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Applying systems thinking approach to accident analysis in China: Case study of "7.23" Yong-Tai-Wen High-Speed train accident

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ABSTRACT

Learning from accidents contributes to improvement of safety and prevention of unwanted events. How much we can learn depends on how deeply we analyze the accident phenomenon. Traditional causal analysis tools have limitations when analyzing the dynamic complexity of major incidents from a linear cause and effect perspective. By contrast, systems thinking is an approach of "seeing the forest for the trees" which emphasizes the circular nature of complex systems and can create a clearer picture of the dynamic systematic structures which have contributed to the occurrence of a major incident. The "7.23" Yong-Tai-Wen railway accident is considered to be the most serious railway accident in Chinese railway history and this research analyzed the accident using the systems thinking approach. From the national accident investigation report, the system elements were identified and the causal loop diagram was developed, based on the system archetype of "shifting the burden". For the problem symptoms in the accident report, the causal loop diagram not only illustrated their symptomatic solutions, but also identified their fundamental solutions. Disclosing how an underlying systemic structure finally resulted in a major accident assists the reader to prevent such accidents by starting from fundamentals.

1. Introduction

In the concepts of system safety and inherent safety in China, accident prevention has changed from passive controls after an accident to active ones (Luo, 2009). Although more attention has been focused on risk management based on hazard identification and risk control (Luo et al., 2003), learning from incidents is still a fundamental approach in accident prevention (Goh et al., 2010; Meng, 2011; Sklet, 2004). Accident prevention depends to a large degree on lessons learned from accident investigation. What we can learn in turn reflects the different perceptions of the accident phenomenon, which in the present day are called the accident models (Benner, 1978; Hollnagel, 2006). Providing conceptualization of characters of the accident, accident models typically show the relation between causes and effects (Qureshi, 2008). From an international viewpoint, accident models have started from relatively uncomplicated single-factor models of, e.g., accident proneness (Greenwood and Woods, 1919) and developed via simple and complex linear causation models to present-day systematic or functional models (Hollnagel, 2004, 2006).

One of earliest causation models is the Domino theory proposed by Heinrich in the 1940s (Heinrich et al., 1980). This model describes an accident as a chain of discrete events which occur in a particular temporal order. Causal factors in an accident which were not linked to technical components were classified as human error as a kind of catchall or "garbage can" (Hollnagel, 2001). Although the simple linear causation model was updated by Bird, Adams, and Weaver (Heinrich et al., 1980), it was later developed as the MES (Multi-linear Events Sequencing) (Benner, 1975) and STEP (Sequential Timed Events Plotting) (Hendrick and Benner, 1986) models, which provide a reconstruction of the process by plotting the sequence of events/actions that contribute to the accident. These models are limited in their capability to explain accident causation in the more complex systems that were developed in the last half of the 20th century (Qureshi, 2008).

In the 1980s, a new class of complex linear accident models endeavored to explain accident causation in complex systems. Reason's (1990, 1997) Swiss Cheese Model of defenses is a major contribution to this class of models, and has greatly influenced the understanding of accidents by highlighting the interrelations between real time "unsafe acts" by front-line operators and latent conditions caused by organizational factors (Hollnagel, 2006; Qureshi, 2008). Although causality is no longer a single linear propagation of effects, the complex linear accident models which were

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developed by Besnard and Baxter (2003) and Shappell and Wiegmann (2000) show that a static view of the organization is inadequate to capture the dynamics and nonlinear interactions between system components in complex sociotechnical systems. Therefore, new accident models based on systems theory, classified as systemic accident models, emerged.

Systemic safety models which describe an accident process as a complex and interconnected network of events have their roots in system theory and cybernetics. System theory includes the principles, models, and laws necessary to understand complex interrelationships and interdependences between components (technical, human, organizational and management) of a complex system. Two notable systemic modeling approaches, Rasmussen's (1997) hierarchical sociotechnical framework and Leveson's (2004) STAMP (System Theoretic Accident Modeling and Processes), endeavor to model the dynamics of complex sociotechnical systems.

With the increasing complexity of sociotechnical systems, modern technology has changed the nature of human work from mainly manual tasks to predominantly knowledge intensive activities and cognitive tasks. Cognitive system engineering (Hollnagel and Woods, 1983) has emerged as a framework to model the behavior of human–machine systems in the context of the environment in which work takes place. Based on its principles, two systemic accident models for safety and accident analysis have been developed: CREAM (Cognitive Reliability and Error Analysis Method) and FRAM (Functional Resonance Accident Model). CREAM is based on the modeling of cognitive aspects of human performance for an assessment of the consequences of human error on the safety of a system (Hollnagel, 1998), while FRAM is a qualitative accident model that describes how functions of system components may resonate and create hazards that can run out of control and lead to an accident (Hollnagel, 2004).

While the approach to achieving safety is moving from accident analysis to resilience engineering (Hollnagel, 2008) internationally, in China however, few of these modern accident models have been applied in accident investigation. China has developed and run its own "mechanism" of accident investigation in which technical failure is still the key and only the traditional simple linear causation models have been adopted to find the causal factors of human error. With the rapid development of the economy, work safety is now being paid much more attention in China, but accident investigation methods have not been improved as expected.

The key benefit from accident analysis is to understand why accidents occur and how to prevent future ones. The traditional theories and methods applied in accident investigation in China still possess the following limitations (Fan and Luo, 2009; Tang et al., 2006; Zeng and Chen, 2011; Zhang and Chen, 2009):

(1) Most causal analysis tools view cause and effect linearly, and so do not consider the accident system holistically.
(2) Most causal analysis tools are not designed to model changes in the system across time and cannot reflect the dynamic properties of an accident.

A new perspective on Chinese accident investigation mechanisms is strongly indicated, so as to examine the nature of the problems from a broader view.

The approach of Systems Thinking is fundamentally different from that of traditional forms of analysis. Instead of focusing on separating the individual pieces of what is being studied, Systems Thinking focuses on how each component interacts with the other components of the system. It works by expanding its view to take into account larger and larger numbers of interactions as an issue being studied (Aronson, 1996) and has developed archetypes to map the nature of the system dynamically over time (Sherwood, 2008). Based on systems theory, Leveson applied the STAMP model to discover the reasons why major accidents which seem preventable and have similar systemic causes keep occurring (Leveson, 2011). Goh applied the Systems Thinking concept to analyze the Bellevue hazardous waste fire accident in Western Australia (Goh et al., 2010). This research showed that the tool of systems thinking employed in analysis of major incidents makes the systemic structure which contributed to the incident more readily understood (Goh et al., 2010).

Turning now specifically to the subject of this paper, on July 23rd, 2011, at 20:30:05, a train crash accident occurred on the Yong-Tai-Wen High-Speed coastal railway line, Zhejiang province, Southeast China. Six cars were derailed and two of them plunged from a bridge 15 m (50 feet) above the ground. The accident killed 40 persons and injured another 172, resulted in downtime of 32 h 35 min and direct financial losses exceeding 193.7 million RMB (about USD 31 million) according to the State Administration of Workplace Safety (SAWS, 2011). The accident raised many issues in the development of the railway sector in China. National organizations, media and the public all focused on the situation in this sector. The accident is considered to be the most serious railway accident in the development of the Chinese railway system (Suo, 2012). At the end of December, 2011, the State Administration of Workplace Safety (SAWS) issued the final investigation report which is regarded as the most detailed accident report in China until now. The open report disclosed the linear causes and effects of the accident. Learning from incidents, accidents and disasters contributes to improvement of safety and the prevention of unwanted events (Drupsteen and Guldenmund, 2014). How much we can learn depends on how deeply we analyze the accident phenomenon. In order to explore and readily understand this accident in depth, the aim of this research was to apply the Systems Thinking tool to build the causal loop diagram for the accident using "sharp end" information from the published national accident investigation report. The second aim was to adopt a proper archetype from the field of Systems Thinking and analyze the accident using an integrated and non-linear approach, trying to find the hidden causative and contributory factors at the "blunt end" which were not discovered in the original accident investigation report.

