

Postprint of Modeling and Analysis of Train Control System Level Transition Based on UML and CPN

Authors: Song Limei, Aihong Zhu

Date: 2018-05-20T00:00:00+00:00

Abstract

Addressing the safety and real-time performance requirements of train control systems, UML (Unified Modeling Language) and Colored Petri Net (CPN) models for the C2-to-C3 level transition were established based on level transition scenarios in the CTCS-3 train control system requirements specification, analyzing factors affecting train safe operation and traffic efficiency—namely transition duration and transition success rate—and verifying the effectiveness of this modeling approach. Verification results demonstrate that the combined UML and CPN modeling approach is suitable for verifying train control system requirements specifications. The established level transition model can satisfy system real-time requirements. Under the premise of ensuring switching success rate, train operating speed is inversely proportional to switching time; the higher the speed, the shorter the switching time, and the higher the train speed, the higher the real-time performance requirements for the system.

Full Text

Modeling and Formal Analysis of Level Transition in Train Control Systems Based on UML and CPN

Song Limei, Zhu Aihong

School of Automation & Electrical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China

Abstract

Aiming at the safety and real-time performance requirements of train control systems, this paper establishes Unified Modeling Language (UML) and Colored Petri Net (CPN) models for the C2-to-C3 transition based on level transition

scenarios in the CTCS-3 train control system requirement specification. The study analyzes the factors affecting train operation safety and traffic efficiency—namely transition duration and transition success rate—thereby validating the effectiveness of this combined modeling approach. Verification results demonstrate that the integrated UML and CPN modeling method is suitable for validating train control system requirement specifications. The constructed level transition model satisfies system real-time requirements. Under the premise of ensuring switching success rate, train running speed is inversely proportional to switching time: higher speeds yield shorter switching times, which consequently impose more stringent real-time performance demands on the system.

Keywords: Chinese Train Control System (CTCS); level transition; UML; Colored Petri Nets (CPN); modeling

0 Introduction

As China's railway network continues to expand, operational safety has become paramount [1]. Level transition, as a critical scenario in train control systems, must ensure train safety while improving traffic efficiency by minimizing transition time. Consequently, in-depth research on level transitions in train control systems is essential.

Early research by domestic and international scholars focused extensively on communication reliability in train control systems and ETCS communication links [2]. In recent years, with China's railway development, studies have gradually shifted toward formal modeling approaches. Foreign scholars have employed hybrid timed automata and SDL methods for functional safety analysis and modeling of CTCS-3 systems [3-4], while domestic researchers have utilized various formal methods including Petri Nets (PN), timed automata, and Timed RAISE to investigate train control system operational scenarios [5-9]. Some scholars have applied UML semi-formal modeling methods to analyze level transition scenarios [10,12], while others have used formal CPN (Colored Petri Net) methods to study the impact of train speed on transition success rates [13-15].

In system modeling and verification, ensuring consistency between the system and model is paramount. UML defines a series of graphical symbols to describe software systems with strict semantics and clear syntax, establishing a standard that enables all software development stakeholders to describe various aspects of the system. Its main characteristics include unified standards, object-orientation, clear concepts, concise modeling notation, process independence, and simple yet diverse graphical expression capable of comprehensively representing system models. However, UML lacks rigorous mathematical definitions and model analysis/automatic verification tools. Conversely, while Colored Petri Nets provide automatic verification tools like CPN Tools for validating system properties such as reachability, boundedness, liveness, safety, and fairness, their complex logical expression makes direct modeling difficult and may compromise system-model consistency. In summary, existing research has

not considered a combined UML and CPN modeling approach for train control system level transition scenarios.

This paper employs a combined UML and CPN methodology to model train control system level transitions. First, UML Message Sequence Charts (MSC) analyze the information interaction process among Train, Driver, Balise, and RBC components during transition scenarios. Second, based on UML-to-Petri-Net transformation rules, the system's CPN model is established. Finally, using the C2-to-C3 transition CPN model, MATLAB processes data from 10,000 simulated transition runs to obtain transition success rates under different switching times and speeds. The results clarify how varying switching times and operating speeds affect transition success rates, providing theoretical support for ensuring system real-time requirements and references for improving train operation efficiency.

1 C2-C3 Level Transition Process

To meet passenger transport demands amid China's railway development, CTCS-2 lines must adapt to CTCS-3 train control system requirements. When a train's head leaves a C2 line and enters a C3 line, it must perform C2/C3 level transition. Before transition, onboard equipment should detect and reliably connect to the GSM-R network. If C3 control conditions are not met at the C2/C3 transition boundary, the train continues under C2 control while the system continuously monitors for C3 control condition satisfaction, automatically transitioning to C3 control when conditions are met. Figure 1 [Figure 1: see original paper] illustrates the balise arrangement during C2-to-C3 transition.

