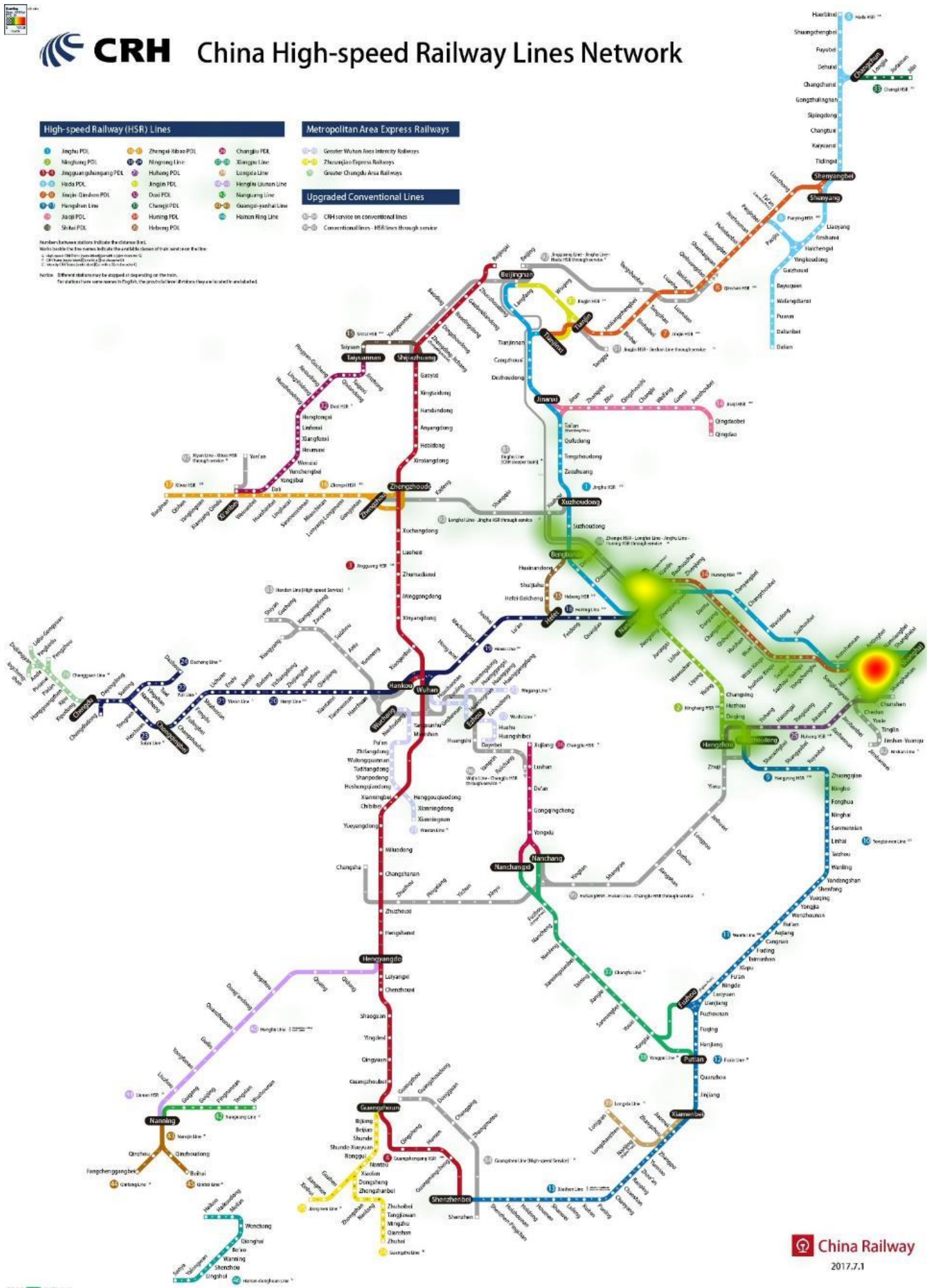
Nanning
Changsha
China Railway
2017.7.1



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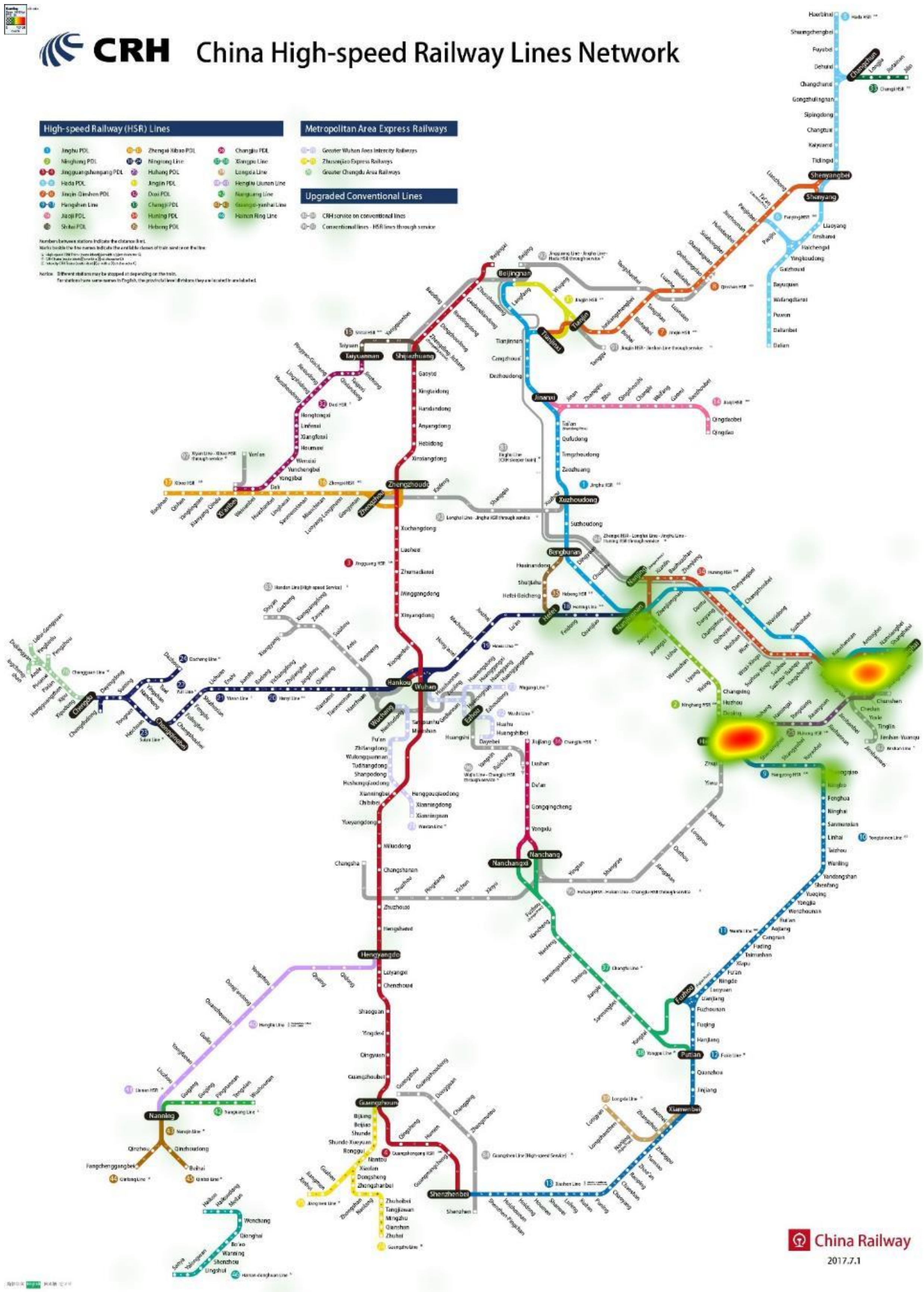
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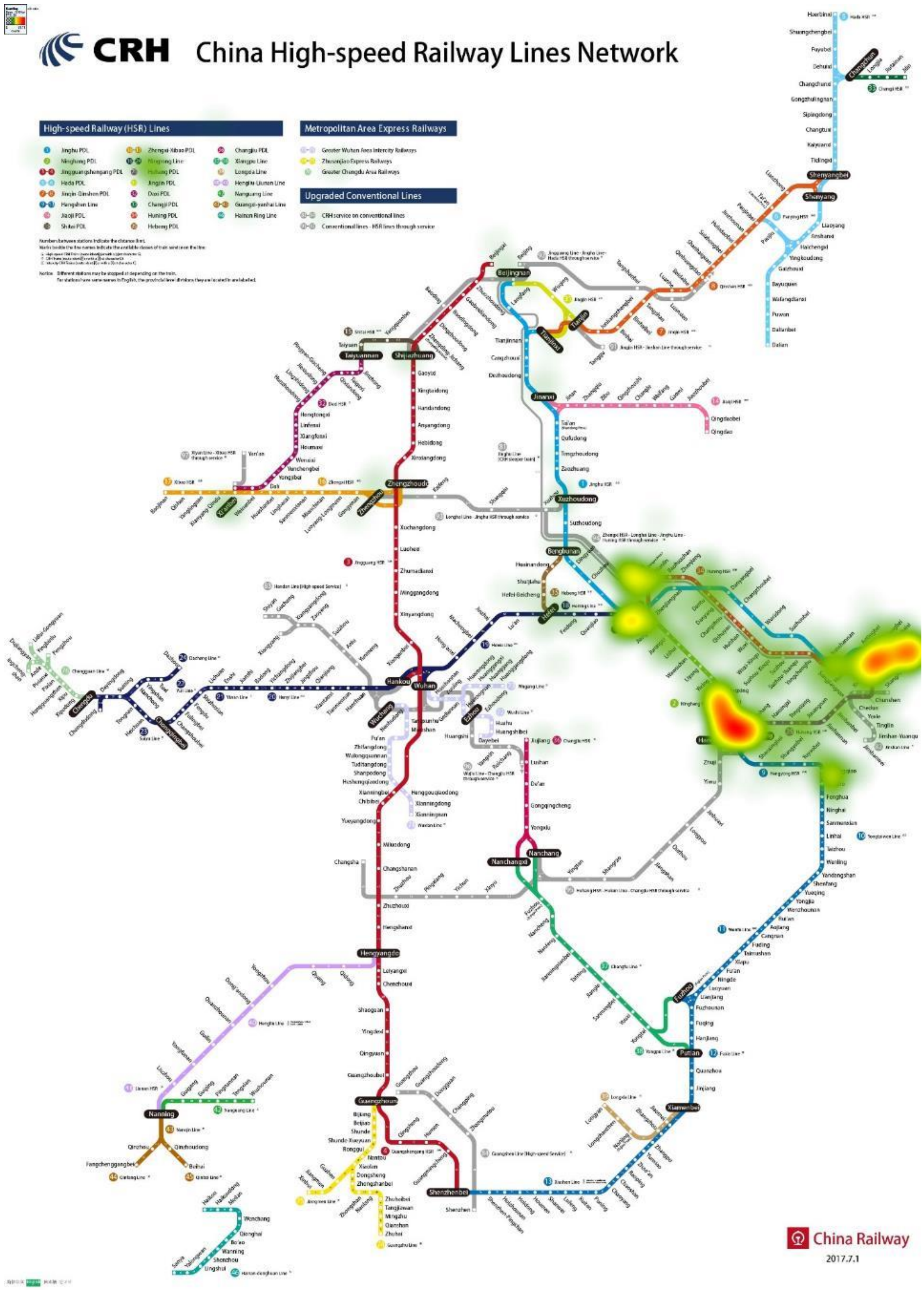
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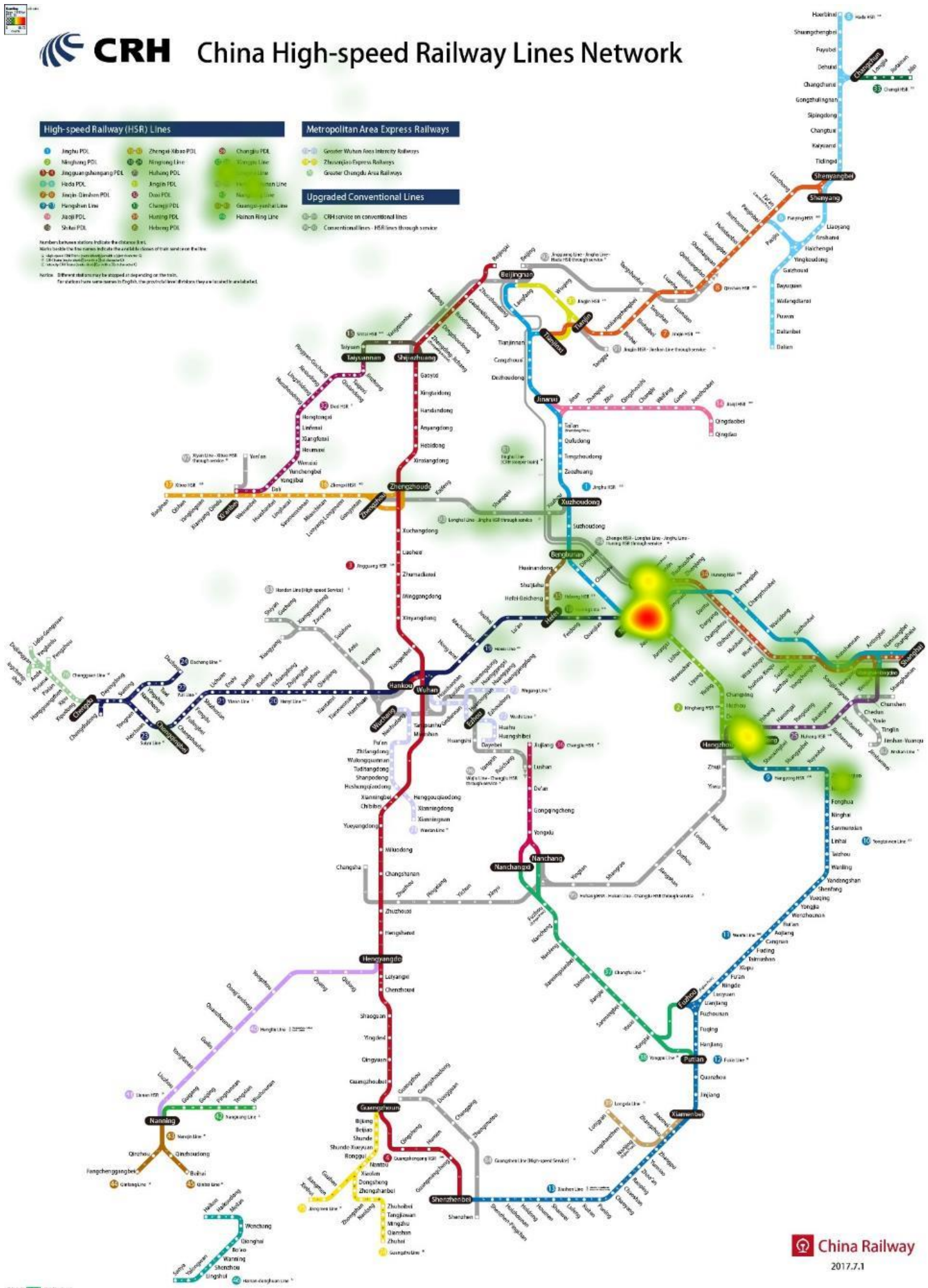
Harbinxi
Changchun
Shenyangbei
Shenyang
Dalian
Beijingnan
Tianjin
Tianjinxi
Shijiazhuang
Taiyuannan
Jinanxi
Qingdao
Zhengzhoudong
Xuzhoudong
Bengbunan
Hefei
Hankou
Wuhan
Changsha
Nanchang
Nanchangxi
Hengyangdong
Fuzhou
Putian
Xiamenbei
Guangzhounan
Shenzhenbei
Nanning
Chengdu
China Railway
2017.7.1