2. Systems thinking, causal loop diagrams and system archetype

Systems may consist of nonlinear, counterintuitive and dynamic feedback loops, and Systems Thinking is a discipline for seeing wholes. Traditional thinking used to break the whole into parts which usually causes the connections to disappear, but Systems Thinking is a framework for seeing interrelationships rather than individual pieces, for seeing patterns of change rather than static "snapshots". It is a "seeing the forest for the trees" approach (Cabrera et al., 2008; Goh et al., 2012; Jackson, 2005; Senge, 2006; Sherwood, 2008).

Real systems are comprised of a large number of interconnected elements/components/entities and exhibit very complex behavior as they evolve over time. Diagrammatically, if two elements have a cause-and-effect relationship, they are linked by a curly arrow. If an increase in the "cause" drives an increase in the "effect", then the link is indicated by " + " at the head of arrow; if an increase in the "cause" drives a decrease in the "effect", then the link is indicated by "−". If an action could not give rise to its result instantaneously, the cause-and-effect relationship is associated with a time delay, and the link is indicated by adding a new symbol "‖". Fig. 1 shows the links of different types.

The sequence and mutual interactions of the numerous individual cause-and-effect relationships make up "chains of causality" of

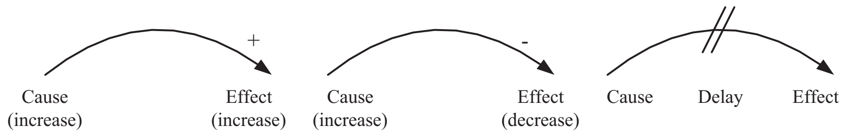

Fig. 1. Links of different types.

the system which are captured in a causal loop diagram. Causal loop diagrams of real systems are composed primarily of closed, continuous chains known as feedback loops. Reinforcing loops are characterized by having an even number of "−"s around the loop and their action is to amplify the original effect on each turn. The left-hand side in Fig. 2 is an example of a reinforcing loop where the safe behavior and its positive consequence create a "virtuous cycle" that encourages growth in the safe behavior. Reinforcing loops behave as a virtuous or vicious circles, depending on the circumstances. Delays often occur between implementation of a certain program or action and the consequences of that action (Goh et al., 2010). The right-hand side in Fig. 2 shows a delay in the feedback from the positive consequence to the safety behavior.

Balancing loops have an odd number of "−"s and their actions seek to achieve or maintain a target or a goal. The left-hand side of Fig. 3 is an example of balancing loop. A company might be tracking a safety performance indicator. The driving force for changes in the indicator is the size of the gap between the target and the actual levels. The safety indicator improves when the gap widens, possibly because more effort or resources are used to improve the situation. On the other hand, when the gap reduces, the pressure to improve might ease and hence the actual level tends to drop (Goh et al., 2010). The right-hand side of Fig. 3 shows a simplified version of the balancing loop.

Reality is made up of circles but we see straight lines, such as the linear relationship between causes and the effects in the final investigation report. In fact, while we may identify the direct cause and result relationship of a variable in the system, it is difficult to understand the underlying causes and results for a complicated dynamic system. How can we see circles of influence rather than the straight lines of this accident? The field of systems thinking has developed archetypes which adopt causal loop diagrams to map the circular nature of cause and effect and demonstrate aspects of the system over time. These archetypes have described the system structure of a wide variety of management situations and aim to highlight the underlying structure of complex situations in a relatively simple fashion so as to facilitate identification of leverage in these situations (Sherwood, 2008; Goh et al., 2010).

As stated above, China runs its accident investigation mechanism in its own way. After an accident occurred, there would be an accident investigation report (although most of them were not public until now). Then the causation of the accident is found, the countermeasures based on the causation are provided and it seems that the problem has been resolved. However, there is not any doubt that many models of accident causation have only

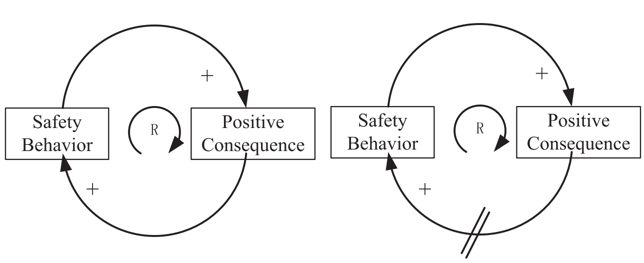

Fig. 2. Example of a reinforcing loop (Goh et al., 2010).

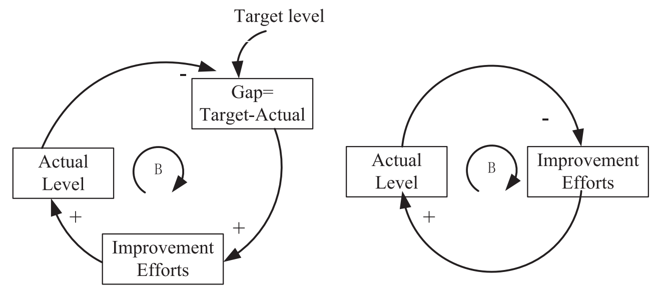

Fig. 3. Example of a balancing loop (Goh et al., 2010).

acknowledged the contribution of human error rather than technical failure in accidents (e.g. O'Hare, 2000; Reason, 1990). So the role of human error has changed from a person approach to a system/organization one, and has been transferred from the more direct cause of accidents to problems deeper inside the system (Leveson, 2004; Rasmussen, 1997; Reason, 1990; Shappell and Wiegmann, 2000). It is obvious that solutions to problems based on today's accident investigation mechanism in China do not reach down to fundamental issues. Moreover, that similar accidents occurred in different sites e.g. several serious railway accidents since 2006 (Xiao, 2013) proves the solutions have only been symptomatic. Solutions that address only the symptoms of a problem, not fundamental causes, tend to have short-term benefits at best. In the long term, the problem resurfaces and there is increased pressure for symptomatic response. Meanwhile, the capability for fundamental solutions can atrophy (Senge, 2006). Therefore, there should be fundamental solutions which accident investigation mechanisms to date have not produced yet.

The archetype of "shifting the burden" can identify both the symptomatic solution and fundamental solution of a problem, while it states that a problem's symptom can be resolved either by using a symptomatic solution or applying a fundamental solution. It hypothesizes that once a symptomatic solution is used, the problem will be alleviated, and pressure to implement a fundamental solution is reduced (Senge, 2006). For the train crash accident, the investigation report listed three underlying problems generating symptoms that demanded attention and provided related recommendations. Because of either the difficulty of the problems or the limitation of traditional theories, the underlying problems are difficult to address. Concerned that the traditional ways of thinking in the investigation report "shifting the burden" of the problems to the symptomatic solutions, this research will adopt the archetype of "shifting the burden" (see Fig. 4) to explore the fundamental solutions to the prevention of such an accident.

