



Multi-agent communication-based train control system for Indian railways: the behavioural analysis

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Abstract Multi-agent technology has been used in many complex distributed and concurrent systems. A railway system is such a safety critical system and careful investigation of the functional components is very important. Study of the various functional components in communication-based train control (CBTC) system necessitates a good structural design followed by its validation and verification through a formal modelling technique. The work presented here is the follow up of our multi-agent-based CBTC system for Indian railway designed using the methodology for engineering system of software agents. Behavioural analysis of the designed system involves several operating scenarios that arise during train run, and helps in understanding the reaction of the system to such situations. This validation and verification are very important as it allows the system designer to critically evaluate the desired function of the system and to correct the design errors, if any, before its actual implementation. Modelling, validation and verification of the structural design through Coloured petri net (CPN) are central to this paper. Analysis of simulation results validates the efficacy of the design.

Keywords CBTC · Multi-agent · Fault resolution · Modelling · Validation and verification · CPN

1 Introduction

Indian railway (IR) operates several different categories of trains, widely varying in terms of their technology, speed, braking characteristics, etc., and termed as mixed traffic. The present static block signalling (SBS) [1] used in IR has several limitations with respect to line capacity utilization and safe train operations, which can be improved through communication-based train control (CBTC) system [2] with moving block signalling (MBS) [3]. It is well known that the train control network is time critical (i.e. real-time response) and mission critical (i.e. reliability). Any operational or equipment fault may cause serious consequences; therefore, safety should be especially concerned [4]. Countries, where CBTC is in use have no such wide variation in the train categories and thus make their operational issues simplified for the implementation of CBTC. Hence, for study of mixed train traffic operation under MBS with the support of multi-agent-based CBTC system, it is necessary to propose a better train control system for IR to overcome the limitations of the present system. It involves developing the architectural design of multi-agent-based CBTC system followed by modelling, validation and verification through formal approach to check the efficacy and correctness of the designed system.

The complex, distributed, dynamic and highly interactive properties of the CBTC system make the multi-agent-based computing technique more suitable for its development [5]. A multi-agent-based computing system has several advantages over a traditional computing system as its distribution property naturally decomposes the system into multiple agents and the interactive property allows these agents interact with each other to achieve a desired global goal. Multi-agent-based computing technique is more suitable for the design and analysis of systems where the

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system is divided into several geographically distributed sub-systems in a dynamic environment and these sub-systems need to interact with each other more flexibly [6]. The operating scenarios of railway transportation system have similarity with the above scenario, thus making the multi-agent technology most suitable [7–12].

Traditionally, the development of multi-agent systems involves *logical structure design* and its *implementation*. Methods used for the evaluation of behavioural properties of multi-agent systems are based on actual implementation and formal modelling. The former is based on agent implementation tools [13] such as Java agent development framework [14], Zeus agent building tool-kit [15], Jack intelligent agents framework [16], etc., whereas the latter is based on Vienna development method [17], Z notation [18], Calculus of communicating systems programming language [19], Language of temporal ordering specification [20], Temporal logic [21], Communicating sequential processes formal language [22], Petri net [23], Coloured petri net (CPN) [24], etc. Formal modelling has several advantages over actual implementation to check the correctness and behaviour of the design through development of various test cases. CPN is a graphical and executable formal modelling technique well suited for model building and behavioural analysis of distributed and concurrent multi-agent systems [25].

Our earlier structural design of multi-agent CBTC system for IR [26] named Indian railways management system (IRMS) discusses the methodology for engineering system of software agents (MESSAGE) [27] based design details of sub-goal *moving authority given* to the block section. Verification and validation of the design through a formal modelling approach are taken up in this work. The rest of the paper is organized as follows. Section 2 covers the related work and Sect. 3 presents an overview of the proposed system. Modelling of the system is presented in Sect. 4, and validation and verification in Sect. 5. Finally Sect. 6 concludes the paper.

2 Review on CPN modelling

Various issues in research related to railway systems have been dealt with through mathematical modelling, simulations, multi-agents, soft computing techniques, etc. The rolling stock characteristics, infrastructure and the operational rules of IR [28] make the system unique from the other railway setup used elsewhere in the world. Taking a cue from related research, the project necessitated the detailed study of existing IR train control system and proposes a multi-agent CBTC system for IR with minimal modifications to the present setup. To the best of knowledge, our work is the first to explore the issues specific to IR that might be important to consider before moving IR to

CBTC on MBS-based infrastructure. In the following, we discuss the use of CPN for the modelling of a few distributed and concurrent systems.

2.1 CPN modelling of multi-agent systems

An agent conversation protocol [29] has been implemented in CPN due to its simplicity and graphical representation along with great support for concurrency. Further, an idea about the implementation of CPN models in a real multi-agent framework is given. It used CPN to investigate the working of the proposed agent conversation protocol before its actual implementation on a real multi-agent framework.

An FIPA (foundation for intelligent physical agents) [30] compliant agent platform called concurrent agent platform architecture is developed in Petri net to provide facility of inter-platform communications in multi-agent nets (Mulan) architecture. It used Petri net to maintain the high degree of concurrency of the multi-agent system.

An urban traffic information system to solve path searching problem is designed as a case [31], to represent the use of CPN for designing multi-agent system. The authors described the multi-agent system as a specialization of distributed object oriented systems and proved the efficacy of CPN for modelling such systems.

A hierarchical CPN-based multi-agent system is presented in [32]. Each agent is modelled as a separate net that is connected with other agents' nets and forms a hierarchical net. The behaviour of the multi-agent system is analysed through the dynamic properties such as reachability, deadlock detection and avoidance, fairness etc.

In our earlier work [33], a multi-agent-based CBTC framework with MBS using the MESSAGE methodology was presented for IR, and a simplified model of sub-goal and *moving authority given* using CPN was built.

2.2 CPN modelling of railway domain problems

The advantages of CPN-based formal modelling to describe a complex system with critical requirements are presented in [34]. It considered railways as a case and followed a modular approach to explain different aspects of modelling a complex system through CPN.

The timed CPN is used to model and analyse both operating schedules and the infrastructure of a railway station in [35]. The paper explains the use of timed CPN to model and analyse the dynamic behaviour of large and complex systems. It also provided a new analysis technique that constructs a reduced reachability graph.

The modelling of interlocking tables using CPN is presented in [36]. The developed CPN models comprise *signalling layout* that represents the physical arrangement of

signals according to SBS system and *interlocking control* that represents actions performed for interlocking according to interlocking tables. These basic models can be reused to model more complex and large interlocking systems. The verification of modelled interlocking tables in various scenarios is presented in [37].

A study of high speed train positioning system on railway line equipped with European rail traffic management system level-2 is presented in [38]. The paper proposed a CPN model of train movement with interaction between train and eurobalises installed on the track that describes the various causes of eurobalise’s degradation. The authors focused on faults related to balise and balise transmission module antenna, while other types of faults those may arise during the train operation are not discussed.

A vehicle-on-board automatic train protection sub-system of CBTC system is implemented in CPN [39]. The work emphasized more on how to refine the basic CPN-based model for further research in the area of vehicle-on-board automatic train protection. The paper exemplifies the

restricted speed estimation for a running train with respect to the obstacle on the track ahead.

To the best of our understanding, none of the above works provided system level structural design details and their behavioural analysis. It becomes very important to supplement the behaviour study of the structural design part of the designed system. With such an objective, we split our work into two components: the structural design followed by formal modelling of the designed system for behavioural analysis. This report is an extension of our earlier work [26] on structural design and focuses only on the behavioural analysis of the IRMS safety critical system through CPN modelling.

3 Architectural overview of IRMS

In this section, the major components of IRMS and their interaction are reproduced from our previous work [26] to help the reader in getting an overview of the system.