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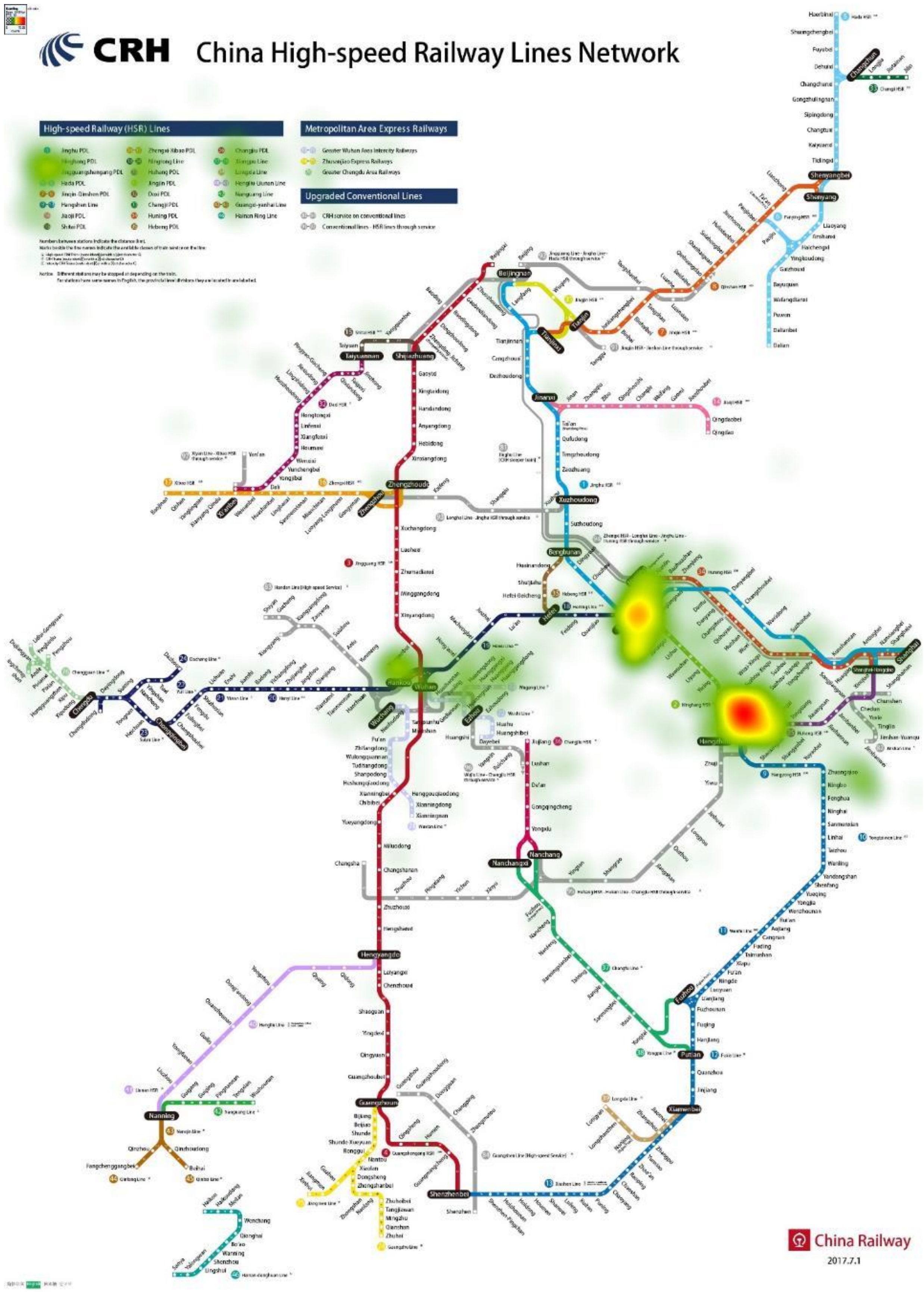
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Shenzhenbei
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Shenyang
Chengdu
Chongqingbei
Shanghai
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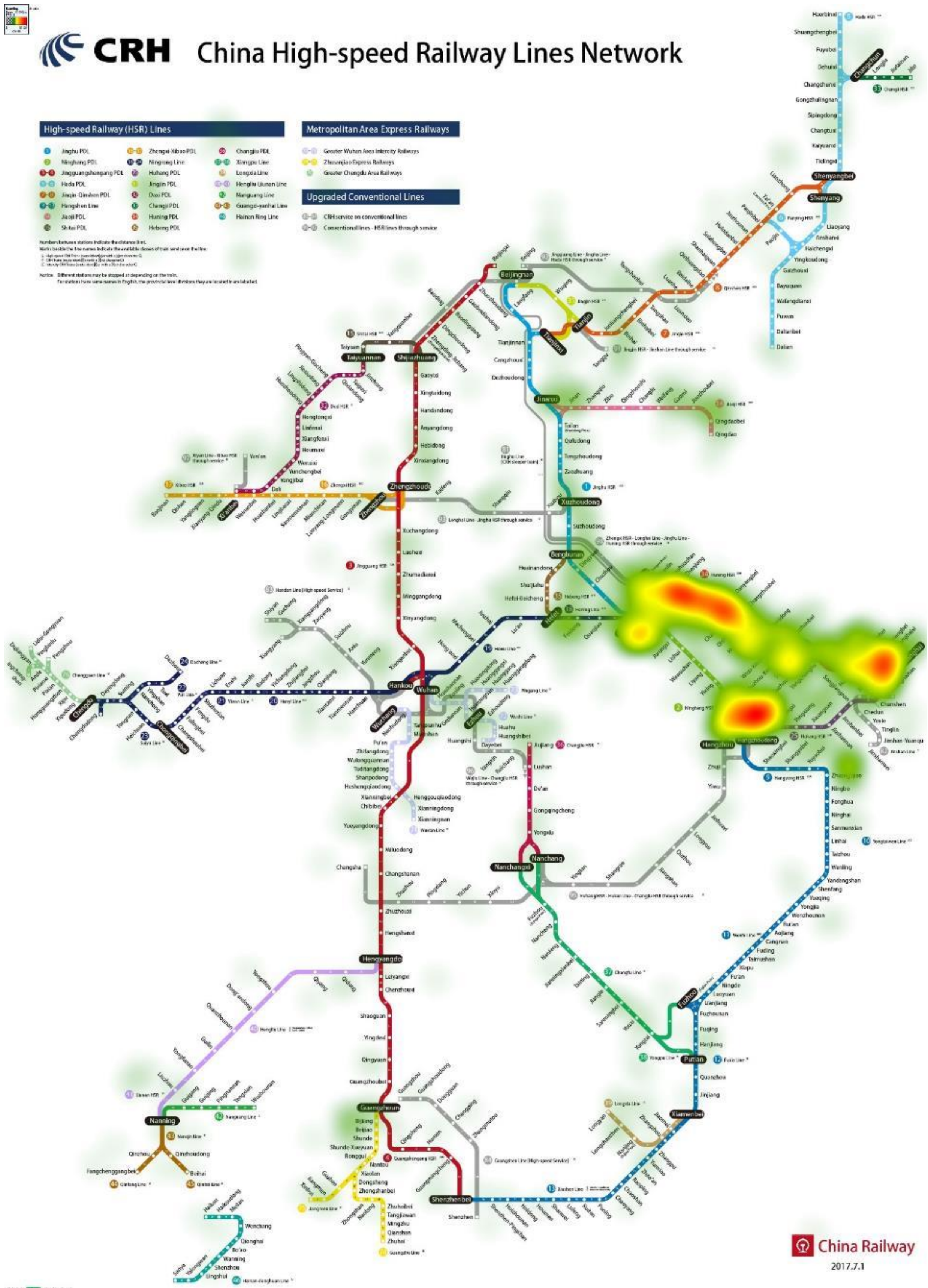
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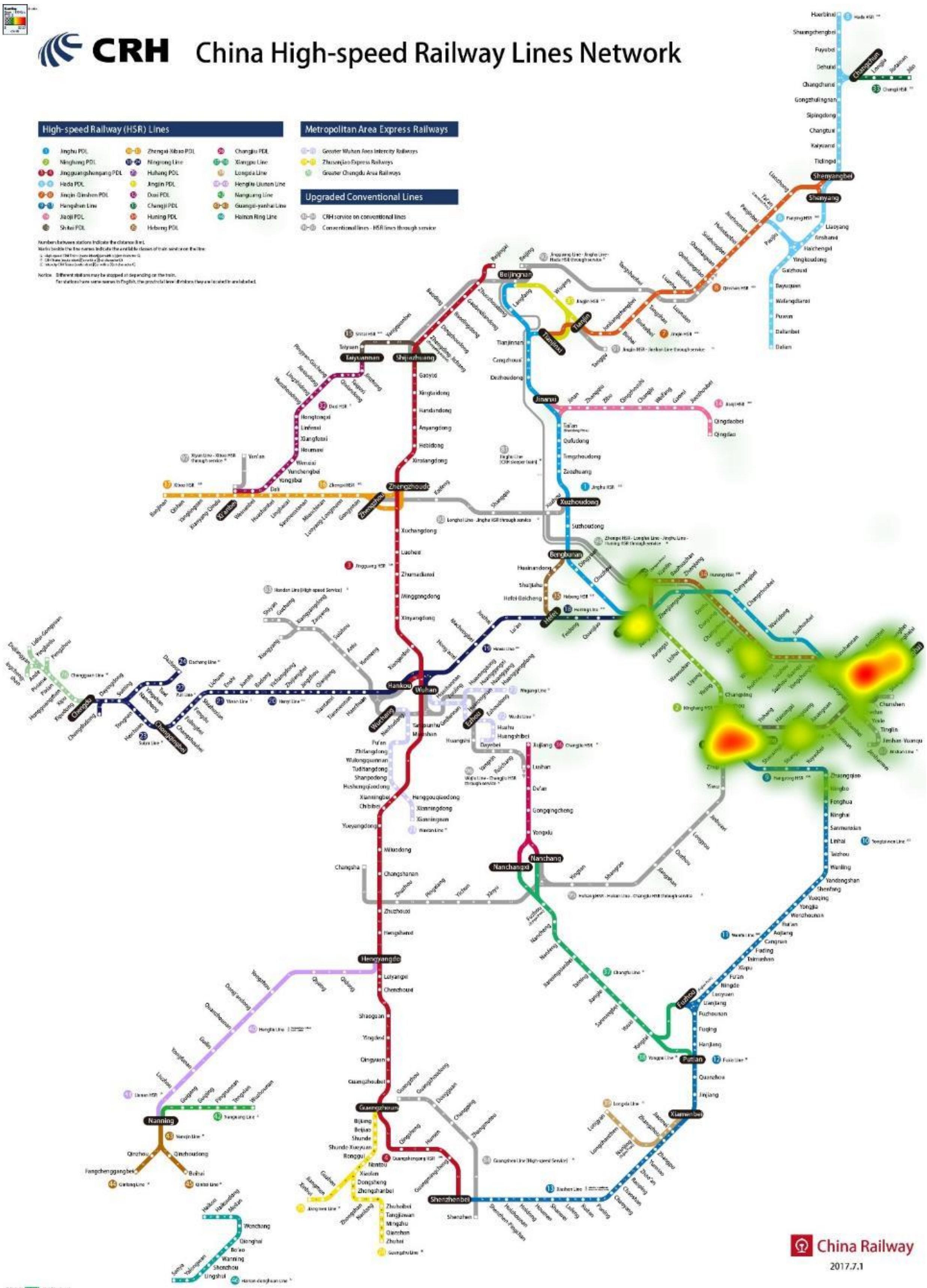