The archetype of "shifting the burden" is composed of two balancing (stabilizing) processes. Both are trying to adjust or correct the same problem symptom. The top circle represents the symptomatic intervention; the "quick fix." It solves the problem symptom quickly, but only temporarily. The bottom circle has a delay. It represents a more fundamental response to the problem, one whose effects take longer to become evident. However, the fundamental solution works far more effectively – it may be the only enduring way to deal with the problem. Often (but not

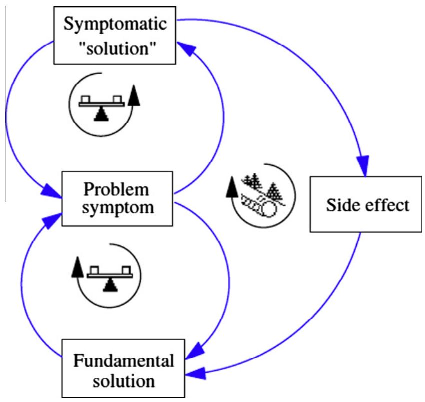

Fig. 4. A shift the burden archetype (Senge, 2006; Goh et al., 2010).

always), in "shifting the burden" structures there is also an additional reinforcing (amplifying) process created by "side effects" of the symptomatic solution. When this happens, the side effects often make it more difficult to invoke the fundamental solution (Senge, 1990). Fig. 4 is an example of a "shifting the burden" archetype. The top loop produces relatively quick positive results that focus on the symptoms and relieve the immediate pressure of the problem. The other balancing process focuses on fundamental solutions to the problem that are more sustainable. But the process is not easily identified. Also symptomatic solutions can easily be driven by side effects and cause the fundamental solutions to be overlooked (Goh et al., 2010).

Systems thinking and causal loop diagrams can depict the causes and results of a variable at a deep level. Therefore, in order to find other causes or contributors to the accident from the investigation report itself, this present research needed to identify the elements of the accident according to the national investigation report, and then build the causal loop diagram based on these elements using the "shifting the burden" archetype.

3. Brief description of the railway system

The Yong-Tai-Wen High-Speed coastal railway line was constructed by Coastal Railway Zhejiang Co. Ltd and its maintenance and operation was performed by Shanghai Railway Bureau (SRB).

China Railway Signal & Communication Corporation (CRSC) was the prime contractor on this line in relation to the signal and communication system. The control system related to this accident is the Chinese Train Control System 2 (CTCS2), and it consists of a ground subsystem and an on-board subsystem (as shown in Fig. 5) and includes the Train Control Center (TCC), Track Circuit (TC), and Automatic Train Protection (ATP). Train Communication Equipment (TCE) is applied for communication between the ground subsystem and the on-board subsystem. The TCC in CTCS2 of the LKD2-T1 type used in Wenzhounan station was designed and developed by CRSC and its subordinate company Beijing National Railway Research & Design Institute of Signal & Communication Co. Ltd. (CRSCD). The approval of the LKD2-T1 TCC was performed by the Chinese Ministry of Railways (MOR) and its related subordinate departments (SAWS, 2011; Suo, 2012). TCC collects route information and device status from the signal system on the ground and receives the operation and schedule information from the Centralized Traffic Control (CTC) located in the SRB.

For CRSC, MOR and SRB, each part was composed of several subcomponents, and their relationships are shown in Fig. 6 in which the rectangles in yellow color represent the organizations related to the accident and the white ones represent their subordinates.

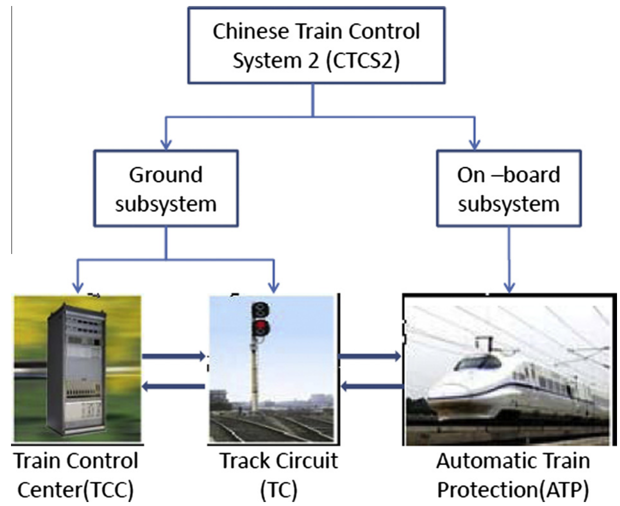

Fig. 5. The structure of CTCS2 (SAWS, 2011).

The orange rectangles represent the responsibility or function of the related organizations. The red rectangles represent the main accident causes. In the investigation report, they built the chain of the causes which caused the train crash accident. But in this research these main accident causes would be regarded as the problem symptoms in the system archetype of "shifting the burden". Based on these symptoms, their symptomatic solutions will be analyzed and the fundamental solution(s) will be explored.

4. Identification of the "7.23" accident system components

On July 23rd, 2011, at 20:30:05, the high-speed train D301 from Beijing to Fuzhou collided with the rear-end of the D3115 train on the Yong-Tai-Wen High-Speed coastal railway line (see Fig. 7) because of a fault in the control system. The area where the accident occurred experienced severe lightning from 19:27 to 19:34 on July 23rd according to the meteorological department. It was the severe lightning which caused the fault in the control system.

Both D3115 and D301 were behind schedule and reached Yongjia railway station at 19:51 and 20:12, respectively. At 20:14:58, D3115 was ordered to leave Yongjia station and was notified to change its operational mode from decentralized autonomous control mode (DACM) to on-sight mode at TC-5829 (see Fig. 7) because of a red-light (in strip shape) displayed in TCC which is called a red-light-strip. A red light strip (shown in Fig. 7) displayed in the TCC always represents the occupancy of the TC by the train. But sometimes an abnormality in the TC may also lead to a red light strip. When D3115 reached 5829AG at 20:21, due to the failure of the TC, it stopped automatically for nearly eight minutes and failed to restart until 20:29:26. After that it kept running at a speed of 16 km per hour under abnormal conditions. During the re-start period, D3115 called the dispatcher six times and was called by the watch keeper three times, but all calls failed to connect.

At the same time, D301 was ordered to leave from Yongjia station for Wenzhounan station at 20:24 by the dispatcher in the CTC. The information in the CTC from Wenzhounan TCC met the conditions for starting D301, but in fact what Wenzhounan TCC transmitted was erroneous information because the data acquisition board in the TCC had been destroyed by lightning at about 19:30 and failed to collect consistent information on the TC occupancy and identify the correct position of D3115. Failures in the Wenzhounan station TCC by the lightning caused an erroneous signal to be sent to D301 and to the signal light, indicating that there