Figure 1: Balise arrangement at level transition scenario boundary

Figure 2 [Figure 2: see original paper]: CTCS-2 to CTCS-3 transition flowchart

The specific meanings of each balise group are shown in Table 1 .

2.1 UML Message Sequence Chart Model

A Message Sequence Chart (MSC) is a 5-tuple:

$$MSC = (I, M, s, r, \{\leq_i\}_{i \in I})$$

where:

- I represents a finite set of entities; M represents a finite set of messages;
- s and r represent two function sets, where message sending is denoted by $s \in M \rightarrow I$ and message receiving by $r \in M \rightarrow I$;
- For $i \in I$, $\leq_i = \{?m|m \in M, to(m) = i\} \cup \{!m|m \in M, from(m) = i\}$ represents the local ordering of message sending and receiving events.

To describe the level transition information interaction process using the 5-tuple $MSC = (I, M, s, r, \{\leq_i\}_{i \in I})$, the following conditions must be satisfied:

The C2-to-C3 transition comprises three parts:

- a) I contains four entity sets: Driver, RBC, Train, and Balise;
- b) M contains message sets related to the driver, RBC system, onboard system, and balise system;
- c) $\leq_{io} = \{(!m, ?m) | m \in M\}$;
- d) $\leq_{inst} \cup_{i \in I}$.

The message sets related to the four systems (Driver, RBC, Train, and Balise) are shown in Table 3. Functions s and r map message set M to I (e.g., $I_T = r(Connect-R)$, $I_B = s(Connect-R)$), where $!m$ denotes message sending events and $?m$ denotes message receiving events, with \leq_i representing the local order of event occurrence. The established MSC model is shown in Figure 3 [Figure 3: see original paper].

In Figure 3, rectangular boxes represent specific information interaction objects (Driver, RBC, Train, Balise), vertical lines represent temporal sequence, and arrows denote information exchange.

2.2 UML Sequential State Diagram Model

For the sequential state diagram in Figure 4, states are transformed into places in Petri Nets, while state changes are transformed into transitions.

3.1 Colored Petri Nets

Colored Petri Nets (CPN) are a formal modeling methodology that integrates mathematics, systems theory, and graphical representation [7]. CPN differs from Petri Nets (PN) by achieving net folding, making PN models easier to understand. Colored Petri Nets classify Tokens by assigning them different colors, thereby enabling PN system folding.

CPN Definition: A CPN is a multi-tuple set:

$$CPN = \{\Sigma, P, T, A, N, C, G, E, I\}$$

where each element's meaning is shown in Table 4.

This paper employs a top-down modeling approach using CPN to establish both top-level and corresponding lower-level models for level transition. Additionally, CPN Tools verification software simulates the constructed models to check for logical and structural errors.

3.2 C2-to-C3 Transition CPN Top-Level Model

Level transition comprises two scenarios: normal position transition and degraded transition. This paper models the CTCS-2 to C3 transition in normal position transition scenarios. All models in this chapter use 0.1s as the unit time.

Based on the transition flowchart in Figure 2, when the train head reaches LTO and meets transition conditions, the system automatically transitions from C2 to C3 control. Extracting information from the message sequence chart, the overall level transition CPN model considers only data interactions among Driver, Balise, Train, and RBC. According to UML state diagram-to-CPN transformation rules, the corresponding CPN top-level model is established as shown in Figure 5 [Figure 5: see original paper].

In the model, tokens are represented as $\{Message\}@Time$, where *Message* denotes current information between Train and RBC, and *Time* represents the token timestamp. Place sets represent Train and RBC states during level transition, with specific meanings explained in Table 5. Transition sets describe various action processes, with specific meanings shown in Table 6.

In the C2-to-C3 transition CPN top-level model, transitions VSC_ConGSM-R, Call_RBC, Position_Report, Arrive_LTA, and Arrive_LTO are all substitution transitions (double rectangles with 同名 small rectangles), each containing subpages.

3.3 C2-to-C3 Transition CPN Subpage Models

Following the substitution transition sequence, the top-level model is refined to derive subpage models. Due to space limitations, only the CPN models for Train-GSM-R connection establishment and Train-to-RBC position information transmission are presented, as shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper].

Transition VSC_ConGSM-R simulates the time delay from when the train passes the GSM-R network connection balise group to the RBC connection balise group. When the train head passes RE, transition Call_RBC simulates the RBC calling process with connection time $T < 10s$; if $T \geq 10s$, the call fails and the train continues at the original level. Substitution transitions Position_Report and Arrive_LTA simulate the information exchange process among RBC, onboard equipment, and train. Substitution transition Arrive_LTO simulates the transition to C3 control.