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Chongqingbei
Chengdudong
China Railway
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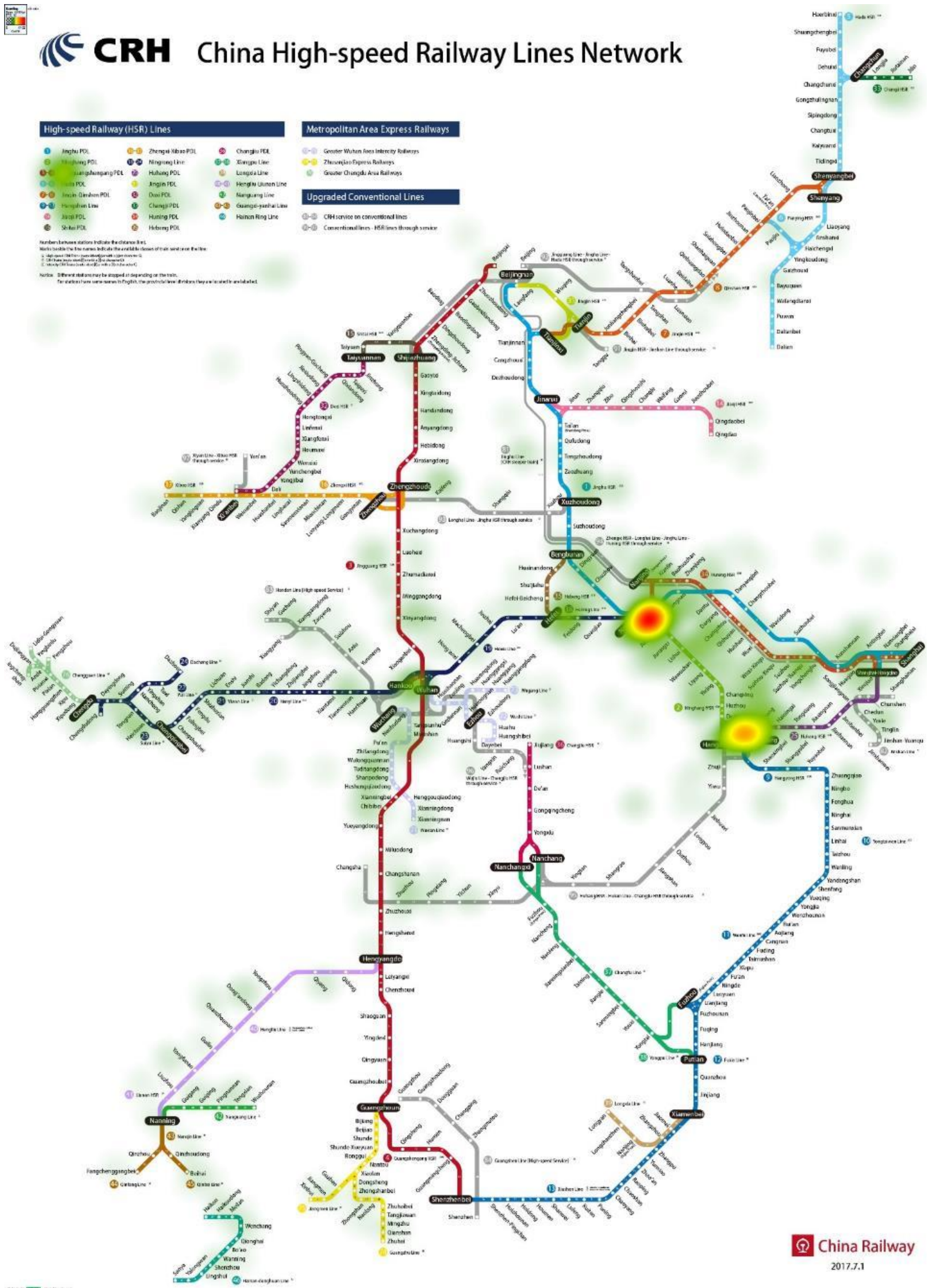
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Nanning
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Shenyangbei
Shenyang
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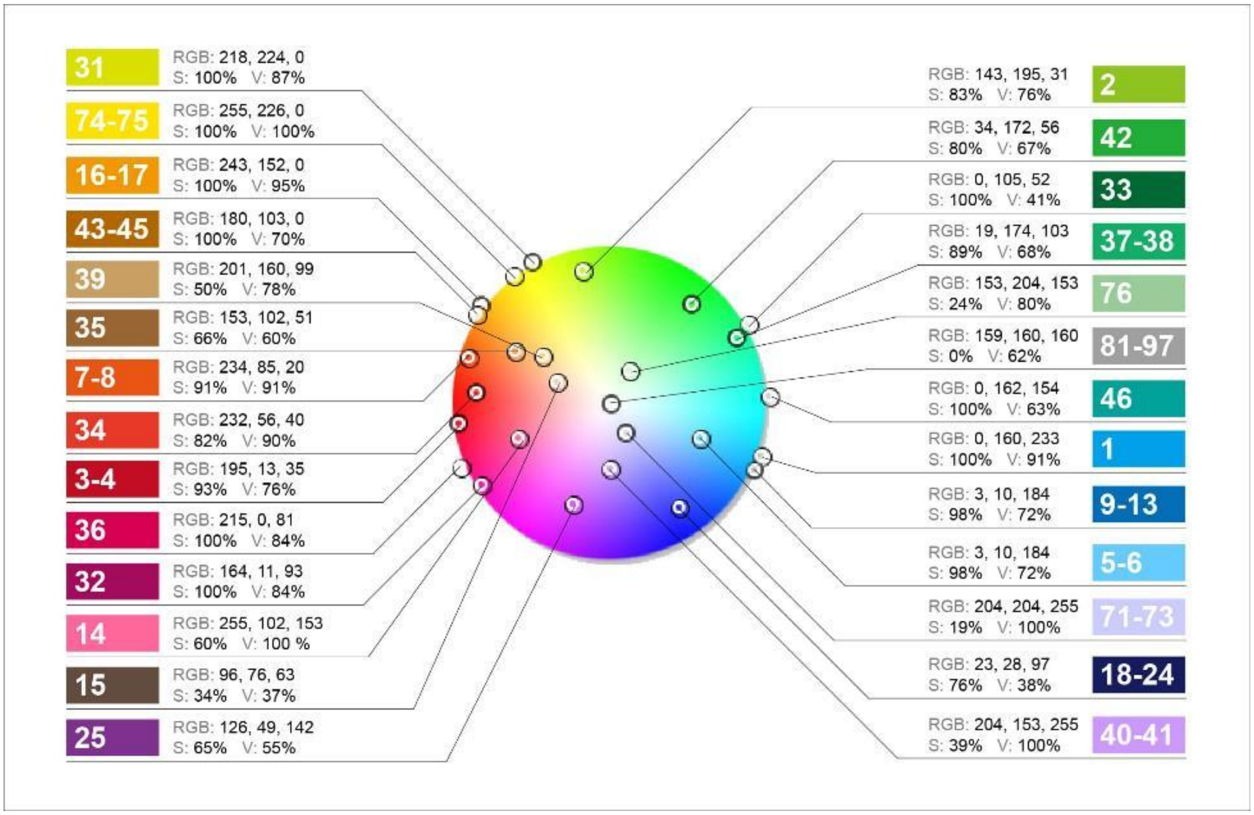
Appendix II: Colour system design examples