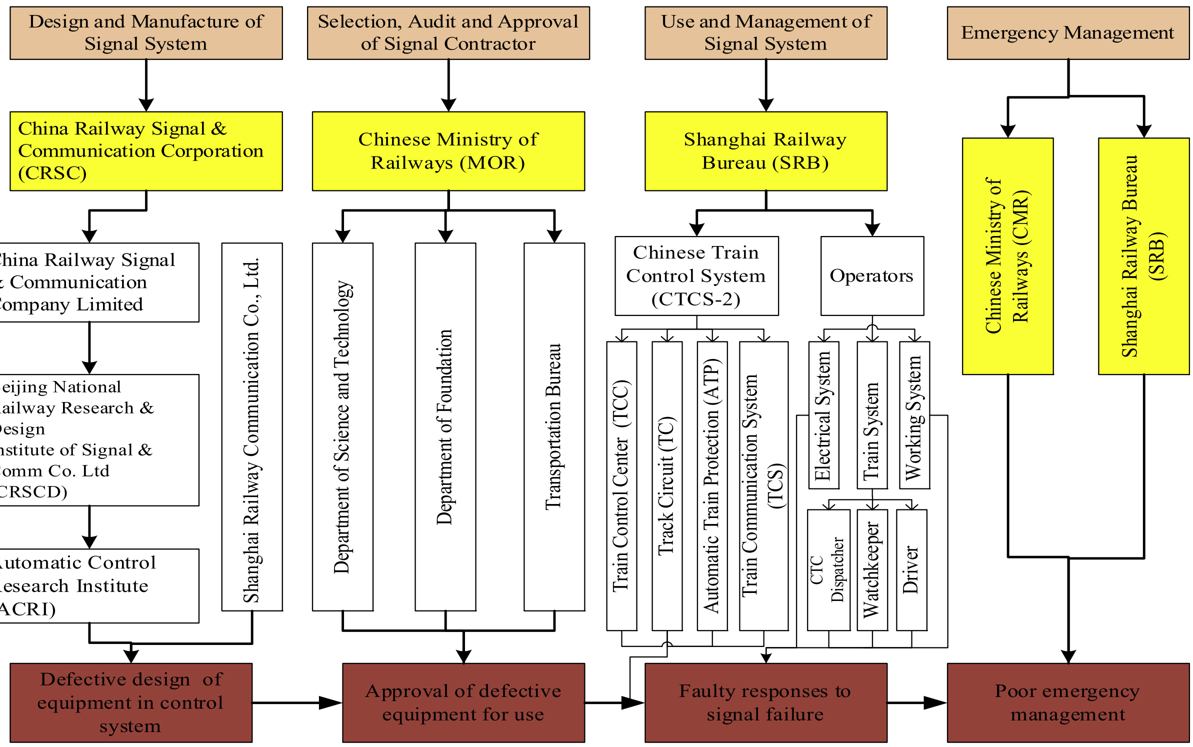

Fig. 6. Generic components associated with the accident.

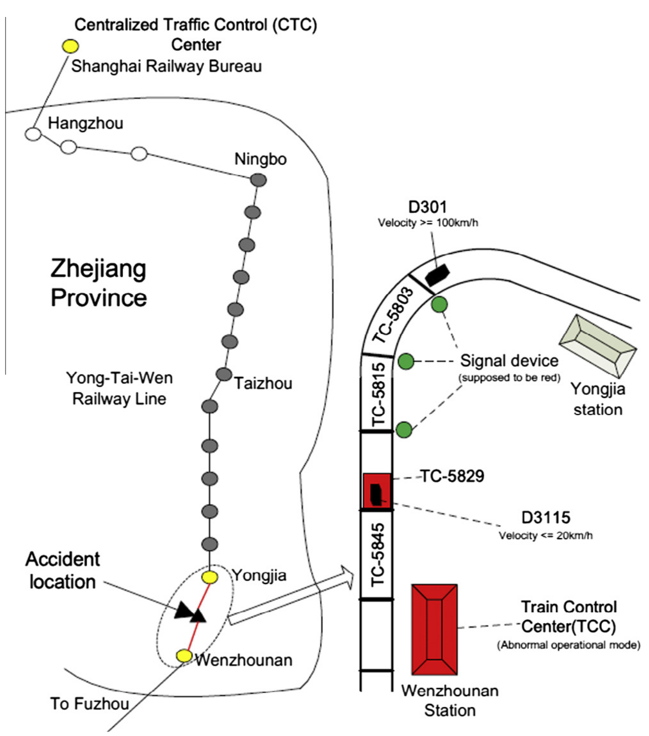

Fig. 7. The location of the accident and its surrounding environment (Suo, 2012).

was no train in section 5829 and the signal lights in section 5815 and 5803 turned green. As a consequence, D301 did not stop or decelerate at Sections 5815 and 5803 (as shown in Fig. 7). At 20:29:32, when D301 reached TC-5829, it was notified to decelerate by the watch keeper in Wenzhounan station. Unfortunately, the call was too late, and D301 rear-ended before the talk was over.

According to the accident investigation report, the causes of the accident were associated with design, approval and use of the LKD2-T1 TCC. The associated issues are shown in the orange rectangle in Fig. 6. Issues associated with emergency management of the accident in the right part were not considered in this research. We can identify the main causes of the accident (red rectangles in Fig. 6) as follows which were linear.

(1) The LKD2-T1 TCC used in Wenzhounan station which was designed and developed by CRSC and its subordinate company suffered serious failure.
(2) As the government regulatory agency, MOR was responsible for contractor selection, administrative examination and approval of related equipment. But MOR and its subordinate departments approved LKD2-T1 TCC with its potential for serious failure for use in Wenzhounan station.
(3) Operators in the SRB could not deal with the failure properly and could not prevent the accident or reduce the loss.

5. Analysis of the "7.23" accident using a systems thinking approach

From April 1st 1997 to April 18th 2007, railway transportation in China has experienced six great "improvements" in train speeds. With the sixth improvement, the speed of a high-speed train has risen to 200 km/h and domestic high-speed trains have started to be in use. High-speed train technology in China is trying to lead the world. But in fact, many of the great improvements have come at a cost to safety. According to the accident sequence shown in Fig. 6, the accident can be described in four parts, but the last part, "poor emergency management", as already noted, is not considered here. The first part is why the equipment in the control system was designed with defects, the second part is why the defective equipment was approved to be used and the third part is why the response to the signal failure was inappropriate. The following analysis will examine each part in three steps.

(1) The first step is to find the components which triggered the problem symptoms in the archetype of "shifting the burden" according to the investigation report and construct the chain(s) of causality;
(2) The next step is to analysis the "quick fix" that appeared to be keeping the problems under control and build the closed feedback loop. This step is finding the symptomatic solution to the problem symptoms.
(3) The third point is to identify fundamental solutions and map side-effects of quick fixes that may be hindering the usability of the fundamental solution.

The arrows in symptomatic balancing processes are shown in black color, and the arrows in fundamental balancing processes are shown in blue color. The arrows related to side effects are shown in red color.

5.1. Analysis of defective design of equipment in the control system

According to the "7.23" accident investigation report, one of the most direct causes was the serious defect of LKD2-T1 TCC. It was designed and developed by CRSC and its subordinates. As the prime contractor for signals and communication organization, CRSC was responsible for the reliability and safety of its signal devices, so it should have established procedures to monitor the whole development process and ensure that the quality of products met national standards. However, against the background of great improvement of the railway industry, CRSC was eager to earn more opportunities for development. The speed in finishing a design project may have been the most important performance indicator. The pressure of rapid design caused a reactive safety attitude to dominate CRSC. CRSCD is a subordinate company of CRSC. As it developed LKD2-T1 TCC, CRSCD should have been responsible for the reliability and safety of its product. The attitude of CRSC to reliability and safety would drive the attitude of CRSCD. In order to respond to the design pressure, the design and development of LKD2-T1 TCC was done in a hurry and without assurance of safety. The leaders in CRSCD made the decision to update LKD1-T to LKD2-T1based on an oral report from the Automatic Control Research Institute (ACRI) although LKD1-T TCC was still in its development stage (SAWS, 2011). Concern with staying on schedule caused less attention to be paid to its compliance with design standards; reactive safety of CRSCD also drove the same attitude in ACRI. Therefore, according to the accident investigation report, a reactive safety attitude was passed from CRSC to its subordinates and then drove the defective design of equipment in control systems. All these links belong to the " + " type. The chain of causality is shown on the right-hand side in the top circle of Fig. 8.