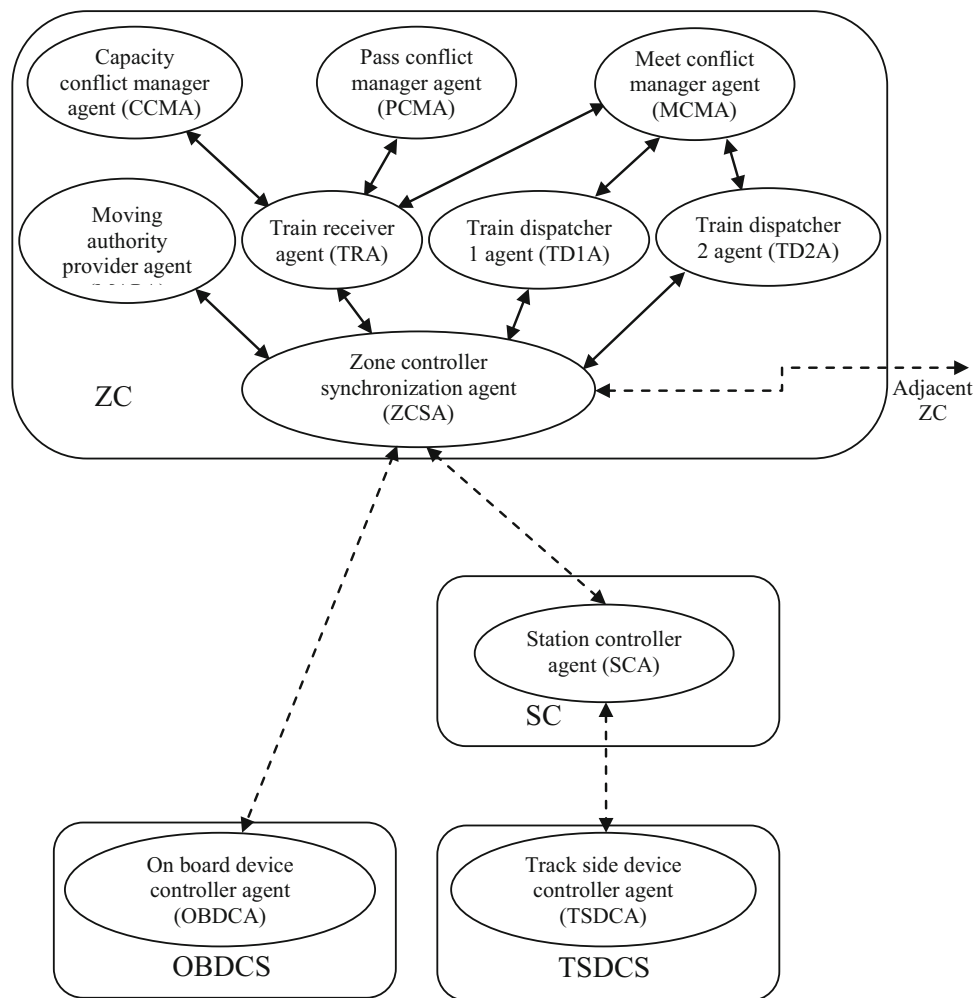


Fig. 1 Abstract level diagram of the IRMS [25]

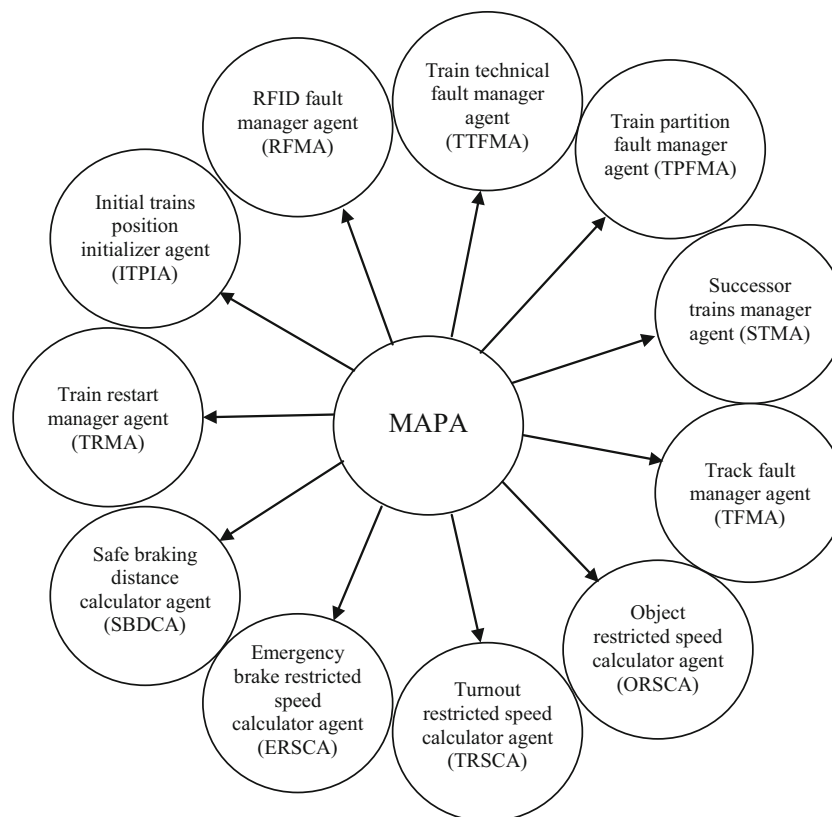


Fig. 2 MAPA's sub-agents [25]

The software agent-based CBTC rail track infrastructure is divided into areas or regions, each under the control of a zone controller (ZC) and each with its own radio trans-receiving system with reliable and continuous radio link. Figure 1 shows the high level architecture of IRMS which describes the important functional components and their corresponding agents. It consists of four principal components: ZC, station controller (SC), trackside device control system (TSDCS) and on-board device control system (OBDCS).

OBDCS comprises a vehicle-on-board controller and several train borne equipment, such as global system for mobile communications-railway trans-receiver antenna, RFID reader, speedometer, accelerator, braking unit, driver display screen, train integrity monitor, etc. Train borne equipment collects the relevant information, such as train number, speed, location identifier, direction, etc., and periodically send it to their respective ZC. Location identifier is the location reference read by train borne RFID reader through track side RFID tags.

Upon receipt of this information, the respective ZC computes a safe moving authority on the basis of track status ahead and train characteristics, and communicates to the respective train. Further, ZC gives instructions to SC to create the route by interlocking for the arrival or departure of trains in the station section. Train handover between two

adjacent ZCs occurs when a train passes the overlapped ZC boundaries.

Each station section has a single SC responsible for interlocking (establishing or releasing a route) for the arrival or departure of trains. The route is created by fixing all switches presented on the path in a required position. SC receives a route from ZC, i.e. sequence of switches and their positions, and gives instruction one by one to TSDCS to fix each switch in a required position. The SC on receipt of positive acknowledgement for all required switches from TSDCS gives route establishment acknowledgement to ZC. If SC receives negative acknowledgement for any required switch, it releases all switches and gives negative route establishment acknowledgement to ZC.

Switches falling under a particular station section are controlled by the respective TSDCS. It is responsible to fix each individual switch in a required position. It receives a switch identifier and its position information from the SC. If the switch is fixed in the desired position, it transmits a positive acknowledgement to SC; otherwise negative acknowledgement. TSDCS also continuously monitors the health and status of all its switches, and reports to respective SC.