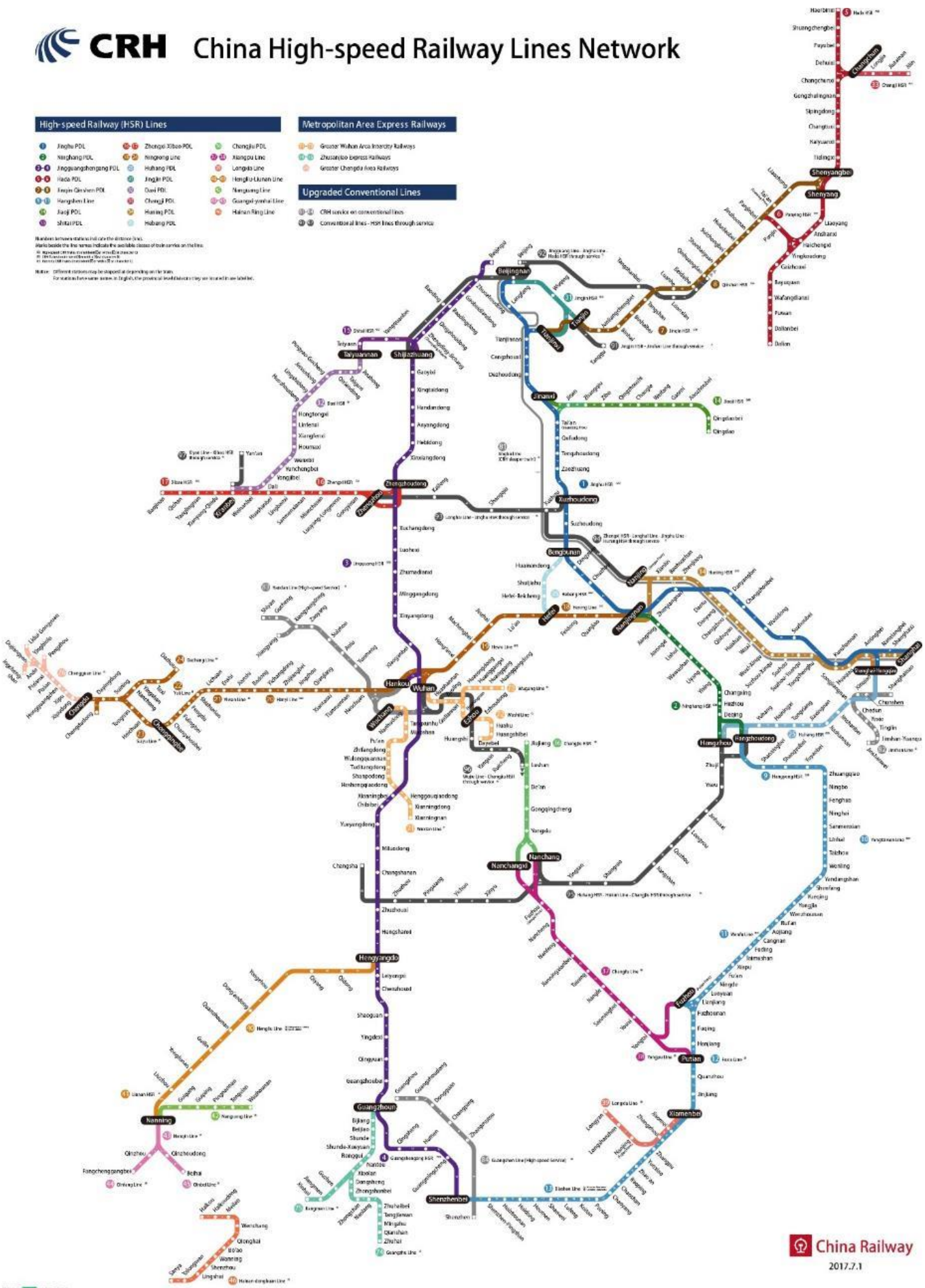
Current colour system analysis

	R	G	B	Saturability	Brightness
3-4	195	13	35	93%	76%
36	215	0	81	100%	84%
34	232	56	40	82%	90%
7-8	234	85	20	91%	91%
14	255	102	153	60%	100%
15	96	76	63	34%	37%
35	153	102	51	66%	60%
43-45	180	103	0	100%	70%
39	201	160	99	50%	78%
16-17	243	152	0	100%	95%
74-75	255	226	0	100%	100%
33	0	105	52	100%	41%
46	0	162	154	100%	63%
37-38	19	174	103	89%	68%
76	153	204	153	24%	80%
42	34	172	56	80%	67%
2	143	195	31	83%	76%
31	218	224	0	100%	87%
18-24	23	28	97	76%	38%
9-13	3	110	184	98%	72%
1	0	160	233	100%	91%
5-6	102	204	255	60%	100%
32	164	11	93	92%	64%
25	126	49	142	65%	55%
40-41	204	153	255	39%	100%
81-84	159	160	160	0%	62%
91-97	159	160	160	0%	62%
71-73	204	204	255	19%	100%