A reactive attitude to safety would increase the unreliability of the system. Safety then was achieved by attempting to control obvious hazards in the initial design and then correcting other problems as they appeared after a product was in use or at least in a testing phase (Roland and Moriarty, 1990). So, in this accident, it seems that no participants in the system gave any thought to the possibility that the potential signal devices hazards might need to be identified. Only after the accident were the signal defects discovered. For CRSC and its subordinates, safety was achieved by lessons identified in the accident, while safety programs were usually established piecemeal based on an after-the-fact philosophy of accident prevention. The problem of "defective design of equipment in the control system" caused by the linear chain of causality (from "pressure of rapid design" to "defective design of equipment in the control system" shown in circle shape) in B1.1 of Fig. 8 was

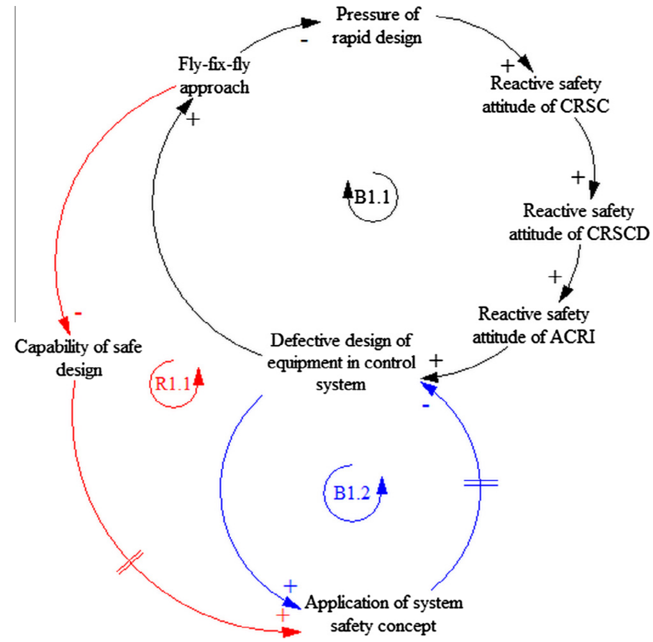

Fig. 8. Causal loop diagram for "defective design of equipment in control system".

solved, at least in part, by a "fly-fix-fly" approach. This approach which decreases the "pressure of rapid design" (the link belongs to the "−" type) and the above chain of causality made up a balancing loop B1.1 in Fig. 8. In this loop, the increase in the problem of "defective design of equipment in the control system" drove more use of the "fly-fix-fly approach" and the "fly-fix-fly approach" is the "quick fix" that appeared to be keeping the problem under control. Once the problem symptoms disappear, the incentive to fix the underlying problem likewise disappears. This "fly-fix-fly approach" is the symptomatic solution of the problem of defective design.

We all know how quickly technology is changing and it is difficult for us just to keep up. As technology advances by leaps and bounds, and business competition heats up with the internationalization of the economy, turnaround time from product design to market launch is shrinking quickly. Safety should be achieved by a proactive effort rather than experiencing accidents. The "fly-fix-fly approach" is only a short-term solution. It solves the problem symptom quickly, but only temporarily. How to build products with high quality, quickly, and still safely needs a long-term solution. The system safety concept offers such solutions.

The system safety concept really started during the American military missile and nuclear programs based on the spectacular ICBM mishaps in the 1950s and early 1960s (Bahr and Kletz, 1997; Gordon, 2013). Some of these accident investigations found that the failures were due to design problems, operations deficiencies, and poor management decisions. Now, this concept is understood broadly as a risk management strategy based on identification and analysis of hazards and application of remedial controls using a system-based approach (Roland and Moriarty, 1990), but from a historical perspective it has been learned that a proactive preventive approach to safety during system design and development is much more cost effective than trying to add safety into a system after the occurrence of an accident or mishap. System safety is the process of managing the system, personnel, environmental, and health mishap risks encountered in the design development, test, production, use, and disposal of systems, subsystems, equipment, materials, and facilities. It is a before-the-fact solution which is an initial investment that saves future losses that could result from potential mishaps (Ericson, 2005). The system safety concept was introduced to China in late 1980s and was accepted later as risk management in which the process of identifying and analyzing hazards was adopted but the strand of life cycle was omitted. Regulations related to safety, even work safety law focus their requirements on occupational safety, but the safety of a system, subsystem, or facilities in their early stages is a blindness in risk management in China. The U.S. military published a national military standard titled Mil-Std-882, "Requirements for a System Safety Program for Systems and Associated Subsystems and Equipment" (DOD, 1969) to assure system safety in industries and the standard has been one of the most cited requirements in procurement contracts in America (Roland and Moriarty, 1990). In the Health and Safety at Work Act (HASAWA) of the UK, Section 6 "duty of suppliers" requires a person who designs, manufactures, imports or supplies any article or substance for work must ensure, so far as is reasonably practicable, that it is safe and without risk to health (Hughes and Ferrett, 2011). So, in this train crash accident, if CRSC had adopted the concept of system safety, it would have balanced the design task and production safety, identified hazards and introduced an acceptable safety level into the system prior to actual design and production. Once the philosophy of system safety has been applied, the system hazards would have been identified in a timely way and evaluated and then eliminated, or controlled to an acceptable level; therefore, the problem of defective design would have been solved thoroughly. "Application of system safety concept" is long-term fundamental solution to the problem of defective design. Although the concept of system safety is not new, the application of it is not very common in China and the effect of it on the problem symptom is time delay because it requires more understanding or is difficult to formulate. The fundamental solution feedback loop is shown in B1.2 in Fig. 8 in blue color.

In the signal and communication organization system, for the problem of defective design, the "fly-fix-fly approach" is a traditional solution. It may be very attractive to management and produce quick responses to the problem. However the symptomatic solution is only a stopgap measure. The accident disclosed the equipment with design defects triggered by severe lightning, but we do not want to rely on further accidents to identify other defects. Increasing use of the "fly-fix-fly approach" would cause the unintended side effect of losing "capability of safe design", which in turn would decrease the opportunity for the "application of system safety concept" approach, make the organization more dependent on the fix-fly-fix approach, and ultimately trap it into using only the symptomatic solution. The side effects reinforced the symptomatic solution (shown as reinforcing feedback R1.1 in Fig. 8 in red color) and the fundamental corrective measures were used less and less. However, in CRSC and its subordinates, if the application of system safety concept had been chosen, as the defective design increased, the use of the fundamental solution would have also increased, and after a time delay there would be a decrease in the original defective design, again keeping them in balance.