To check the correctness and behaviour of the design, various operational scenarios (such as RFID fault, train equipment's fault, train partition fault, track fault,

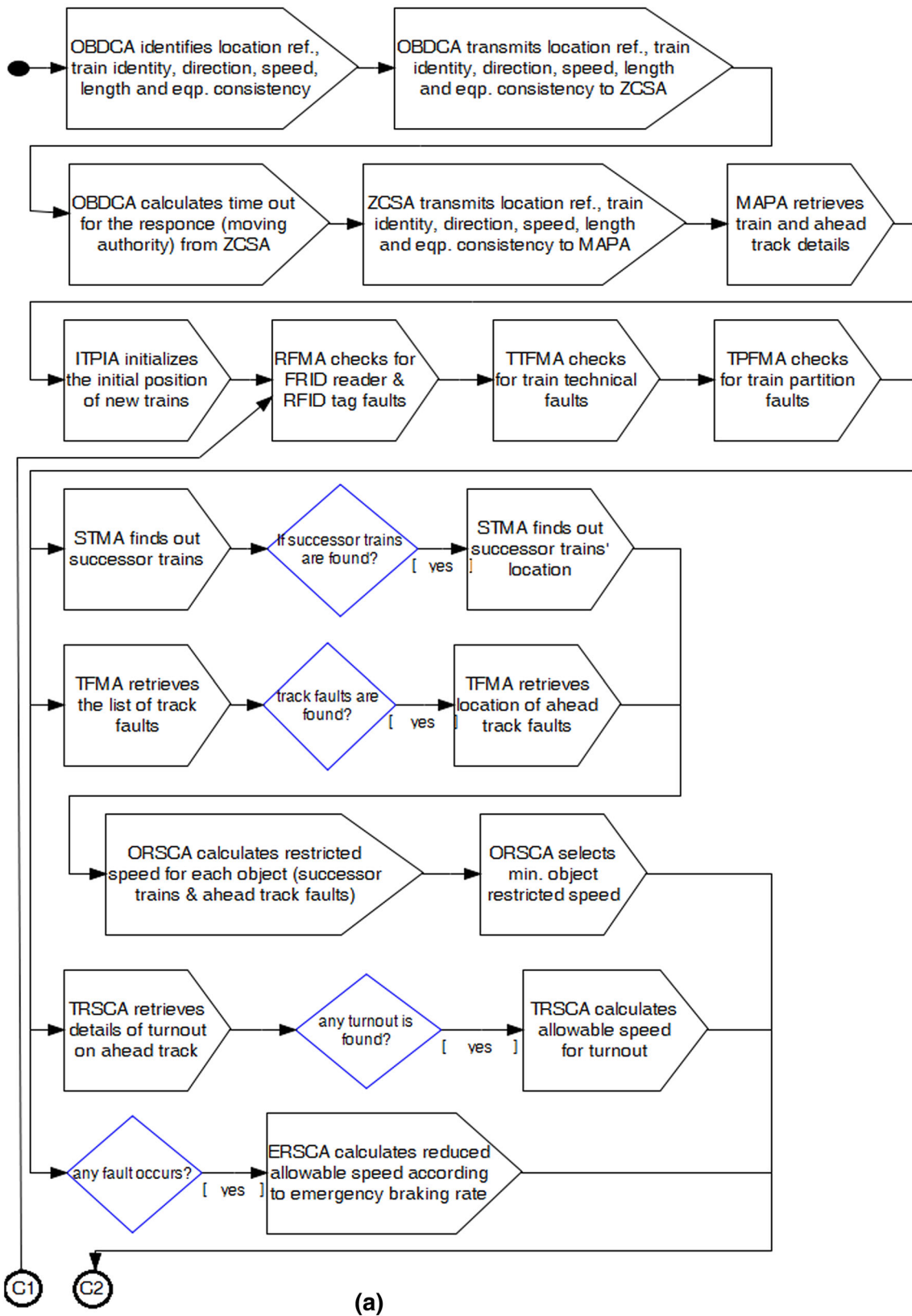


Fig. 3 Workflow of sub-goal moving authority given [25]

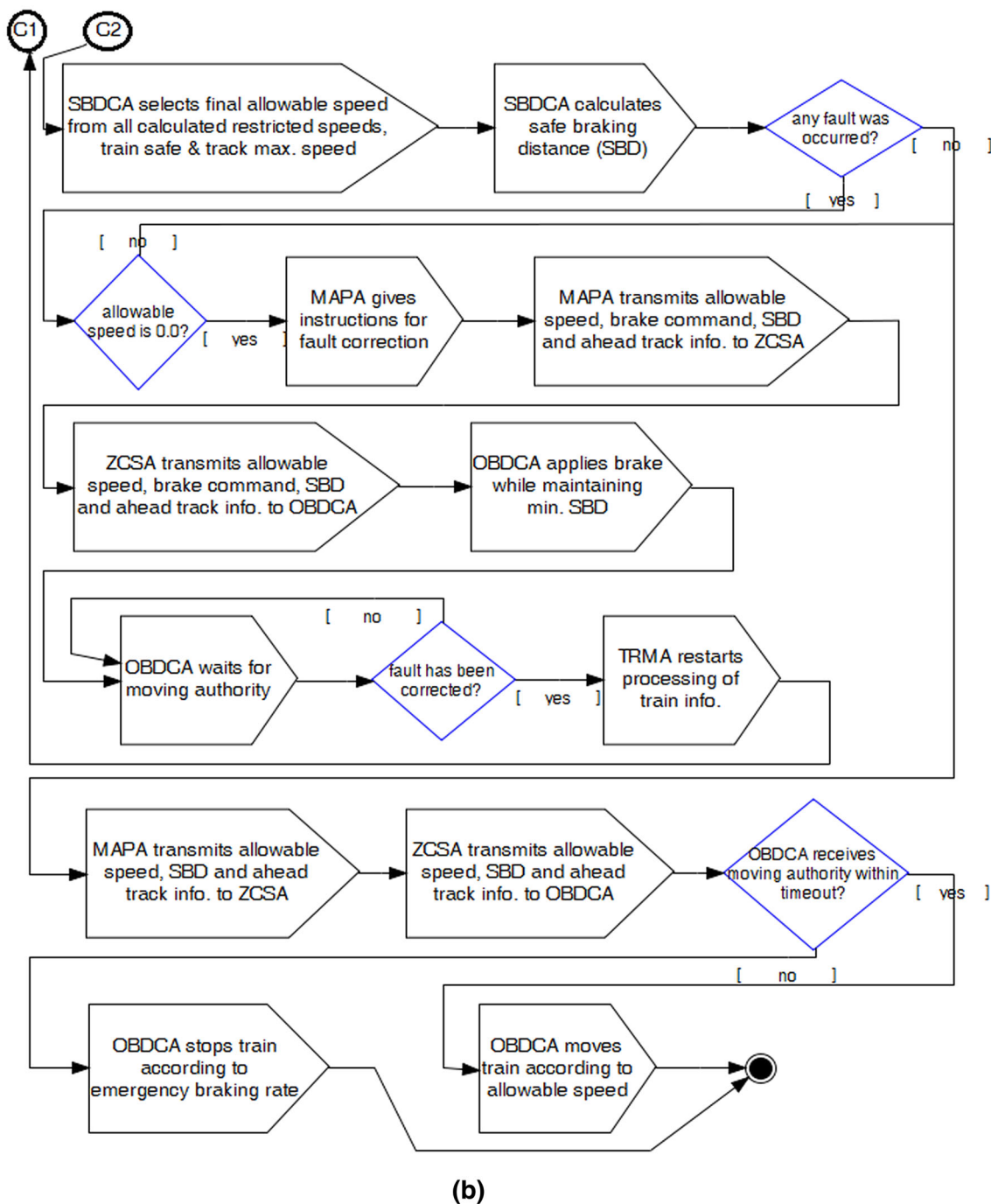


Fig. 3 continued

communication fault) in block section are considered. The system has several agents and their sub-agents, which are distributed geographically and work cooperatively to accomplish the sub-goals. The sub-goal *moving authority given* is the key component for ensuring safety during various faults occurring at runtime. This sub-goal is accomplished by moving authority provider agent (MAPA) with support from other agents. Figs. 2 and 3 describe the various sub-agents of MAPA and their interaction with other agents, respectively, to

provide moving authority. Circles with label C1 and C2 in subfigures (a) and (b) of Fig. 3 connect both subfigures.

4 CPN modelling

The modelling aspects of IRMS followed by a detailed discussion on MAPA and its sub-agents are carried in this section.