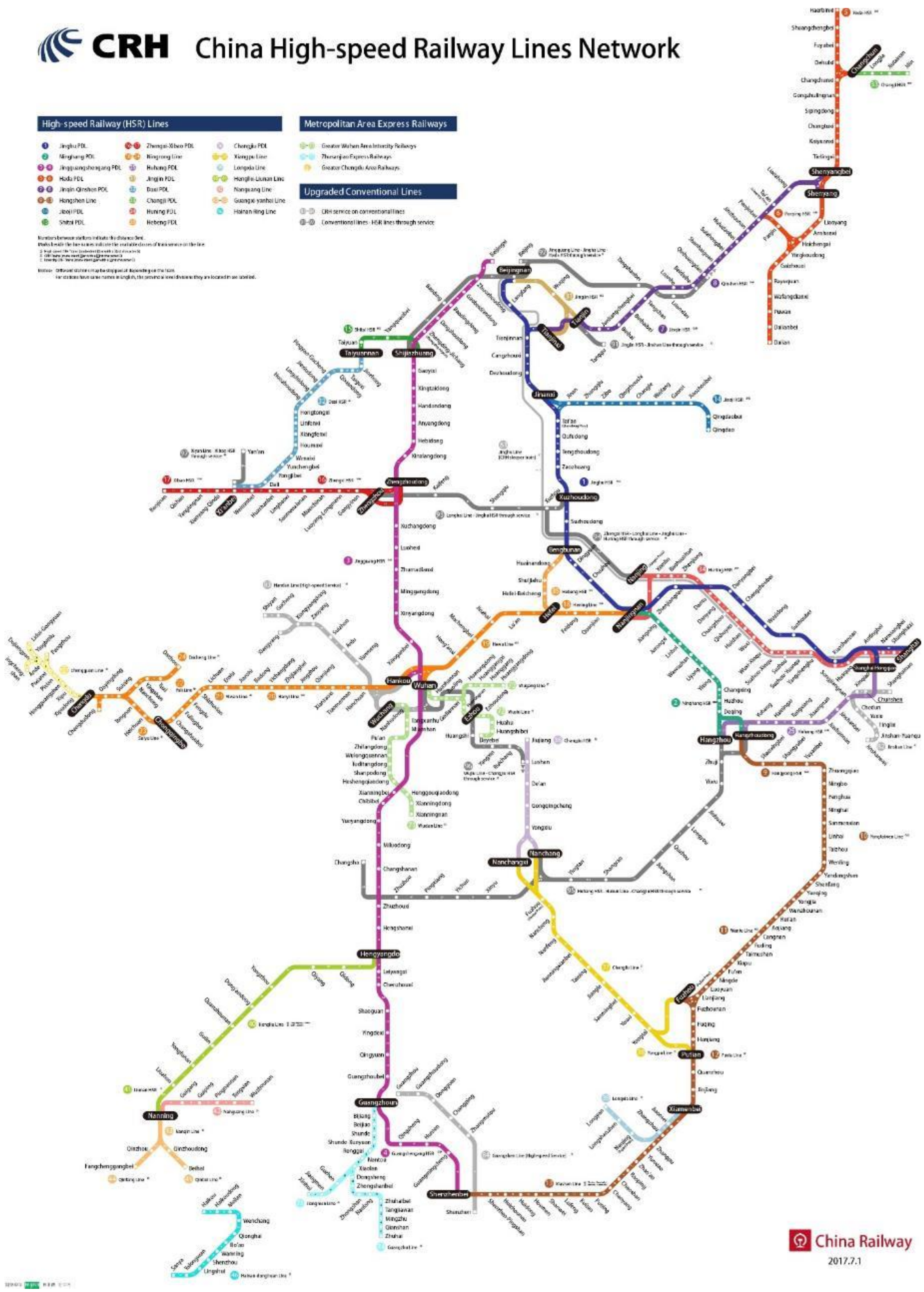


31 RGB: 218, 224, 0 S: 100% V: 87%
74-75 RGB: 255, 226, 0 S: 100% V: 100%
16-17 RGB: 243, 152, 0 S: 100% V: 95%
43-45 RGB: 180, 103, 0 S: 100% V: 70%
39 RGB: 201, 160, 99 S: 50% V: 78%
35 RGB: 153, 102, 51 S: 66% V: 60%
7-8 RGB: 234, 85, 20 S: 91% V: 91%
34 RGB: 232, 56, 40 S: 82% V: 90%
3-4 RGB: 195, 13, 35 S: 93% V: 76%
36 RGB: 215, 0, 81 S: 100% V: 84%
32 RGB: 164, 11, 93 S: 100% V: 84%
14 RGB: 255, 102, 153 S: 60% V: 100 %
15 RGB: 96, 76, 63 S: 34% V: 37%
25 RGB: 126, 49, 142 S: 65% V: 55%
RGB: 143, 195, 31 S: 83% V: 76% 2
RGB: 34, 172, 56 S: 80% V: 67% 42
RGB: 0, 105, 52 S: 100% V: 41% 33
RGB: 19, 174, 103 S: 89% V: 68% 37-38
RGB: 153, 204, 153 S: 24% V: 80% 76
RGB: 159, 160, 160 S: 0% V: 62% 81-97
RGB: 0, 162, 154 S: 100% V: 63% 46
RGB: 0, 160, 233 S: 100% V: 91% 1
RGB: 3, 10, 184 S: 98% V: 72% 9-13
RGB: 3, 10, 184 S: 98% V: 72% 5-6
RGB: 204, 204, 255 S: 19% V: 100% 71-73
RGB: 23, 28, 97 S: 76% V: 38% 18-24
RGB: 204, 153, 255 S: 39% V: 100% 40-41