5.2. Analysis of the approval of defective equipment for use

Railway transportation in China has experienced six great "improvements"in train speeds and has tried to pursue an even greater one. As the government regulatory agency, MOR is responsible for the safety of railway construction in China. The regulation style in MOR is inspectorate-driven. The regulation style increases the reactive audit in its sub-departments. In relation to the accident, there were three functional departments which approved the defective equipment for use. The Transportation Bureau of MOR is responsible for the selection of contractors, the Department of Science and Technology is responsible for setting up standards about project audits related to technology issues. The Department of Foundation is responsible for the final approval of the project and of the equipment for use. According to the accident report, it was found that the Transportation Bureau should not have selected CRSC as the signal and communications contractor. The Department of Science and Technology had not set up clear rules or specifications for the project audit and the Department of Foundation had problems in managing new equipment. The reactive audit by the three departments together approved the defective equipment for use. The chain of causality is shown on the left-hand side of the top circle in Fig. 9.

The regulatory approach adopted by China belongs to an inspectorate-driven style. Business including safety issues in companies are supervised by related government regulatory agencies and the companies fulfill their task only by obeying the requirement from the government regulatory agencies.. Therefore, although safety is important, safety was not integrated into the project and no department was really responsible for the system safety of the project. If there were not severe lightning on the evening of July 23rd, the accident would not have occurred. All these faults in management would not have emerged. Only the accident led to MOR and its sub-departments identifying the problem of "approval of defective equipment for use". In this part, "fly-fix-fly approach" is still the symptomatic solution of the approval problem shown as the balancing feedback of B2.1, B2.2 and B2.3 in Fig. 9.

With the fast pace of technology change, the time-to-market for new products has significantly decreased and strong pressures exist to decrease this time even further. There will no longer be the luxury of carefully testing systems and designs to understand all the potential behaviors and risks before commercial or scientific use (Leveson, 2002). In this accident, if risk management had been used, or the concept of system safety had been introduced, the application of the system safety concept would have been encouraged by MOR and its sub-departments. Incorporating safety in design and development would be the first prioritized condition for contractor selection or setting up standards. Then the problems related to the signal devices could have been identified in the process of audit and the whole trend of the causal loop diagram would

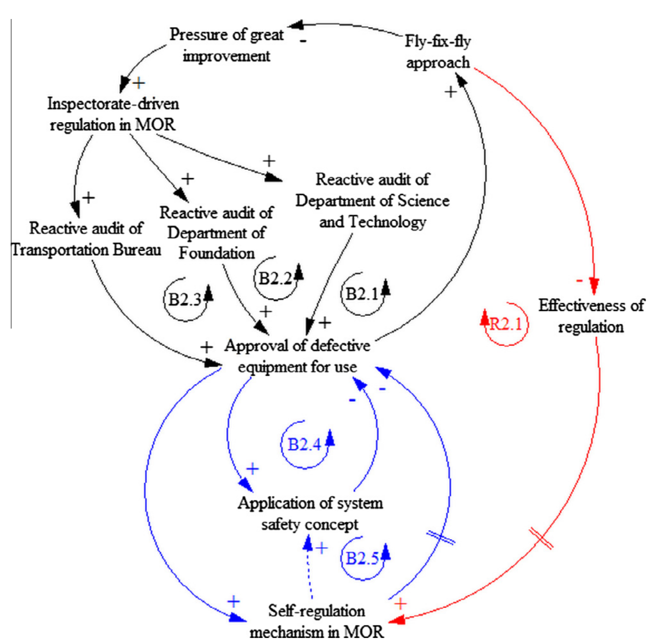

Fig. 9. Causal loop diagram for "approval of defective equipment for use".

have been changed. Therefore, the "application of system safety concept" in MOR is important to the problem of "approval of defective equipment for use"; it also can be regarded as a fundamental solution for the problem symptom.

Today, with the fast pace of technology change and new production, the inspectorate-driven regulation adopted by MOR means it is difficult to keep pace with these developments in technology, and it is of limited capacity to assure identifying defective design in time. In fact, similar problems once disturbed the regulatory agencies of the United Kingdom in late 1960s. Then Alfred Robens, who was a British politician, was asked to head a major inquiry into OHS practices in the UK and this led to the famous 1972 Robens Report which championed the idea that enforcement should be targeted at "self-regulation" by employers rather than reliance on prosecution in the courts. Since 1970, this new approach of self-regulation has been chosen as the main strategy in improving occupational health and safety standards in the workplace in several countries including the United Kingdom, Canada and Australia (Robens, 1972; Taylor et al., 2004). It moved the regulatory style away from inspectorate-driven to a new model based on consultation with workers, cooperation, information and training. The model has been proved to lower accident rates significantly in the UK (Amodu, 2008). As to present day China, safety issues in companies are still driven by the supervision of government regulatory agencies. Against the logic of self-regulation in Robens Report, the risk created by companies in China is seen as the responsibility of the government regulatory agencies. In order to prevent accidents, a new technical situation or an occurrence of an accident always leads these agencies to impose a new set of detailed rules which the companies must attempt to implement. In practice these rules either have to be broken or the job cannot be done because safety regulations are made so tight or so complicated. At the same time, these kinds of reactive regulations are distinct limits to bringing about better standards of safety and health.

The philosophy of "self-regulation mechanism" should be introduced to MOR and the department bodies, adopting positive performance indicators and contracting part of the operation to accredited consultants. Then the companies will accept primary responsibility for reducing accidents, and the regulatory agencies will contemplate something in the nature of continuous official supervision and rigorous enforcement, and could also provide the companies with skilled and impartial advice and assistance. Based on the "application of system safety concept", the "self-regulation mechanism in MOR" should be a deep level fundamental solution to the problem. The solution is based on using a different management mechanism in China, and it needs more time for MOR to understand and test, so the balancing loop is associated with a time delay. The fundamental solution is shown in balancing loop B2.4 and B2.5 in Fig. 9.

However, the "fix-fly-fix approach" is only a superficial solution but is easier to perform. With increase in its use, the side effect of "effectiveness of regulation" would be decreased and also it would decrease the performance of fundamental solutions. The reinforcing loop is shown in R2.1 in Fig. 9 and the situation would not be solved and would even deteriorate without any intervention of the type discussed here.

5.3. Analysis of the faulty response to the signal failure

Defects in design of the TCT would decrease its reliability in use. Based on the fault in the equipment directly caused by the lightning strike, the operators' related faulty responses to the signals failure ultimately triggered the accident. In the accident, the control system CTCS-2 was designed to meet the requirements of the Chinese high-speed train which had a speed of more than 200 km/h (SAWS, 2011). The TCC is the ground control center for train control information located at each station. It collects route information and device status from the signals system on the ground (e.g. TC) and receives the operation and schedule information from the Centralized Traffic Control (CTC). By using this information, it generates train control information through logic calculation. Also, the status of the signal device on the ground and the train status are transmitted to the CTC. In addition, it transmits this control information to on-board devices through signal devices on the ground. The TCC in Wenzhounan station was struck by lightning hundreds of times on the evening of July 23rd. This resulted in the data acquisition board in the TCC failing to collect consistent information and transmitting erroneous signals to the signal lights. When D3115 restarted in TC5829 in on-sight mode from 20:21:46 to 20:28:49, the information that TCC transmitted was that there was no occupancy of the Track Circuit (TC) by the train. The information was collected during the destruction of the data acquisition board. At 20:24:25, based on the erroneous signal, the dispatcher ordered D301 to start.

Track Circuit (TC) is used for transmitting signals and monitoring track occupancy. TC on the Yongwen line was the ZPW-2000A style, which was used to undertake inspection of track occupancy and transmit information. On the evening of July 23rd, four sending boxes, two receiving boxes and one attenuator in TC-5829 were also destroyed because of lightning which caused a communication failure between TC-5829 and TCC. Usually the occupancy of the TC by the train would be displayed in the TCC as a red light strip (shown in Fig. 7), but sometimes an abnormality in the TC may also lead to a red light strip.