4 Model Simulation and Analysis

Simulating 10,000 transition runs of the “C2-to-C3 level transition CPN model” and processing the data with MATLAB yields the results shown in Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper].

The relationship between transition success probability and transition time is shown in Table 7. The results indicate that with a switching time of 104s, the transition success rate reaches over 99.8%, meeting specification requirements. Figure 8 [Figure 8: see original paper] shows that train switching time primarily concentrates between 84-102s. Assuming discussion of transition time required when trains run at initial speeds of 250km/h, 240km/h, and 220km/h from

the advance warning point (LTA) to the transition execution point (LTO), the results are shown in Figure 9 [Figure 9: see original paper].

From Figure 9, the relationship between train switching time and success probability at different speeds is obtained, as shown in Table 8 .

5 Conclusion

This paper models the CTCS-3 train control system C2/C3 level transition using a combined UML and CPN approach. Starting from UML models, relevant information is extracted to establish CPN models. MATLAB simulation of model runtime data focuses on investigating how different speeds and switching times affect transition success rate, yielding the following conclusions:

- a) When trains perform level transitions at different speeds, higher operating speeds result in shorter transition times.
- b) To ensure over 99.8% transition success rate, higher operating speeds demand greater real-time performance for level transitions.
- c) When transitioning at CTCS-2 ceiling speed of 250km/h, transition success rate improves by 0.3%.
- d) The combined UML-CPN modeling approach, with MATLAB simulation of model runtime data, produces results that meet specification requirements and satisfy system real-time performance demands to a certain extent.

References

- [1] Zhang Youbing, Tang Tao. Modeling and formal analysis of RBC handover in CTCS-3 based on colored Petri nets [J]. Journal of the China Railway Society, 2012, 34(7): 49-55.
- [2] Trowitzsch J, Zimmermann A. Using UML state machines and petri nets for the quantitative investigation of ETCS [C]//Proc of International Conference on Performance Evaluation Methodologies and Tools. 2006: 34.
- [3] Liu J, Tang T, Zhao L, et al. Functional safety analysis method for CTCS level 3 based on hybrid automata [C]//Proc of the 15th International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing. Washington DC: IEEE Computer Society, 2012.
- [4] Alur R, Etessami K, Yannakakis M. Inference of Message Sequence Charts [J]. IEEE Trans on Software Engineering, 2003, 29(7): 623-633.
- [5] Wang Yuanpeng, Hu Xiaohui, Chen Yong, et al. Modeling and simulation of CTCS level transition caused by balise failure [J]. Computer Engineering and Applications, 2016, 52(8): 234-239.
- [6] Wang Jian. Modeling and simulation of CTCS-2/CTCS-3 level transition process in high-speed railway train control system based on stochastic Petri nets

- [D]. Chengdu: Southwest Jiaotong University, 2015.
- [7] Liang Nan, Wang Haifeng. Real-time performance analysis of RBC in CTCS-3 based on SPN [J]. Journal of the China Railway Society, 2011, 33(2): 67-71.
- [8] Kang Renwei, Wang Junfeng, Lü Jidong. Modeling and verification of high-speed railway train control system level transition based on UPPAAL [J]. Journal of Beijing Jiaotong University, 2012, 36(6): 63-67.
- [9] Cao Yuan. Research on formal modeling and verification methods for high-speed railway train operation control systems [D]. Beijing: Beijing Jiaotong University, 2011.
- [10] Zhao Xiaoyu, Cheng Ruijun, Cheng Yu, et al. Formal modeling and parameter analysis method of train control system based on HUML [J]. Journal of the China Railway Society, 2016, 38(11): 80-87.
- [11] Liu Jintao, Tang Tao, Zhao Lin, et al. Functional safety analysis method for CTCS-3 based on UML model [J]. Journal of the China Railway Society, 2013, 35(10): 59-66.
- [12] Zhao Lin, Tang Tao, Liu Jintao, et al. Train control system modeling method based on UML extension mechanism [J]. Journal of the China Railway Society, 2012, 34(12): 64-70.
- [13] Yang Liuqian, Zhang Youpeng. Research on modeling method of RBC handover scenario based on UML and colored Petri nets [J]. Computer Measurement & Control, 2012, 20(4): 1116-1119.
- [14] Xu Tianhua, Zhao Hongli, Tang Tao. Reliability analysis of ETCS wireless communication based on colored Petri nets [J]. Journal of the China Railway Society, 2008, 30(1): 38-42.
- [15] Jiang Jinlong, Zhou Xianzhong, Sun Yongcheng, et al. Hierarchical modeling and analysis method based on UML and Petri nets [J]. Journal of System Simulation, 2006, 18(2): 290-293.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.