4.1 Modelling of IRMS

The CPN model is hierarchically structured into 36 subnets or pages. Each agent functionality is modelled on a separate page with page name same as the agent's. Page IRMS (see Fig. 4) is the top page and provides an abstract view of a block section and the associated track-cum-communication infrastructure of the system. Table 1 describes the model and simulation parameters, and Table 2 characterizes the mixed traffic. Page IRMS has the following four types of substitute transitions. The place connecting two substitute transitions represents a communication link between them.

Table 2 Train characteristics of mixed traffic

Train characteristics	Value
Train maximum speed	36.11–41.66 m/s
Train safe speed	27.77–33.33 m/s
Train length	150–200 m
Train CBTC system response time	0.5–1.5 s
Propulsion disable response time	0.5–1.5 s
Coast time	0.5–1.5 s
Acceleration rate	0.25–0.35 m/s
Normal braking rate	0.35–0.45 m/s
Emergency braking rate	0.55–0.65 m/s
Position uncertainty distance	10 m

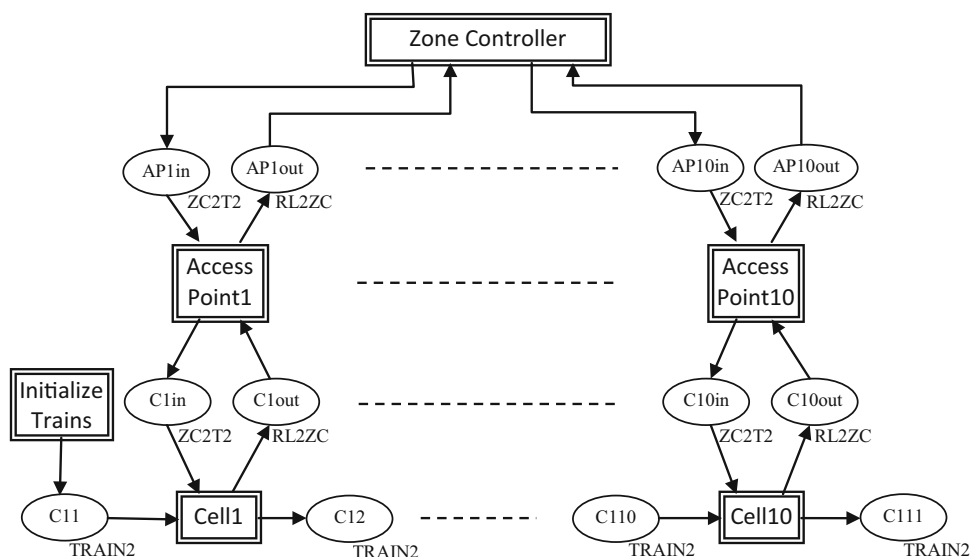


Fig. 4 Top-page IRMS

Table 1 Model and simulation parameters

Model parameters		Simulation parameters	
Component	Description	Parameter	Value
Zone controller	Central controller responsible for both station section(s) and block section(s)	Area under ZC (one block section considered under one ZC)	50 km
Block section	Section between two station sections. A block section has multiple cells	Number of block section	01
		Number of cells	10
		Number of access points per cell	01
RFID tag	For train location information and placed equidistant along the track	Block section length	50 km
		Number of RFID tags per cell	500
Train	Trains with different characteristics are taken to form mixed traffic	Inter RFID spacing	10 m
		Number of trains	4

- *Initialize Trains* It models mixed traffic scenario. Mixed traffic is a crowd of trains with different physical characteristics such as train type, length, maximum speed, braking capacity and varying running schedules. Specific tokens represent trains and their values represent trains' static and dynamic characteristics.
- *Cell* Each block section is divided into a number of cells. This type of transition implements the functions necessary for the OBDCS installed on trains and track infrastructure.
- *Access Point* Substitute transition models the functionalities of access points to facilitate the communication between OBDCS and ZC.
- *Zone Controller* ZC encompasses several functionalities (see Fig. 1). However, the scope of the paper limits the discussion to two important functionalities within ZC. First, the MAPA with a variety of fault scenarios and resolution mechanisms; and second, the desired functionalities of ZCSA essential for achieving the sub-goal *moving authority given*.

The mixed traffic generated by page *Initialize Trains* runs within the pages *Cell1* to *Cell10* according to the assigned schedule. Each page of type *Cell* models the segment of track equipped with installed RFID tags and the functionality of train's OBDCS. Train location information along with other necessary information is transmitted from respective *Cell* type page to *Zone Controller* page via corresponding *Access Point* page type.

The page *Zone Controller* comprises two substitute transitions ZCSA and MAPA. Page ZCSA models the functionality of agent ZCSA responsible for communication between pages *Access Point* and *MAPA*. Page ZCSA maintains a list of trains running under its control and models the handover process of trains across ZCs. The operations performed by page *MAPA* are described in the next sub-section. Page ZCSA receives a moving authority for the train from page *MAPA* and forwards it to the corresponding page of type *Cell*, via a connected page of type *Access Point*.

The page of type *Cell* forwards the received moving authority to the corresponding train's OBDCS. The train's OBDCS updates its information and follows the moving authority. At the time of sending the train's location and other essential information to the *Zone Controller* page, OBDCS sets a time out of receiving the corresponding moving authority. If the response is not received within the set timeout, a communication failure is assumed and train's OBDCS activates the emergency braking mechanism. Train retards according to its emergency braking characteristics. The last saved location information is considered as a train's current location by page *MAPA*. Moving authority to trailing

trains is provided based on this information for them to allow adjust their speed. Normal operations are resumed upon regaining the communication link.

4.2 MAPA model

Functional details and the modelling aspects of agent MAPA and its sub-agents are described. The model implements file handling procedures to store and process information related to the train and track. The page *MAPA* contains the following eleven substitute transitions, each modelling the functionality of its sub-agents.

- Page *ITPIA* implements the initialization of trains' position, length and direction at ZC.
- Page *RFMA* models the mechanism to handle RFID faults resulting from either tag or reader malfunctioning. Flag value 1 indicates fault when two successive RFID locations are not recorded. The flag value is further used by page *ERSCA* for taking decision on applying emergency brake.
- Train's consistency information (handled by page *TTFMA*) defines the overall health status of its equipments, and flag value is set to 1 when the status is healthy. Flag status is used to take decision for applying the emergency brake by page *ERSCA*.
- Train partition is a fault scenario where the coaches of a running train decouples, resulting in multiple parts of the same train. Page *TPFMA* handles these faults by taking current location and train information as input. The train partition fault flag is set to 1 when partition occurs. It records the last RFID tag number corresponding to the parted train's rear end that is used for the estimation of trailing train's moving authority.
- Page *ERSCA* uses the flag values pertaining to the above faults for applying the emergency brake if required for the affected train according to its braking characteristics.
- Track fault is a fault scenario where a train may be allowed to run at some restricted speed or not allowed at all. Page *TFMA* operates on the file containing track health information and their corresponding allowable speed of the trains. This information is used by page *ORSCA* for safe moving authority calculation. The track health file is continuously updated from the track fault detection devices.
- Collision-free train running depends much on maintaining a safe distance from its successor trains. This necessitates recording of successor trains' rear end location for the calculation of safe moving authority for the trailing train. Page *STMA* implements this functionality.
- The moving authority for a train is affected by successor trains and ahead track faults which are

referred to as obstacles. In some kind of track faults, the train is allowed but with restricted speed. Page *ORSCA* takes the successor trains' (including parted trains') information and fault data of track ahead to calculate the allowable speed corresponding to each obstacle and takes the minimum of all. It is used by page *SBDCA* for final allowable speed calculation.

- Turnouts on rail track have speed restrictions and the running trains must follow these restrictions. Page *TRSCA* implements and ensures the prescribed speed restrictions. It takes the specifications of the turnout ahead (like its location and allowed speed) and train information to calculate the allowable speed.
- Safe braking distance is an important factor for collision-free train operation. To ensure this, the system must alert the running train sufficiently ahead in time so that the train can be stopped according to its braking characteristics. Page *SBDCA* takes the obstacle restricted speed from page *ORSCA*, emergency brake restricted speed from page *ERSCA* and turnout restricted speed from page *TRSCA* as input to estimate the final allowable speed. The safe braking distance is computed based on the final allowable speed and train's braking characteristics.
- When a fault is detected, a train's normal running is affected either by completely stopping the train or allowing running at a restricted speed until normalcy is restored. Page *TRMA* models detection of fault and waits for a random period. This random period models the fault recovery time. Once restored, the system initiates the process of computing the moving authority.