ATP is the on-board device which can be used to achieve overspeed protection. It would stop the train immediately if it detected errors or failures in the TC. If the train wants to go ahead, it must wait for 2 min and change decentralized autonomous control mode (DACM) into on-sight mode. Both D301 and D3115 were fitted with ATP. The Train D3115 failed to restart three times before the accident because the ATP detected erroneous signals from the TC.

TCE is a mobile communication system among drivers, dispatchers and watch keepers in the railway system. Before the accident, the driver of D3115 failed to call the dispatcher six times. It is an important aspect of the control system, but it does not belong to CTCS-2.

According to the accident report, SRB and its operators' faulty response to the signals failure triggered the tragedy. Because of SRB's poor safety management program, the operators did not respond to the signal failure correctly, and so lost the opportunity to prevent the occurrence of the accident. The operators in the Chinese railway industry are usually associated with the train system, electrical system and working system. The train system operators include drivers, dispatchers and watch keepers (See Fig. 6). The fault in the TCT affected the dispatcher's decision, and this then went further to affect the dispatch to the driver, the watch keeper and other operators. It was further claimed that none of them took actions according to regulations when there were emergencies in the third section near Wenzhounan station (SAWS, 2011). They made mistakes either because they did not realize the hazards or did not know how to cope with them (Suo, 2012). Therefore, because of the poor safety management in SRB, the performance of its three subordinates was poor and the operators, except for the two drivers, adopted a faulty response to the signal failure. These made up the chains of causality and resulted in "faulty response to the signal failure". In the accident investigation report, 56 persons were mentioned of which 27 persons belonged to SRB. These persons included those who were on duty on July 23rd and their leaders. Similar to the other problem symptoms, in this part, the "fly-fix-fly approach" was still the quick fix to the "faulty response to signal failure". The balancing feedback is shown in the top balancing loop of Fig. 10 in black color.

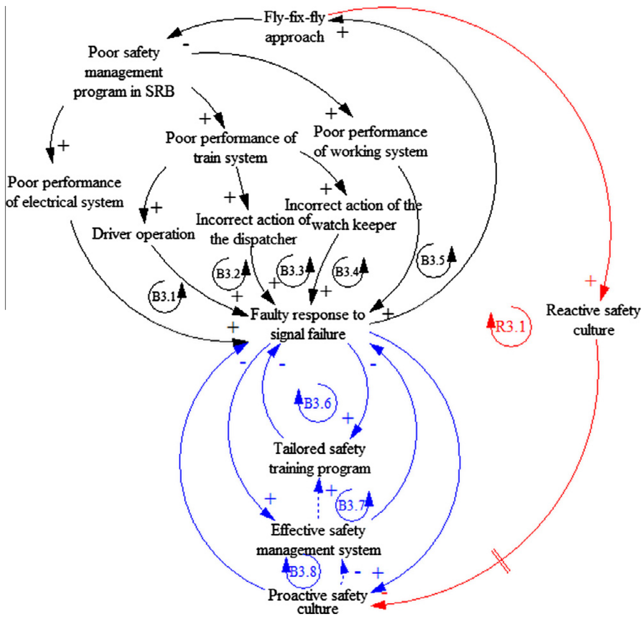

Fig. 10. Causal loop diagram for "faulty responses to signal failure".

While facing the unusual situation, the operators of the electrical system and the working system took wrong action which reflected the fact that the related procedures and training were poor. Although in the accident report, it was claimed that the inappropriate response to signal failure was due to poor training of SRB and its staff, there is a positive aspect to this. That is, if it was not for the accident, the operators would not have had any chance to be trained about "how to respond to the signal failure". Even after the accident, though they now know how to respond correctly, they still may face other different emergencies. They still lack systematic training. On the other hand, the procedures for the operators are too broad and it is difficult for them to understand as thoroughly as managers hoped. A further question is "Is it true that had the operators complied with the procedures which existed, the accident would not have happened?" If so, a detailed "tailored safety training program" should be set up after risk evaluation based on information from the designer and manufacturer and from best practices. And the quality and validity of the training program should reflect the quality and validity of the safety management system and safety culture in the whole company. All these elements, "tailored safety training program" and "effective safety management system" make up the fundamental solution to the problem of "faulty response to signal failure". The balancing loops of B3.6 and B3.7 are shown in Fig. 10 in blue color.

In recent years, investigations into major incidents in developed countries often highlight poor safety culture as one of the key causal factors (Goh et al., 2010). The term "safety culture" was first introduced by the International Safety Advisory Group (INSAG) (INSAG, 1986) after the Chernobyl nuclear accident in Ukraine and was meant to capture management and organizational factors as well as attitudes that are important to safety (Mengolini and Debarberis, 2012). Since then, used as explanation for accidents (e.g. Starbuck and Farjoun, 2005) and safety management performance of organizations (e.g. Hudson, 2007), safety culture has attained an important status in the discourse of accident prevention (Henriqson et al., 2014).

Notwithstanding controversies in the literature about conceptual definitions, methods, and measurements of safety culture (e.g. Glendon and Staton, 2000; Guldenmund, 2000; Cox and Flin, 1998; Haukelid, 2008), and that "the issues of culture and power are so intertwined that safety culture research should incorporate perspectives of power and conflict" (Antonsen, 2009), there is some agreement that safety culture refers to both individuals and institutions (Henriqson et al., 2014). A strong safety culture places a high priority on safety-related beliefs, values and attitude to risk at the workplace (Cooper, 2000; Guldenmund, 2000; Short et al., 2007; Edwards et al., 2013) and there arises a kind of consensual agreement between individuals and institutions (Antonsen, 2009; Henriqson et al., 2014). Individuals are called upon to be responsible for safe behavior and, at the same time, organizations are invoked to be responsible for assuring the proper engagement with safety at the organizational level (Sibley, 2009).

In recent years safety culture has received significant attention in both academic researches and industrial practices internationally, while the poor safety performance in Chinese industries also has received increased attention by the government and public; therefore, the emergence of safety culture in China does not come "out of the blue".

However, although some Chinese national companies have built their concept of safety culture into their companies, most of the time, safety culture is understood as no more than safety slogans or safety pamphlets, which are used to influence the attitude of workers. In fact, safety culture should first of all include a commitment to safety from the top leadership. In this case, if the concept of "proactive safety culture" had been introduced, a sustainable safety leadership team would have been built, and the system management program would have been applied. Also, if this concept had been introduced, mutual, meaningful, and measurable safety improvement goals would have been set, responsibility and accountability throughout the organization would also have been defined and personnel training at all levels within the organization would have been carried out. So when the failure of equipment appeared in the CTC, then the operator would have been able to take proper action, and the loss of lives may have been prevented. Proactive safety culture adopted in practice will not only increase the workers' notion of taking some of the responsibility themselves, by addressing their participation and empowerment, but will also enforce managerial supervision and adoption of innovative industrial best-practice (Henriqson et al., 2014). Therefore, "proactive safety culture" is a deep fundamental solution to the problem of "faulty response to the signal failure" (shown in balancing feedback of B3.8 in Fig. 10.). Also because of the delay the solution is harder to implement. The "fly-fix-fly approach" is easier to implement but usually causes the side effect "reactive safety culture" in the whole company shown in the reinforcing loop in R3.1 in Fig. 10. The "reactive safety culture" would make the situation progressively worse over time.

