



# System dynamics approach for modelling the variation of organizational factors for risk control in automatic metro



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## ABSTRACT

The automatic metro inspires a new way of thinking about the development of urban transportation systems, specifically how the overall system completes the automatic functions. The insights into the potential correlation between safety and system variation are crucial for safe and effective operation management in the automatic metro. Thus, this paper propose a system dynamics (SD)-based model to construct the operational feedback mechanisms of the automatic metro through investigation, interview, and empirical analysis of the Beijing and Shanghai metro systems, covering the aspects of organization resource assignment, organizational experience and avoidance of driver error. From the model, the variation trend of the dynamic processes can be used to analyse the key elements or variables over time. Three key factors (the safety policy, delay time for organizational experience, and resource assignment coefficient), are identified to evaluate the crucial linkage between safety and variation over time. The changing trend of system risk influenced by the combination of these three factors is further analysed to demonstrate how the functionalities of organization should be synchronized with the transformation of different grades of automation. The paper specifies an explicit framework that recognizes the relationships among the automation degree, organization policy and system risk at the macro level and comprehensively reveals the adaptation process of organization corresponding to the revolution process of the automation degree of the metro.

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## 1. Introduction

The deviance of organization is defined as an event or activity that deviates from organizational goals or normative expectations (Vaughan, 1999), and it is affected by several factors, such as the organizational setting (resource assignment, experience and relationships) and the social context (political, technological, economic, and cultural) (Stringfellow, 2010). The performance deviation of the organization is one type of root cause of accidents because of the complex causal interactions between equipment, humans and organization.

There are already many organizational research studies based on the accident causation model. The Swiss Cheese model was the most popular linear accident model, which considered organizational influences to affect all decision-making as latent failures (Reason, 1990). Based on this, many methods of risk analysis were

proposed to analyse the roles of humans and organizations. These methods include the following: Human Factors Analysis and Classification System (HFACS; Shappell and Wiegmann, 2000), Safety Occurrence Analysis Methodology (SOAM; Licu et al., 2007), Accident Analysis for Humans and Organizations (AcciMap; Svedung and Rasmussen, 2002), and Events and Causal Factors (ECF; Buys and Clark, 1995). These methods categorize the organizational factors to identify the types of errors, problems, or incorrect decisions and discuss the influence of organizational factors on the actions of humans and the equipment operation. Nevertheless, they do not identify the dynamic interactions between system components under the context of the environment. They are insufficient for understanding the dynamic complexity of the system.

The linear accident models are not appropriate for the risk analysis of socio-technical systems composed of equipment, humans and organization because they cannot describe and analyse the nonlinear characteristics and the dynamic complexity of socio-technical systems. However, the root causes of accidents in socio-technical systems are affected by the dynamic interactions between the system elements (Hollnagel, 2004; Hollnagel et al.,

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2008), and additionally, owing to the time delay existing in the system, the relationship between a cause and accident becomes much more complicated.

Therefore, the basic principles of system thinking have been incorporated to describe and analyse the complex correlations in a socio-technical system instead of using a linear model theory. Systems Theoretic Accident Model and Processes (STAMP), based on the systems theory, was presented to analyse the accident in view of system control (Leveson, 2011), and transform the system safety into a control problem. However, STAMP is useful for the analysis of technical systems rather than organization. To narrow the gap between the organizational and technical models from the system perspective, Kontogiannis and Malakis (2012) elaborated the method of STAMP based on the Viable System Model (VSM) and revealed several patterns of organizational breakdowns taking a Helicopter Emergency Service as a case. Moreover, Kazaras et al. (2013) identified the control flaws of the organizational process using the STAMP-VSM joint framework. However, these models are static and ignore the time delay between the cause and effect in the system.

Nevertheless, the organizational hazards identified in the initial phase vary with the change in system performance over time, and the effect of organizational factors on the system risk changes with the variation in the context of the system environment. From a long-term perspective, the organizational factors should be dynamically analysed to trace the system evolution and development from a macro perspective.

System dynamics is a successful approach for causation analysis that focuses on dynamic processes in comprehensive system thinking. With the approach of system dynamics, interactive influences among systemic state variables are described in reinforcing and balancing causal loops, and systemic factors, such as organizational behaviour and system risk, can be described in a causal relationship to reveal the nature of the nonlinear relationship and dynamic complexity of a socio-technical system.