5 Validation and verification

Validation allows checking whether or not the developed model meets the expected behaviour and verification allows identifying errors and anomalous properties in the developed model. CPN provides a simulation facility for the validation and a state space graph for the verification of the developed models.

5.1 Validation

A simulation study under mixed traffic condition is done to understand the behavioural aspects of the model to achieve sub-goal *moving authority given*. The prime objective is to provide a moving authority for the trains to ensure collision-free movement and to study the proactive behaviour of IRMS to fault scenarios. The CPN model has been tested for its validity through simulation report analysis. The

simulation report is used to extract relevant data to create graphical representations of simulation results.

Availability of aggregated time series data pertaining to various faults is not maintained by any department in IR. Mostly, the faults are rectified by the local technical field staff and practically there is no record keeping mechanism of such data for future analysis. Thus, obtaining such fault related data and fitting it to a model was not possible.

To evaluate the working of the model in the actual traffic scenario, we conducted several experiments for a group of trains with different characteristics representing the mixed traffic. The system deals with two kinds of parameters associated with the track: operator defined which is static and deterministic such as the maximum allowable speed on the track, turnout restricted speed. The other arising in real time is dynamic and random, e.g. speed restrictions due to track faults, train equipment faults or any kind of obstacle on the track. Due to the static and dynamic parameters, trains' normal running is affected. However, as the static parameters are deterministic, the system has prior knowledge about this. The system takes care of such restrictions while estimating moving authority for the trains. On the other hand, the occurrence of dynamic parameters is known at runtime and this is challenging while estimating moving authority for the trains. In our work, both scenarios have been taken to test the overall responsiveness of the proposed system. The results obtained are categorized into two parts: one showing the relationship between speed and location to represent the safe moving authority provided to the trains for their safe running in case of any fault scenario identified in runtime, and second, the relationship between time and location to represent the collision-free running of the trains in the same scenario. For the purpose of describing the behavioural analysis, we considered only one instance from several simulation experiments for each fault type.

5.1.1 RFID fault

Failure of RFID tag or RFID reader results in failure of recording the location information, and in such a scenario the train(s) must be stopped for safety reasons. A tag fault is detected, a by page *RFMA* at RFID tag 2,501 by train 1120 (Fig. 5) running at speed 31.53 m/s. Page *ERSCA* estimates speed according to emergency braking characteristics of the affected train. The affected train and the following trains adjust their speeds according to the moving authority received from *MAPA* (shown by decreasing speed curves). The increasing speed curves (starting at tag 2,531) indicate the train encountered healthy RFID tags, and eventually regain the normal speed at tag 2,591. The speed curves of all trains gradually drop to zero in the same

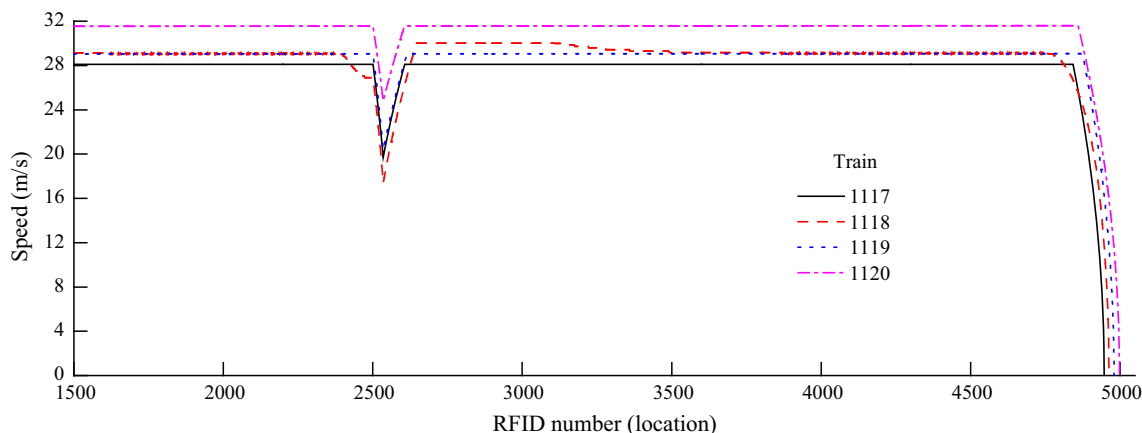


Fig. 5 Speed versus location (RFID tag fault)

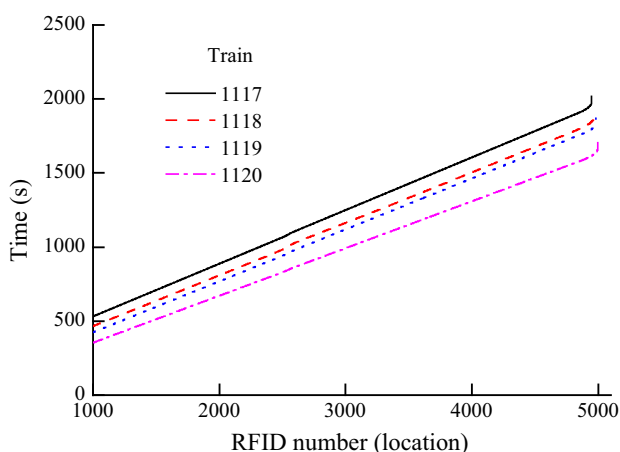


Fig. 6 Time versus location (RFID tag fault)

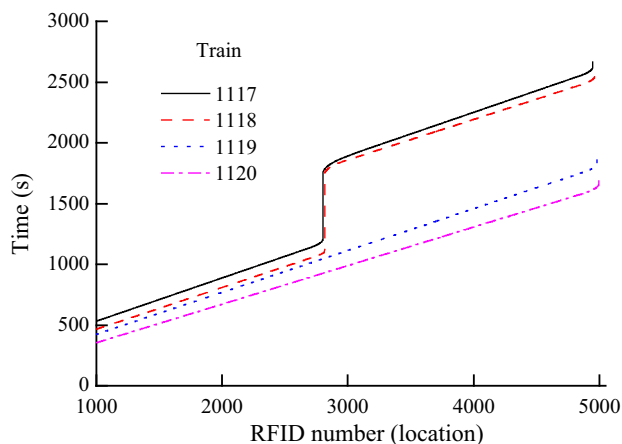


Fig. 8 Time versus location (Train equipment fault)

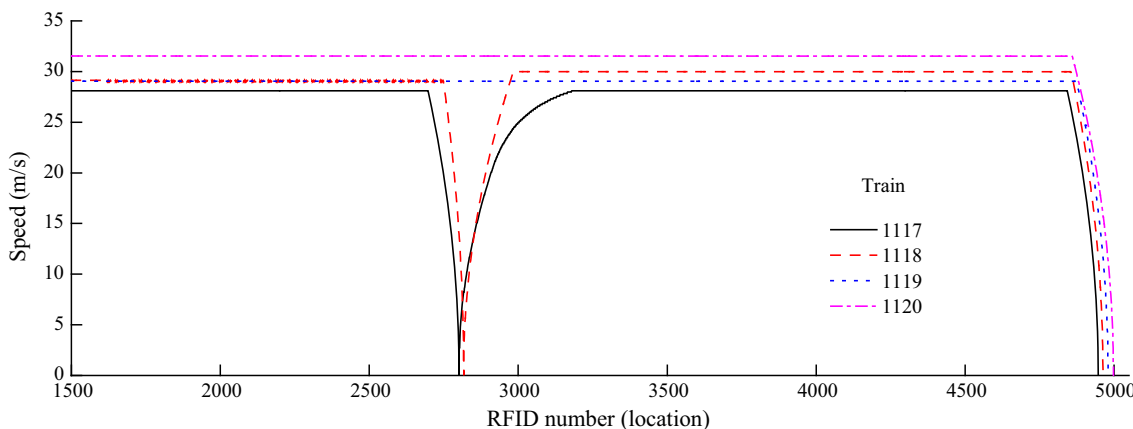


Fig. 7 Speed versus location (Train equipment fault)

sequence of their dispatch prior to the end of the block section at RFID tag 5,000. The non-intersecting time curves in Fig. 6 represent the running of a collision-free

train during handling of RFID faults. The time curves pertaining to trains between location 2,501 and 2,530 show a slight jump, indicating the slow speed of trains in the