6. Discussion

As the interactive complexity grows in the systems we build, accidents caused by dysfunctional interactions among components become more likely (Leveson, 2011). Based on the previous analysis, the holistic causal loop diagram is shown in Fig. 11.

In Fig. 11, the three red rectangles represent the main causes of the accident according to the investigation report. These contributors are also the key problem symptoms in the causal loop diagram. Compared with Fig. 6, Fig. 11 not only shows the elements of the accident system, and identifies the contributors relating to every element, it also discloses how these elements interacted with each other and drove the accident which finally occurred.

Because of the pressure for great improvement and rapid design, the culture in the system became risk-blind; a "fly-fix-fly

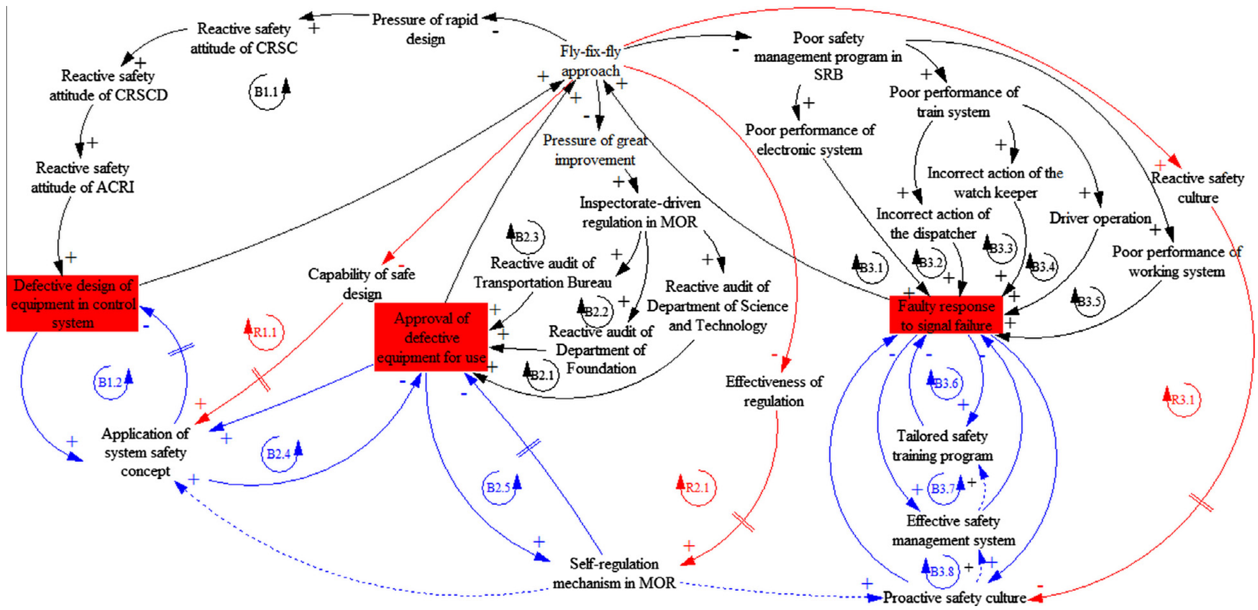

Fig. 11. Causal loop diagram for the 7.23 accident.

approach" to safety management dominated the whole system. From the product design and approval stage to its final use, no section was aware of or sensitive to the risk. Organizations have a tendency to navigate in a space bounded by the protection and production axes (Goh et al., 2012; Reason, 1997). Uncertainty in the work system and production pressure usually increases the probability of an accident and the "fly-fix-fly approach" is only a quick superficial fix and does not tackle the root problems. The corrective measures based on it will not tackle the fundamental problems.

Each symptom in the diagram has the same symptomatic solution, but the fundamental solutions seem complicated. In fact, the elements in the fundamental solutions also make up the chain of causality. The introduction of "self-regulation mechanism in MOR" would increase the "application of system safety" in the left part and "proactive safety culture" in the right part. They are indicated in dotted lines in blue and the links are all " + " types (shown in Fig. 11). With the "shifting the burden" archetype, when a symptomatic solution is applied to the problem, although it seems to work, that can mean the end of further investigation. In Fig. 11, it is easy to find that the quick solution leads to side effects in the three parts, and they are not recognized as related to the original problems of "defective design in equipment of control system", "approval of defective design" or "faulty response to signal failure". The side effect feedback loops are of the reinforcing type. Usually the occurrence of an external event—maybe just a single one—can flip the reinforcing loop from exponential growth into exponential decline. The external event which is called a "dangle" usually represents key external policies, targets, or drivers (Sherwood, 2008). For R1.1 and R3.1 in Fig. 11, the element of "self-regulation mechanism in MOR" is a dangle; it would change the two feedback loops from vicious circle to virtuous circle fundamentally and improve the influence of the other fundamental solutions. Introduction of "self-regulation mechanism in MOR" is the key policy initiative for railway accident prevention in China.

7. Conclusion

Learning from accidents contributes to improvement of safety and prevention of unwanted events. How much we could learn depends on how deeply we analyze the accident phenomenon. Although accident models have developed via linear causation models to systematic models and the approach of achieving safety has transferred from accident analysis to resilience engineering outside China, the accident analysis field is less developed than in other countries. Systems thinking is an approach of "seeing the forest for the trees" which emphasizes the circular nature of complex systems. The "7.23" accident is considered to be the most serious railway accident in the development of Chinese railways. In order to find unidentified contributory factors to the accident, this research adopted a systems thinking approach to analyze the accident based on the published national accident investigation report. The archetype of "shifting the burden" was adopted in this research because it can identify both a problem's symptomatic solution and fundamental solution and disclose why the phenomenon of short-term improvements leading to long-term dependency.

The research defined the components of the system according to the accident report and focused on the problem symptoms of "defective design of equipment in control system", "approval of defective equipment in use" and "faulty response to signal failure". Based on the problems, chains of causality were constructed and the contributory factors which triggered the problem symptoms were identified.

This research analyzed the "quick fixes" that appeared to be keeping the problem symptoms under control, and built the closed feedback loop. It showed that the symptomatic solution of all the problems in the Chinese railway industry has been a "fly-fix-fly approach". But that was only a superficial fix. These easier "solutions" only ameliorate the symptoms; they leave the underlying problem unaltered. The underlying problem grows worse, unnoticed because the symptoms apparently clear up, and the system loses whatever abilities it had to solve the underlying problem. As a long-term fix, the solution could not tackle the fundamental problem and could not prevent the accident at its root.

This research also analyzed the fundamental solutions of the problem symptoms such as "application of system safety concept", setting up "tailored safety training program", "effective safety management system" and "proactive safety culture", as well as introducing "self-regulation mechanism in MOR". These solutions not only help us to identify the unidentified contributory factors in the accident report, but also show the direction to take on providing accident prevention countermeasures. Based on the archetype of "shifting the burden", it showed that these fundamental solutions take time and there will be delays before their effects would be visible. And because of the delays, these solutions have side effects. In this research, the causal loop diagram showed that the fundamental solutions are systemic, and that they also make up the chain of causality. As a dangle of R1.1 and R3.1, introduction of "self-regulation mechanism in MOR" would flip the side effects from vicious circle to virtuous circle and it would also reinforce the other fundamental solutions. Introduction of the self-regulation mechanism is the first priority key policy for railway accident prevention in China.

Acknowledgements

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