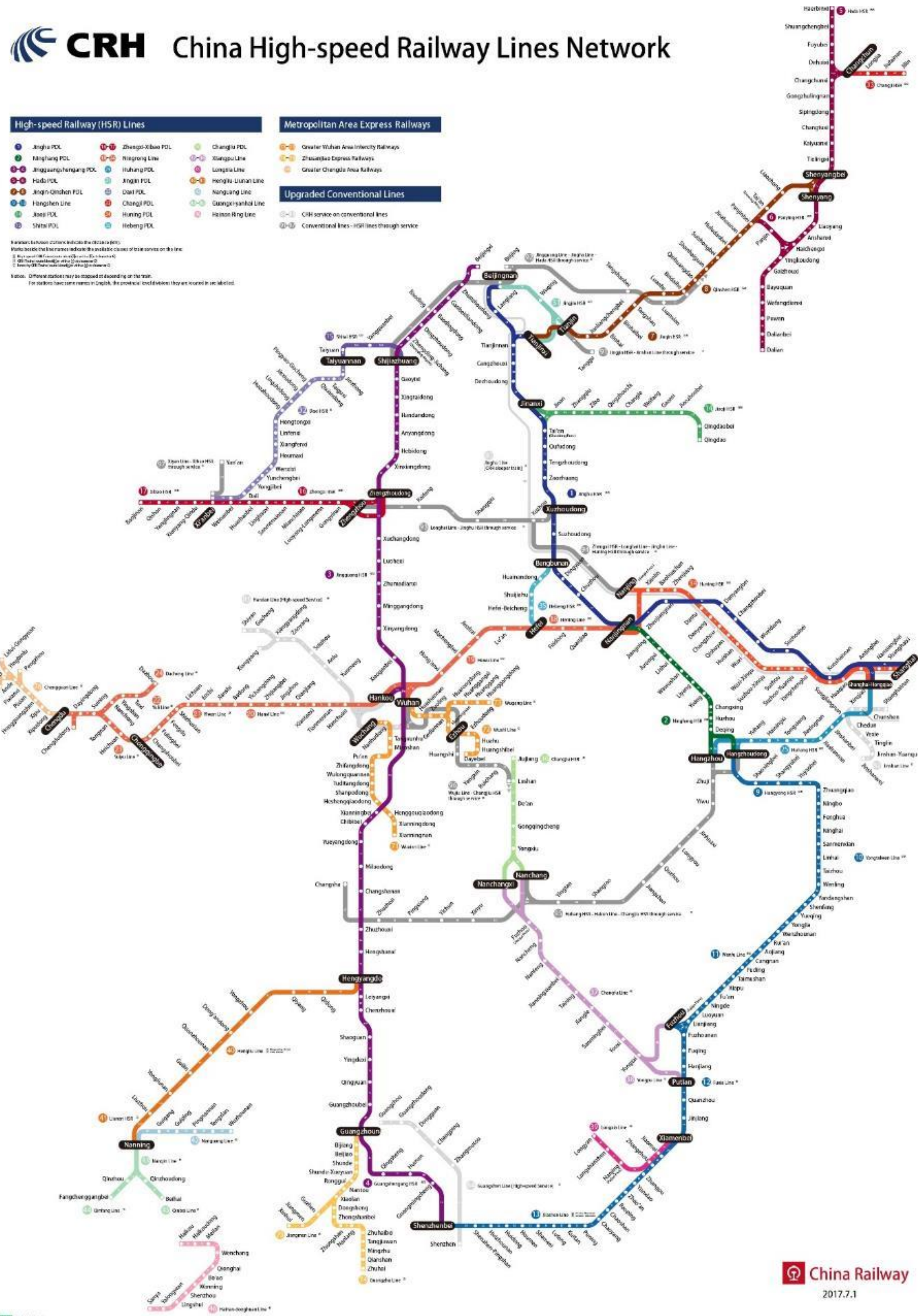
Diverging scheme



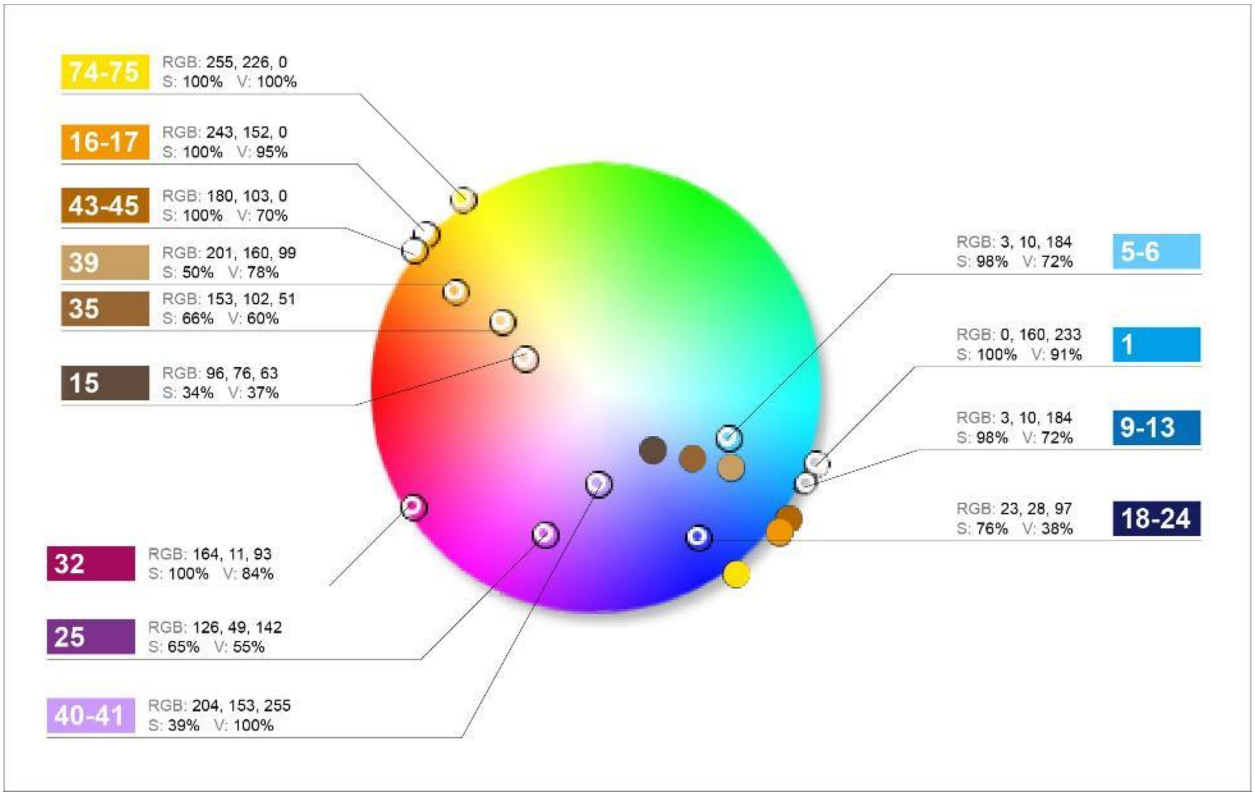
Qualitative scheme

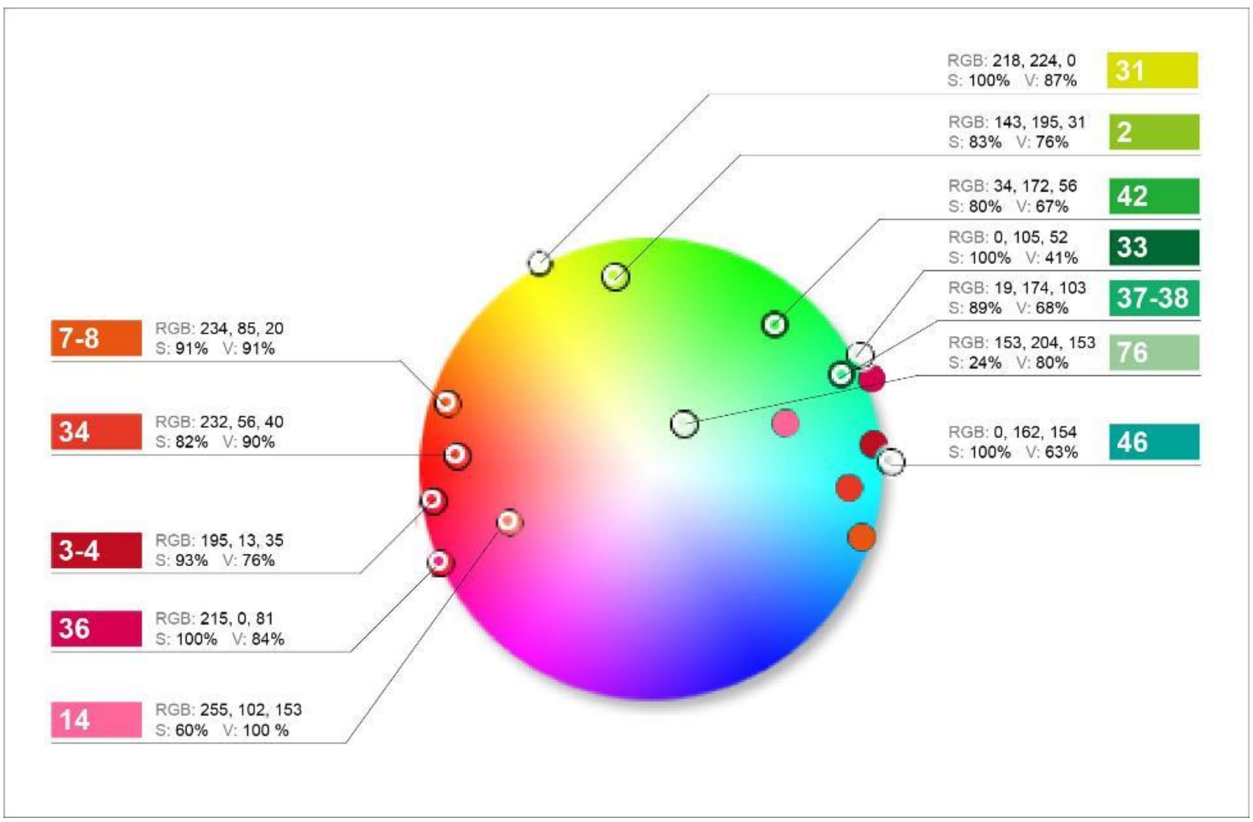


Sequential scheme



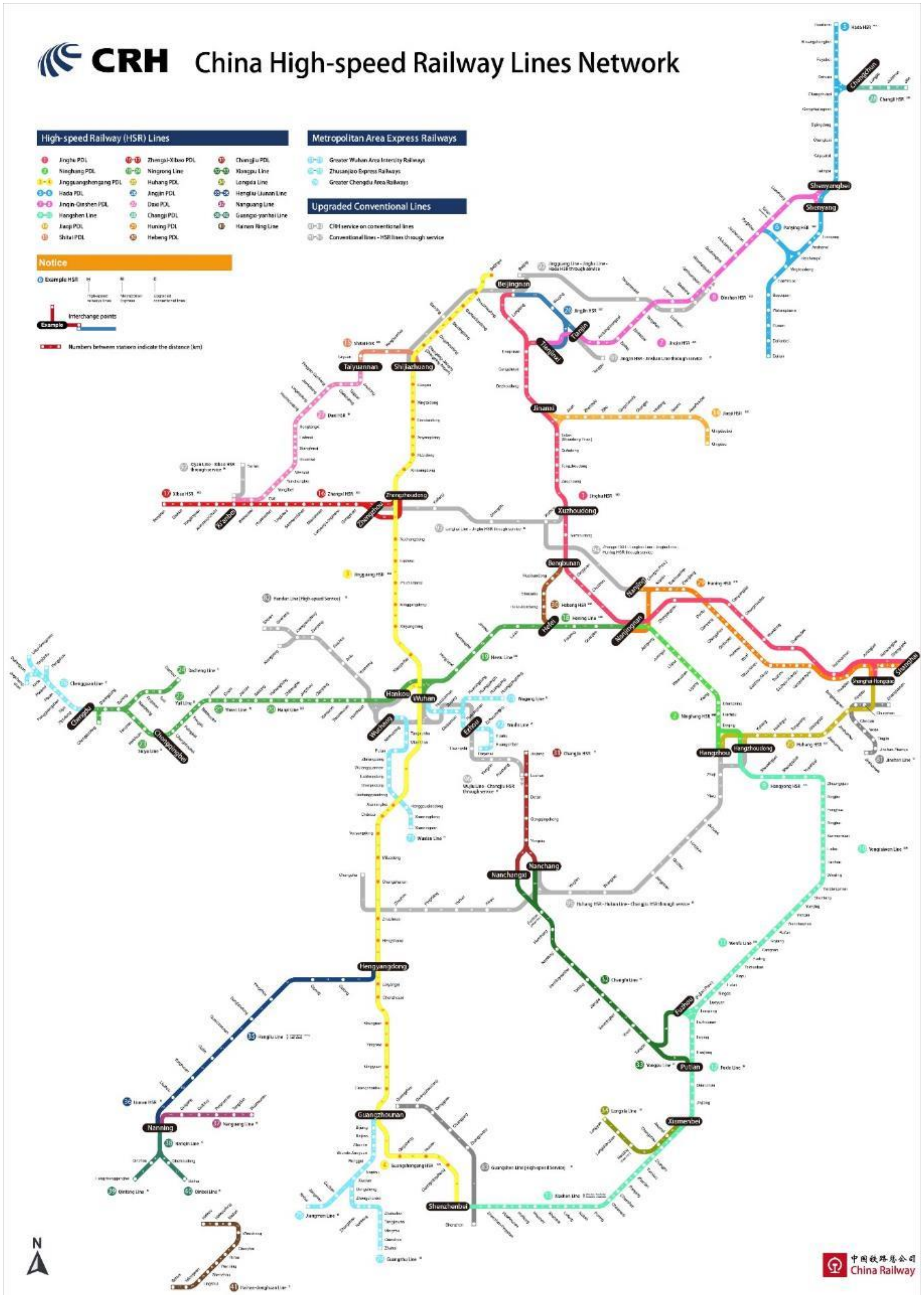
Complementary colour analysis



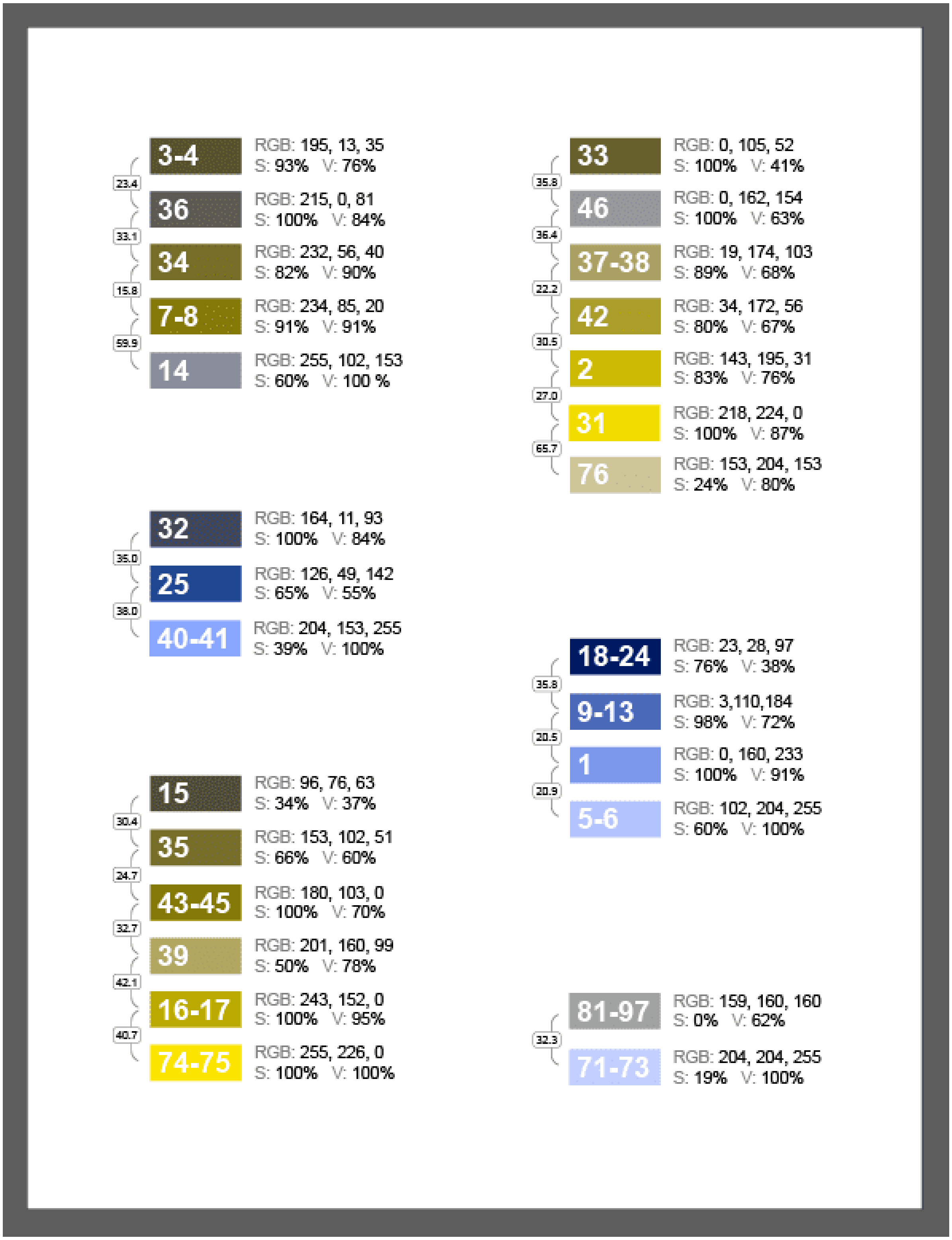