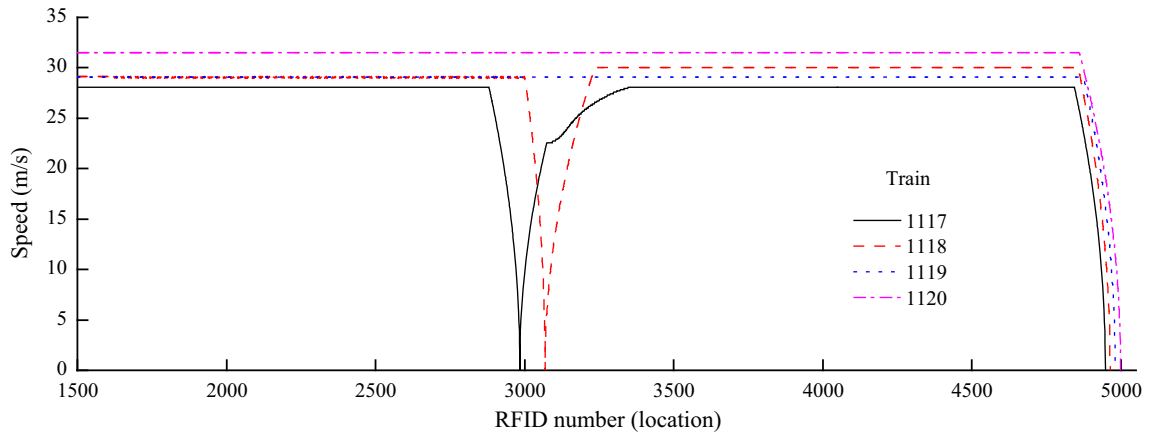


Fig. 9 Speed versus location (Train partition fault)

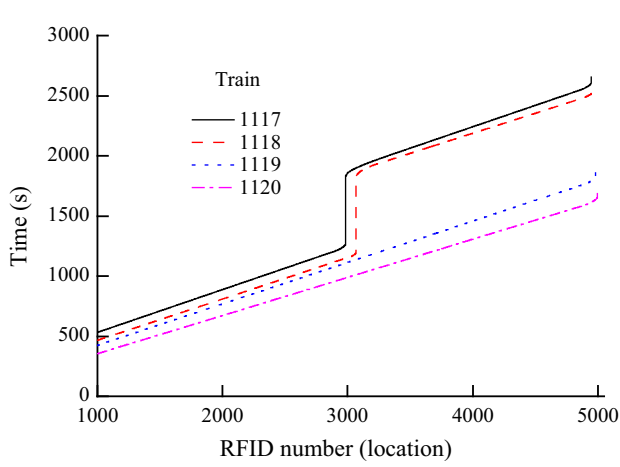


Fig. 10 Time versus location (Train partition fault)

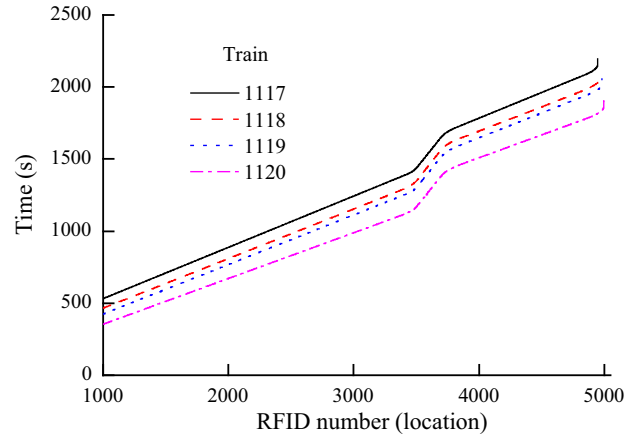


Fig. 12 Time versus location (Track fault with 10.0 m/s restricted speed)

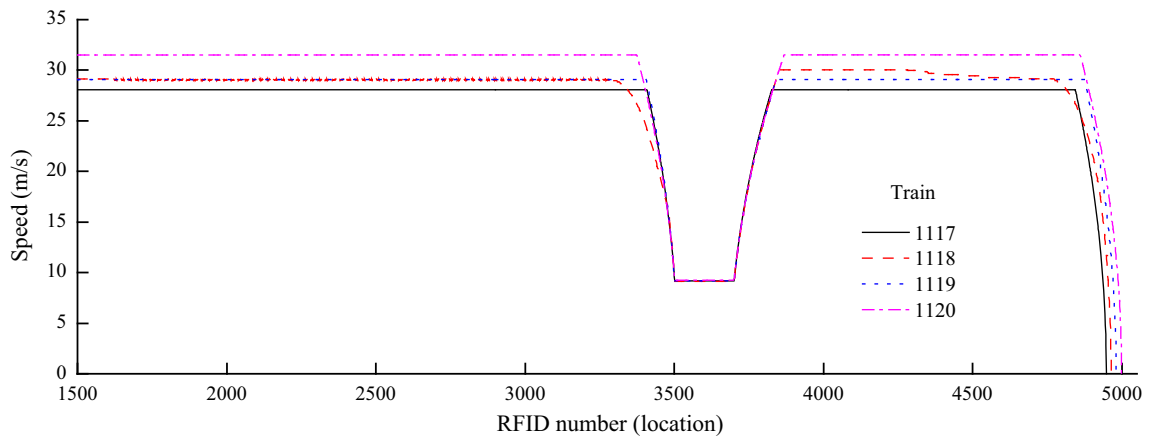


Fig. 11 Speed versus location (Track fault with 10.0 m/s restricted speed)

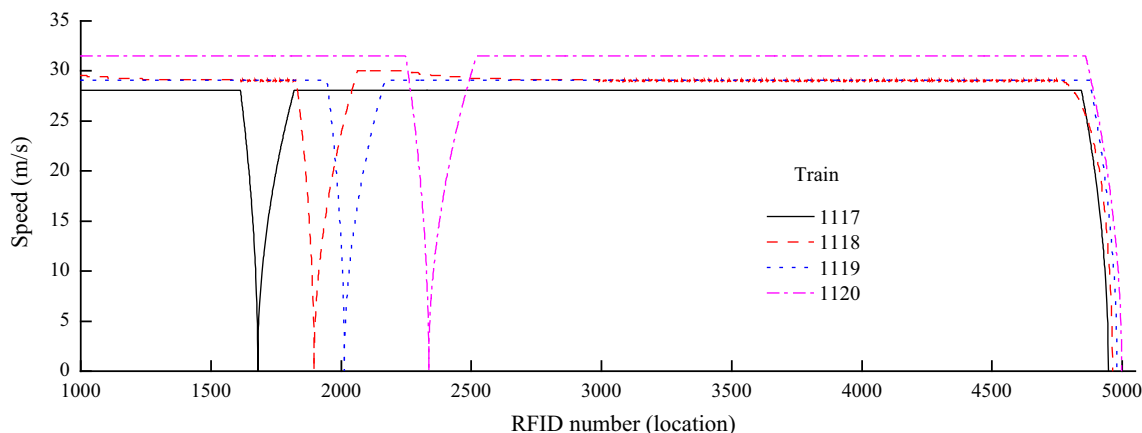


Fig. 13 Speed versus location (Communication fault)

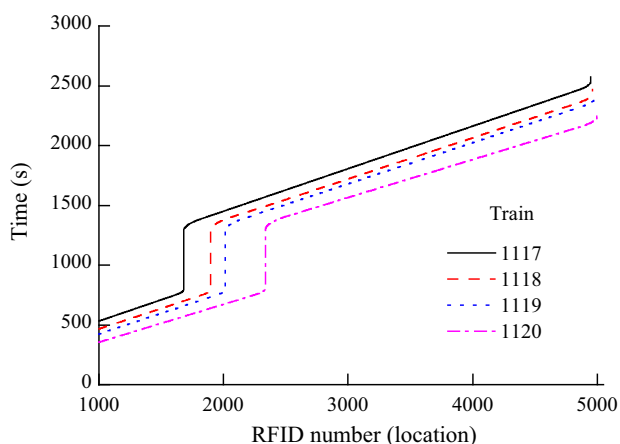


Fig. 14 Time versus location (Communication fault)

fault section. Finally, when trains stop at the end of the block section, the upward movement of their time curves (see Fig. 6) indicates that the trains have stopped.