Some researchers have applied system dynamics to the prediction of the changing trend of system performance concerning the relationship among the nonlinear factors over time. A system dynamics-based model was proposed to analyse the mental processes of construction workers, which helped to analyse the feedback mechanism and the resultant dynamics regarding the safety attitudes and behaviours of workers (Shin et al., 2013). Another dynamic executable modelling framework based on the STAMP method was presented to analyse safety-related decision-making in a complex system and monitor the increased risk before an accident occurs (Dulac, 2007). Nevertheless, there are no available applications on the evolution process of the automatic metro regarding both the system risk and organizational factors.

Several international standards and research studies have addressed general methods for system risk analysis and evaluation regarding railway applications. The most popular standard, EN50126, specified the risk matrix that requires risk evaluation to be performed by combining the frequency of occurrence of a hazardous event with the severity of its consequence (CENELEC, 1999), and the EN50129 standard provided the Safety Integrity Level (SIL) rates corresponding to the Tolerable Hazard Rate (THR) for the safety-related function (CENELEC, 2000). Moreover, the Formal Models and Safety Analysis (ForMoSA) approach, combining engineering practices, formal method and mathematics, was proposed to assess system safety in a structured and formal way as a Qualitative and Quantitative analysis method (Flammini, 2012). Another quantitative method was proposed to address the risk management of railway infrastructures, mainly considering physical threats based on a reference mathematical model, and it extended the classical risk equation to precisely evaluate the impact on risk indices of parameters related to protection

mechanisms (Flammini et al., 2009). However, none of these research studies has taken into account the feedback mechanisms between the system safety and organization management of the automatic metro.

To discover and control holistic risk arising from the variation of the automatic metro, a dynamic model embodying organizational factors and system risk was proposed in this paper to investigate the changing process of the automatic metro with regard to the social aspects. Compared with the existing research methods on the static analysis of safety, this model explored the influence mechanism of organizational factors on system risk over time. The new model approach enables one to trace the dynamic evolution process of key organizational factors in the automatic system and to predict system risk under a complex correlation of the organization around the automatic system.

The remainder of this paper is organized as follows: in the second section, the essential changing trend of automatic functions between organizational management and technical evolution in the automatic system is specified. After describing the hypothesis and boundary selection in the third section, a dynamic model for the automatic system is presented in the fourth section to describe the control loop concerning the assignment of organization resources, organizational experience and avoidance of driver error. The causal structure and variables in the model are obtained based on investigation, interview, and empirical analysis of the metro system in Shanghai and Beijing. In section five, several simulation processes for causal loops are elaborated to address the dynamic mechanisms of key variables, and the variation predictions of system risk influenced by organizational factors, such as the resource assignment coefficient, delay time for organizational experience, and safety policy, are employed to find what should be improved to maintain the safety with the migration process of the automation degree. Finally, various conclusions are drawn. Rather than the automatic metro remaining isolated from the societal aspects of operational management, we advocate that the organization should increase its efforts with regard to a higher automation degree to keep the metro system in a safe state: more organizational resources, a stricter safety policy and less delay time for experience.

## 2. Case Study: Automatic functions of the metro

The metro system is defined into several grades based on the automatic functions implemented by the system equipment. Table 1 shows the different grades of automation (GOA) defined in the international standard 62290-1 (IEC, 2006). In several cities of China, such as Beijing and Shanghai, the metro system has been operated with GOA1 or GOA2 for a long time, in which the responsibilities of the driver in the front cabin are to accelerate or brake the train and supervise the safe departure of the train from stations. In these systems, the indispensable tasks for the driver are to supervise the guideway and stop the train in case of a hazardous situation during the operation process. However, human error is one of the root causes of several accidents (Dinges, 1995). To avoid errors of the driver, the Shanghai Line 10 and Beijing Airport Line were operated with GOA3 until the year 2015 and will be operated with GOA4 in the future. In a system with GOA3, there are no drivers required in the front cabin of the train, and in a system with GOA4, there are no drivers or attendants in the train.

The basic functions of train operation are allocated as responsibilities of the operation staff or implemented by the system, as shown in Table 2. The key feature of the grade of automation is to share the responsibilities of basic train operation and passenger-related functions between the operation staff and system. The ratio of automatic functions at different automation levels

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