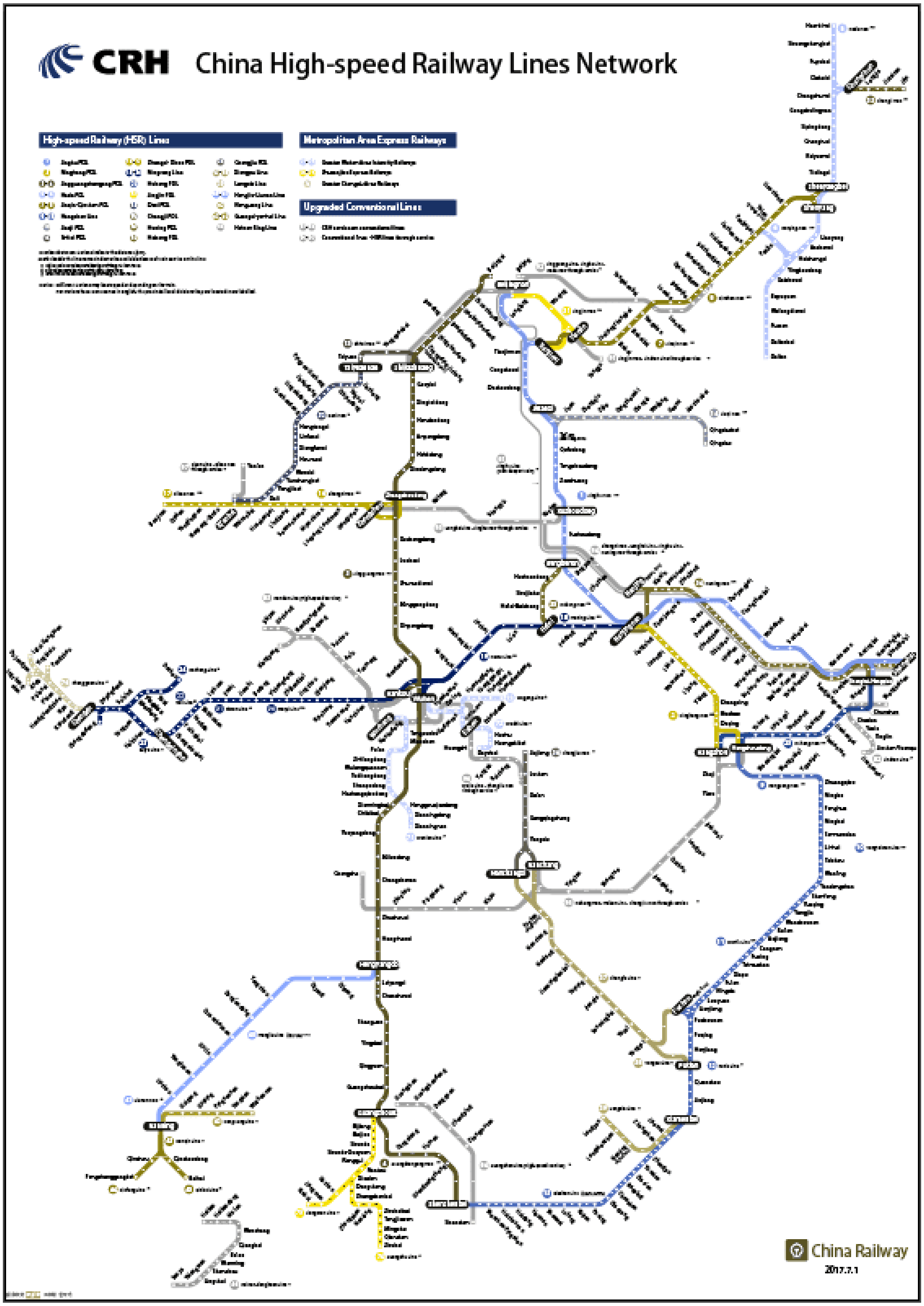
New colour system analysis

Newly colour-coded map



Colour deficient users' views

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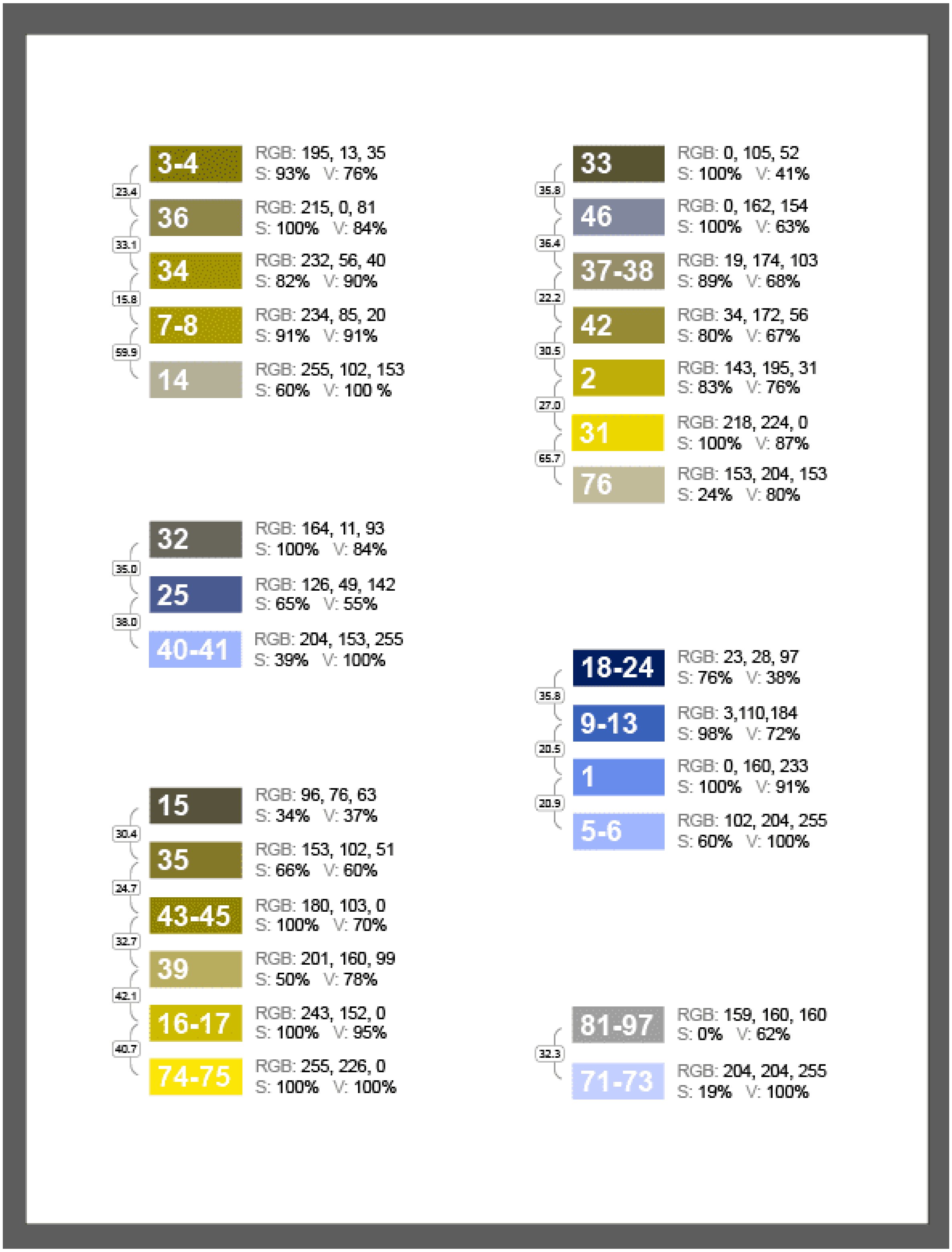
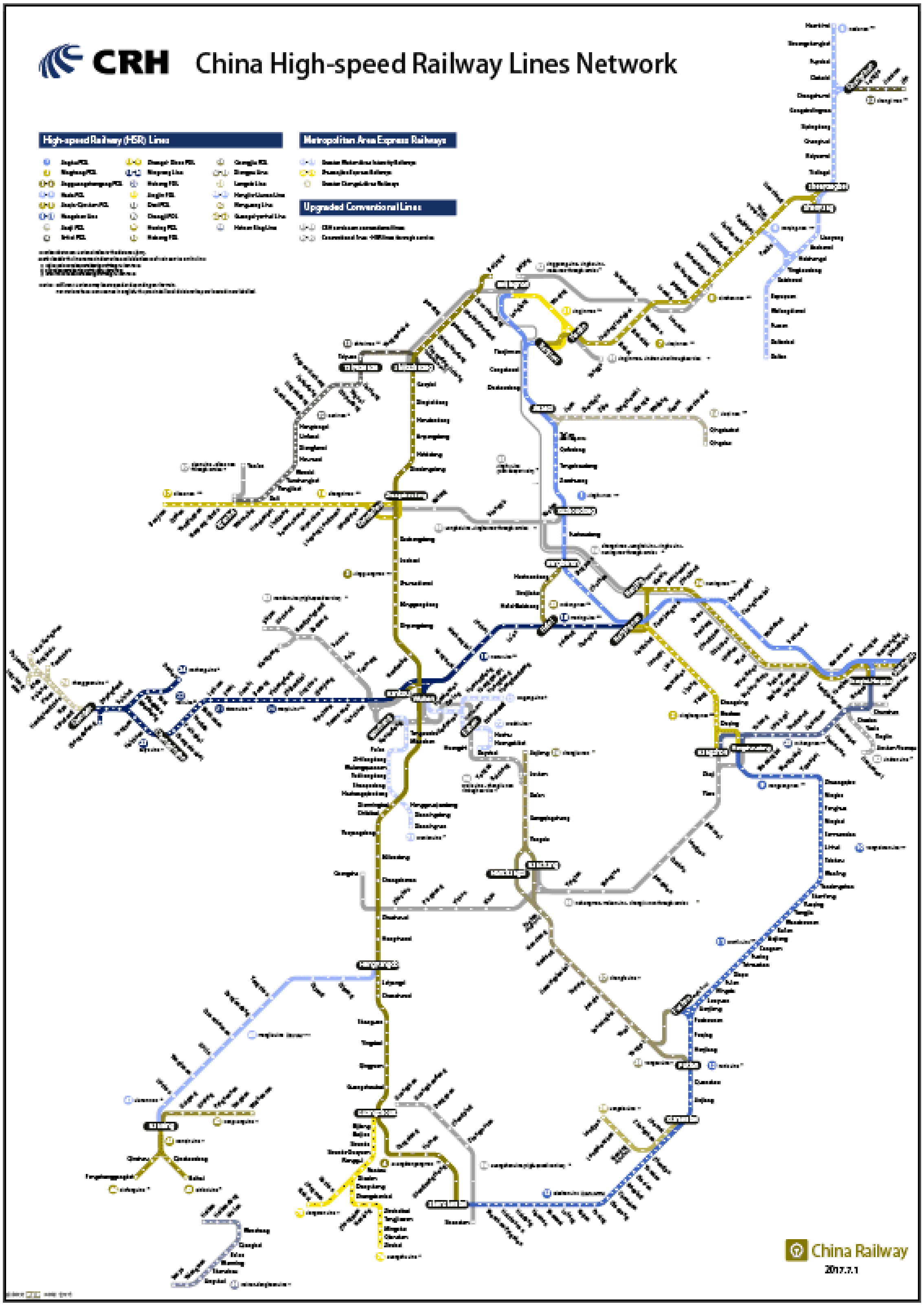