5.1.2 Train equipment fault

Page *OBDC*A periodically sends a consistency report to *ZC* indicating the health status of train borne equipment. Pages *TFMA* and *ERSCA* of *MAPA* process the consistency report and an issue emergency brake command if a fault is detected. Equipment fault in train 1118 detected at location 2,750 (Fig. 7) causes page *MAPA* to command the application of emergency brakes. The train decelerates from its present speed of 29.5 m/s and finally stopped at tag 2,820. Trailing trains decelerate according to the moving authority received to maintain a safe braking distance from leading trains. The time curve of train 1118 going vertically straight (Fig. 8) at location 2,820 represents the fault rectification time (528.45 s). Time curves of trailing trains show that all trailing trains are stopped due to the fault on

the leading train. The increasing speed curves (starting at tag 2,820) indicate that the fault has been rectified and eventually all trains regain their normal speed.

5.1.3 Train partition fault

When a partition fault is detected, the trailing trains are not allowed to enter into the area between the locations where train partition was detected and its final halt point, until the parted coaches are coupled. The response of the system to partition faults is shown in Fig. 9. Pages *TPFMA* and *ERSCA* of *MAPA* detect the partition of train 1118 at location 3,001 and instruct to apply the emergency brake. Upon receiving moving authority, it starts deceleration from its present speed of 29.5 m/s and finally stops at location 3,071. The rear end’s parted coaches may be anywhere between the RFID tag 3,001 and 3,071. Trailing trains receive moving authority to stop prior to the location 3,001. The time curve of train 1118 going vertically straight (Fig. 10) at location 3,071 represents the fault rectification time (654.76 s). The results show that system is able to move trains safely even in train partition fault situations.

5.1.4 Track fault (restricted speed 10.0 m/s)

Trains are allowed to run at some restricted speed when a portion of the track is not healthy enough to support train run at normal speeds. Pages *TFMA* and *ORSCA* of *MAPA* deal with track faults to control speeds of trains according to the applicable speed restrictions. Figure 11 depicts a restricted speed region between location 3,501 and 3,700 where the trains are required to run at reduced speed of 10.0 m/s. The leading train 1120 running at speed 31.53 m/s decelerates at location 3,374 and reaches the restricted speed at location 3,501. After the restricted speed region,

Table 3 State space report

Statistics		
State space		
Nodes:	41,782	
Arcs:	161,171	
Secs:	300	
Status:	partial	
Scc graph		
Nodes:	41,782	
Arcs:	161,171	
Secs:	2	
Boundedness properties	Upper	Lower
Best integer bounds		
IRMS'A2T11 1	2	0
RMS'A2Z11 1	2	0
.....
Best upper multi-set bounds		
IRMS'A2T11 1 l'(51, 111, 2.236, 200.0, 1,(501, 510.0, 41.66, 10.0, 80,000.0, 26.4098)) ++		
l'(51, 112, 2.4083, 200.0, 1,(501, 510.0, 41.66, 10.0, 80,000.0, 28.5, 292)) ++		
l'(52, 111, 3.1622, 200.0, 1,(501, 520.0, 41.66, 10.0, 80,000.0, 32.8198)) ++		
l'(52, 112, 3.4058, 200.0, 1,(501, 520.0, 41.66, 10.0, 80,000.0, 37.058))		
.....		
Best lower multi-set bounds		
IRMS'A2T11 1	Empty	
IRMS'A2Z11 1	Empty	
.....		
Home properties		
Home markings		
Initial marking is not a home marking		
Liveness properties		
Dead markings		
2,628 [41,782, 41,781, 41,780, 41,779, 41,778,...]		
Dead transition instances		
ITPIA'm40 1		
MAPA1'Restart1 1		
STMA'm47 1		
TPFMA'm48 1		
TPFMA'm51 1		
TRMA'restart 1		
Live transition instances		
None		
Fairness properties		
No infinite occurrence sequences		

trains accelerate to their normal speed while maintaining safe braking distance between them. The time curves of the trains (Fig. 12) between location 3,501 and 3,700 show an upward trend, indicating trains running at restricted speed and taking more time to cross the restricted region in the track section.

5.1.5 Communication fault

Fault during communication in safety critical systems can be attributed to the message omissions, bit flips and timeliness of message arrivals. Scenarios arising out of these faults affect the safe movement of trains. Bit flip faults can be handled with the help of any message consistency check methods and are not considered here. If the train does not receive moving authority from ZC within a timeout, its OBDCA stops train by application of emergency brake. Figure 13 depicts communication failure between all trains and ZC for 550.0 s (at the simulation time 750.0 s). All trains decelerate as a result of emergency braking shown by the decreasing speed curves, and their corresponding stop locations indicate that the trains maintain safe distance. Trains accelerate when the communication is regained. The vertical straight part of the time curves (Fig. 14) of trains represents that the trains have stopped due to communication failure.

5.2 Verification

The state space report obtained from the model is analysed to check the correctness of the model and see if the model satisfies dynamic properties. Complex models with a large number of continuous variables generate large state space graph and report that is difficult to analyse. To arrive at a state space graph and report that is convenient to analyse, we reduced the number of trains from four to two and the track length from 50 km (5,000 RFID tags) to 1 km (100 RFID tags). Despite of this size reduction, the resulting state space graph was too large for visual analysis. Whereas, the size of state space report was relatively convenient in comparison state space graph. Therefore, the standard state space report for the reduced model (Table 3) is considered for verification.

The partial state space graph created 41,782 nodes and 161,171 arcs in 300 s of simulation run. The graph contains strongly connected components (SSC) equal to the state space nodes, implying that the model does not have any SSC with more than one node, and hence no infinite occurrence sequences. In other words, the execution of model terminates. The integer and multi-set bounds represent the maximum and minimum number of tokens and their values each place may contain. Due to the large quantity of places and tokens involved in the model, their

discussion is insignificant and not necessary. The initial marking of the model is not a home marking which means the initial marking is not reachable from all reachable markings. The model has 2,628 dead markings, indicating that there are 2,628 different ways to the model stopping. The model contains 6 dead transitions, meaning that these transitions were not enabled during the simulation run. Absences of the live transitions indicate the model termination. The fairness properties show how often the individual transitions occurred. As shown in the report, the model does not have any infinite occurrence sequences. The state space report gives a first rough idea about if the model works as expected and presents a number of useful information about its behaviour. A faulty model reflects errors in its state space report.

6 Conclusion

A CPN-based formal model of *moving authority given* sub-goal for block section is presented. The state space report verifies the model correctness in terms of the reachability, boundedness, liveness and home properties. Various fault scenarios have been modelled to make the behaviour analysis of the overall model. The outcome of the behavioural analysis allowed us to justify the design correctness of the proposed CBTC system for IR. The test of our models based on actual fault data collected over a period can help correlate the proposed models' behaviour with the present simulation results. Further, such actual data can be statistically modelled to understand the pattern of fault occurrence that may help IR to take preventive measures.

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References

1. Goundan PR, Jhunjhunwala A (1999) Axle counter based block signalling for safe and efficient train operations. In: Proceedings of the IEEE VTS 50th vehicular technology conference, 19–22 September 1999, Amsterdam, pp 824–828
2. Zhu L, Yu FR, Ning B, Tang T (2013) A novel communication-based train control (CBTC) system with cooperative wireless

- relaying. In: Proceedings of the IEEE international conference on communications, 9–13 June 2013, Budapest, pp 6422–6426
3. Lockyear MJ (1996) Changing track: moving-block railway signalling. *IEE Rev* 42(1):21–25
 4. Li S, Yan L, Xing H et al (2014) Enhanced robustness of control network for Chinese train control system level-3 (CTCS-3) facilitated by software-defined networking architecture. *Int J Rail Transp* 2(4):239–252
 5. Zambonelli F, Parunak HVD (2003) Signs of a revolution in computer science and software engineering. In: Petta P, Tolksdorf R, Zambonelli F (eds) *Engineering societies in the agents world III*. Lecture notes in computer science, vol 2577. Springer, Berlin
 6. Adler JL, Blue VJ (2002) A cooperative multi-agent transportation management and route guidance system. *Transp Res Part C* 10(5/6):433–454
 7. Khan MS, Benkrid K (2010) Development techniques of multi-agents based autonomous railway vehicles control systems. *Word Acad Sci Eng Technol* 48:558–568
 8. Proenca H, Oliveira E (2004) MARCS multi-agent railway control system. In: Lemaître C, Reyes C, González J (eds) *Advances in artificial intelligence-IBERAMIA*, vol 3315. Lecture notes in computer science, Springer, Berlin, pp 12–21
 9. Hu X, Zhou X, Dang J (2006) A designing method of simulation software for Chinese train control system based on hybrid software agent model. In: Proceedings of the 5th international conference on machine learning and cybernetics, 13–16 August 2006, Dalian, pp 148–153
 10. Tsang CW, Ho TK (2008) Optimal track access rights allocation for agent negotiation in an open railway market. *IEEE Transac Intell Transp Syst* 9(1):68–82
 11. Lind J, Fischer K, Bocker J, Zirkler B (1999) Transportation scheduling and simulation in a railroad scenario: A multi-agent approach. In: Kopfer H, Bierwirth C (eds) *Logistik management*. Springer, Berlin, pp 171–183
 12. Verma A, Pattanaik KK (2014) Mobile agent based train control system for mitigating meet conflict at turnout. *Proc Comput Sci* 32:317–324
 13. EURESCOM (2001) Project P907 - PIR5.1. Analysis of existing agent-oriented tools
 14. Bellifemine F, Poggi A, Rimassa G (1999) JADE-A FIPA-compliant agent framework. In: Proceedings of the 4th conference on the practical application of intelligent agents and multi-agent technology, London, pp 97–108
 15. Nwana HS, Ndumu DT, Lee LC, Collis JC (1999) ZEUS: a toolkit for building distributed multi-agent systems. *Appl Artif Intell J* 1(13):129–185
 16. Busetta P, Ronnquist R, Hodgson A, Lucas A (1999) JACK intelligent agents—components for intelligent agents in Java. *Agent link news* 2:2–5. DIALOG. <http://www.agentlink.org/newsletter/2/newsletter2.pdf>
 17. Jones CB (1990) *Systematic software development using VDM*, 2nd edn. Prentice-Hall Inc, Upper Saddle River
 18. Spivey JM (1989) *The Z notation: a reference manual*. Prentice-Hall Inc, Upper Saddle River
 19. Milner R (1989) *Communication and concurrency*. Prentice-Hall Inc, Upper Saddle River
 20. Bolognesi T, Brinksma H (1987) Introduction to the ISO specification language LOTOS. *Comput Netw ISDN Syst* 14(1):25–59
 21. Gabbay DM, Hodkinson I, Reynolds M (1994) *Temporal logic: mathematical foundations and computational aspects*. Clarendon Press, Oxford
 22. Hoare CAR (1985) *Communicating sequential processes*. Prentice Hall international series in computer science, Hemel Hempstead
 23. Wang J (2007) Petri nets for dynamic event-driven system modeling. In: Fishwick P (ed) *Handbook of dynamic system modeling*. Chapman and Hall/CRC Press, Boca Raton
 24. Jensen K (1996) *Coloured Petri Nets: basic concepts, analysis methods and practical use*, vol 1. Springer-Verlag, London
 25. Fernandes J, Belo O (1998) Modeling multi-agent systems through Coloured Petri Nets. In: Proceedings of the 16th IASTED international conference on applied informatics, Garmisch, 1–4 February 1998, pp 17–20
 26. Verma A, Pattanaik KK (2014) Multi-agent CBTC system for Indian railways: the structural design. *J Softw* 10(3):250–259
 27. Caire G, Coulier W, Garijo F et al (2002) Agent oriented analysis using MESSAGE/UML. In: Wooldridge MJ, Weiß G, Ciancarini P (eds) *Agent-oriented software engineering II*, vol 2222. Lecture notes in computer science, Springer, Berlin, pp 119–135
 28. Government of India, Ministry of Railways (2008) *General rules for Indian railways with subsidiary rules and special instructions*. India, South Central Railway
 29. Cost RS, Chen Y, Finin T, Labrou Y, Peng Y (1999) Modeling agent conversations with Coloured Petri Nets. In: Working notes of the workshop on specifying and implementing conversation policies, Autonomous agent 99, Seattle, Washington, May 1999, pp 59–66
 30. Duvigneau M, Moldt D, Rolke H (2003) Concurrent architecture for a multi-agent platform. In: Giunchiglia F, Odell J, Weiß G (eds) *Agent-oriented software engineering III*, lecture notes in computer science, vol 2585. Springer, Berlin, pp 59–72
 31. Moldt D, Wienberg F (1997) Multi-agent systems based on Coloured Petri Nets. In: Azéma P, Balbo G (eds) *Application and theory of Petri Nets*, lecture notes in computer science, vol 1248. Springer, Berlin, pp 82–101
 32. Ma B (2005) Modeling multi-agent systems with hierarchical Coloured Petri Nets. In: Li D, Wang B (eds) *Artificial intelligence applications and innovations, the international federation for information processing*, vol 187. Springer, Dallas, pp 167–171
 33. Verma A, Pattanaik KK, Goel PP (2014) Mobile agent based CBTC system with moving block signalling for Indian Railways. In: Proceedings of the 2nd international conference on railway technology: Research, development and maintenance, Ajaccio, Corsica, paper 278, 8–11 April 2014
 34. Choppy C, Petrucci L, Reggio G (2008) A modelling approach with Coloured Petri Nets. In: Kordon F, Vardanega T (eds) *Reliable software technologies*, lecture notes in computer science, vol 5026. Springer, Berlin, pp 73–86
 35. Aalst WMP, Odijk MA (1995) Analysis of railway stations by means of interval timed Coloured Petri nets. *Real-Time Syst* 9(3):241–263
 36. Vanit-Anunchai S (2010) Modelling railway interlocking tables using Coloured Petri Nets. In: Clarke D, Agha G (eds) *Coordination models and languages*, lecture notes in computer science, vol 6116. Springer, Berlin, pp 137–151
 37. Vanit-Anunchai S (2010) Verification of railway interlocking tables using Coloured Petri Nets. In: Dave C, Gul A (eds) Proceedings of the 12th international conference on modeling and languages, 7–9 June 2010. Springer, Berlin, pp 137–151
 38. Dhahbi S, Abbas-turki A, Hayat S et al (2011) Study of the high-speed trains positioning system: European signalling system ERTMS/ETCS. In: Proceedings of the 4th international conference on logistics, 1–3 June 2011, Hammamet, pp 468–473
 39. Chen L, Ning B, Xu T (2007) Research on modeling and simulation of vehicle-on-board automatic train protection subsystem of communication based train control system. In: Proceedings of the IEEE international conference on vehicular electronics and safety, 13–15 December 2007, Beijing, pp 1–5