3-4
RGB: 195, 13, 35
S: 93% V: 76%
23.4
36
RGB: 215, 0, 81
S: 100% V: 84%
33.1
34
RGB: 232, 56, 40
S: 82% V: 90%
15.8
7-8
RGB: 234, 85, 20
S: 91% V: 91%
59.9
14
RGB: 255, 102, 153
S: 60% V: 100 %
33
RGB: 0, 105, 52
S: 100% V: 41%
35.8
46
RGB: 0, 162, 154
S: 100% V: 63%
36.4
37-38
RGB: 19, 174, 103
S: 89% V: 68%
22.2
42
RGB: 34, 172, 56
S: 80% V: 67%
30.5
2
RGB: 143, 195, 31
S: 83% V: 76%
27.0
31
RGB: 218, 224, 0
S: 100% V: 87%
65.7
76
RGB: 153, 204, 153
S: 24% V: 80%
32
RGB: 164, 11, 93
S: 100% V: 84%
35.0
25
RGB: 126, 49, 142
S: 65% V: 55%
38.0
40-41
RGB: 204, 153, 255
S: 39% V: 100%
18-24
RGB: 23, 28, 97
S: 76% V: 38%
35.8
9-13
RGB: 3,110,184
S: 98% V: 72%
20.5
1
RGB: 0, 160, 233
S: 100% V: 91%
20.9
5-6
RGB: 102, 204, 255
S: 60% V: 100%
15
RGB: 96, 76, 63
S: 34% V: 37%
30.4
35
RGB: 153, 102, 51
S: 66% V: 60%
24.7
43-45
RGB: 180, 103, 0
S: 100% V: 70%
32.7
39
RGB: 201, 160, 99
S: 50% V: 78%
42.1
16-17
RGB: 243, 152, 0
S: 100% V: 95%
40.7
74-75
RGB: 255, 226, 0
S: 100% V: 100%
81-97
RGB: 159, 160, 160
S: 0% V: 62%
32.3
71-73
RGB: 204, 204, 255
S: 19% V: 100%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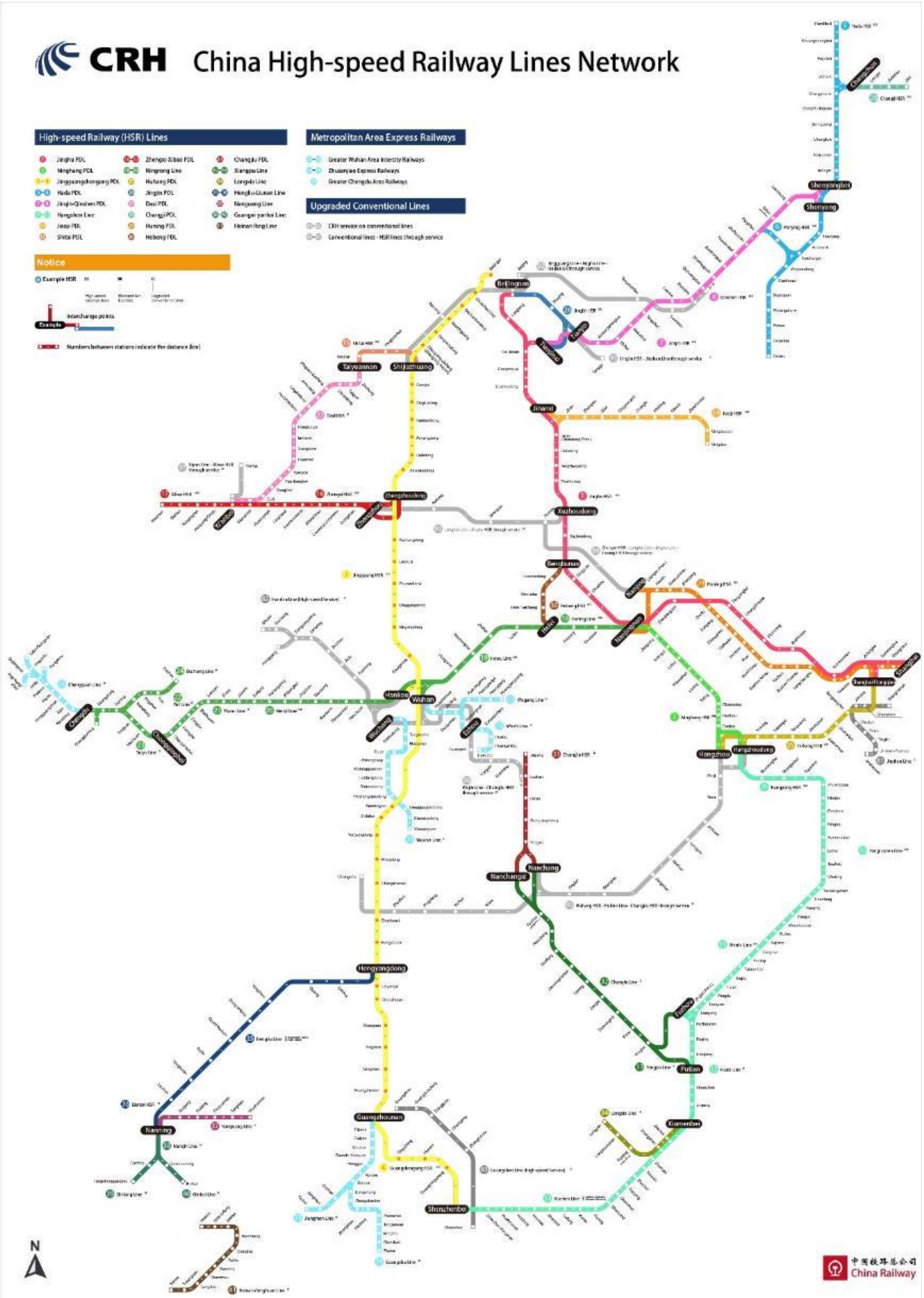
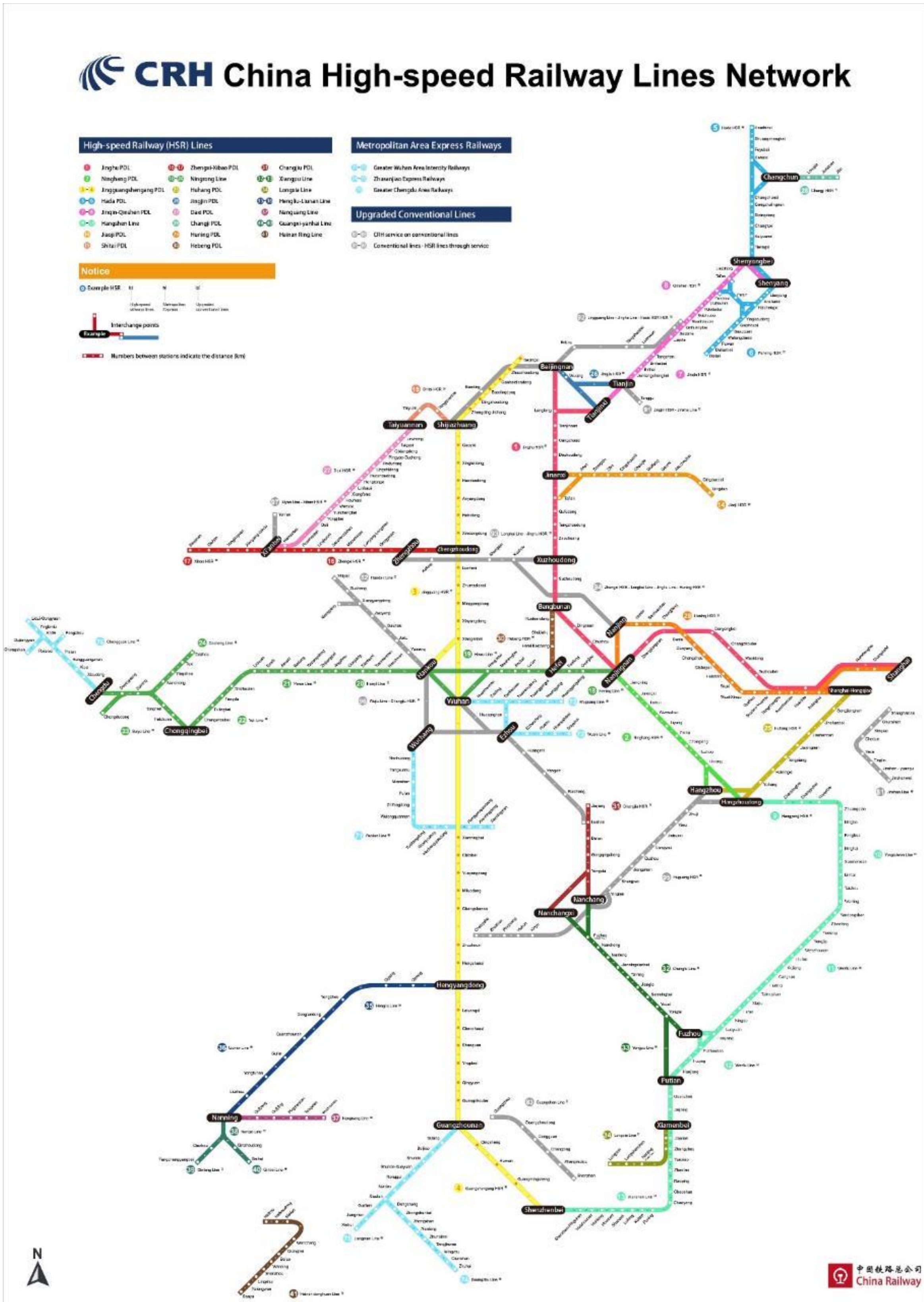
Appendix III: Transit line layout design examples

The improved existing map



The octolinear layout



The 60° octolinear layout

The curvilinear layout