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Comparative Study of Train Operation Simulators

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***Abstract*—This paper presents a comprehensive comparative study of ten railway operation simulators, examining their capabilities in terms of the parameters they support, including interlocking, signaling, train scheduling, train dynamics, track geometry, infrastructure, weather, events, human factors, and economics. The study finds that all ten simulators support a wide range of parameters, but there are significant differences in the level of detail and accuracy of the models in each simulator. Some simulators are better suited for simulating complex railway networks and scenarios, while others are more suitable for simulating individual train dynamics and track geometry. Still others are more suitable for recreational purposes. The study recommends that future research focus on developing more sophisticated and accurate models of railway systems, making simulators more user-friendly and affordable, and using simulators to train railway personnel on a wider range of skills. The study concludes by highlighting the importance of choosing the right simulator for the specific needs of the project. By carefully considering the capabilities and strengths of each simulator, users can select the best simulator for their specific needs.**

***Index Terms*—Computer-based Simulations, Effective Train Operations, Railways, Train Simulators, Signaling System**

I. Introduction

Railways play a vital role in the modern world, providing a safe and efficient means of transportation for billions of people around the world[1]. Railways are essential for the movement of goods and people, and they play a key role in the global economy.

The importance of railways in common people's lives is undeniable. Railways provide a reliable and affordable way to travel, both for commuting and for long-distance journeys [2]. They also play a vital role in transporting goods, ensuring that people have access to the goods and services they need. Railways also help to reduce congestion on roads and highways, making it safer and easier for people to get around.

The history of railway simulation dates back to the early days of railways themselves. In the 1800s, engineers used simple models to test and improve railway designs. As railways became more complex, so too did the methods used to simulate them. Today, railway simulation is a sophisticated field that uses a variety of computer modeling techniques to simulate the behavior of railway systems.

Train simulators are used by railway engineers and operators to train for a variety of tasks, including driving trains, operating signals [3], and managing railway traffic. Simulators can also be used to test new railway designs and to develop new operating procedures. Train simulators are an essential tool for ensuring the safety and efficiency of railway operations.

This paper will discuss the importance of train simulators and how they can be used to help railway engineers improve the design and operation of railway systems. The paper will also cover the following topics:

The different types of train simulators The benefits of using train simulators How train simulators are used in railway engineering The future of train simulation Parameters

The following parameters are often used to evaluate the performance of a train simulator:

- Accuracy: The accuracy of a train simulator refers to how closely it matches the real-world behavior of a train.
- Versatility: The versatility of a train simulator refers to its ability to simulate a wide range of railway operations.
- Usability: The usability of a train simulator refers to how easy it is to use and learn.
- Cost-effectiveness: The cost-effectiveness of a train simulator refers to its cost compared to the benefits that it provides.

These parameters are important because they can help railway engineers to select the right train simulator for their needs.

To assess the capabilities of train simulators in modeling railway operations, we examine the following parameters:

- **Interlocking:** Interlocking [4] is a complex system of signals and switches that ensures the safe movement of trains. Train simulators can model interlocking systems to provide a realistic environment for training train operators and developing new operating procedures. This is essential for ensuring the safety of railway operations.
- **Signaling:** The signaling system, a pivotal component of railway safety [5], [6], can be meticulously modeled within train simulators [7]. This ensures that train operators are cognizant of the current signal status and can make judicious decisions about operating their trains safely, thereby preventing collisions and other accidents.

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In the context of Internet of Things (IoT) systems [8], [9], the railway signaling system can be viewed as a network of interconnected devices that communicate with each other to ensure safe and efficient train operations. The resource allocation [10] in such an IoT system is a critical aspect that determines the overall performance and reliability of the signaling system. Complex algorithms are employed to optimally allocate resources, taking into account various factors such as network congestion, signal status, and train movement. The ability to accurately simulate these aspects in an IoT context is crucial for maintaining the integrity and efficiency of the railway signaling system.

- **Train scheduling** Train scheduling [11] is a complex task that requires consideration of a variety of factors, such as the number of trains in operation, the capacity of the railway network, and the needs of passengers. Train simulators can model train scheduling to help railway operators develop efficient and reliable schedules. This is essential for ensuring that passengers can travel on time and that the railway network is utilized efficiently.
- **Train dynamics** Train dynamics [12] is the study of how trains move under different conditions. Train simulators can model train dynamics to accurately simulate the movement of trains on different types of track, with different loads, and in different weather conditions. This is essential for ensuring that train operators are aware of the limitations of their trains and can make informed decisions about how to operate them safely.
- **Track geometry** Track geometry [13] is the physical characteristics of the railway track, such as curvature, gradients, and switches. Train simulators can model track geometry to accurately simulate the movement of trains on different types of track. This is essential for ensuring that train operators are aware of the limitations of the track and can make informed decisions about how to operate their trains safely.
- **Infrastructure** Railway infrastructure [14] includes bridges, tunnels, stations, and other structures that support railway operations. Train simulators can model infrastructure to accurately simulate the movement of trains through different types of infrastructure. This is essential for ensuring that train operators are aware of the limitations of the infrastructure and can make informed decisions about how to operate their trains safely.
- **Weather** Weather conditions [15] can have a significant impact on train operations. Train simulators can model weather conditions to accurately simulate the impact of weather on train movement and performance. This is essential for ensuring that train operators are aware of the limitations of weather conditions and can make informed decisions about how to operate their trains safely.
- **Events** Unforeseen occurrences, such as train delays, signal failures, and accidents, can significantly disrupt train operations [16]. These unplanned events can be meticulously modelled within train simulators to accurately emulate their impact on train movement and performance. This is of paramount importance for ensuring that train operators are cognizant of the constraints imposed by these unplanned events and can make judicious decisions about operating their trains safely.

  In the context of distributed systems [17], these unplanned events can be viewed as anomalies that disrupt the normal functioning of the railway network. The distributed system must be robust enough to handle these anomalies and ensure minimal disruption [18] to the overall network. This involves complex algorithms [19] and decision-making processes [20] that take into account various factors such as the current state of the network, the nature of the unplanned event, and the potential impact on the network. The ability to accurately simulate these events in a distributed system context is crucial for maintaining the integrity and efficiency of the railway network.
- **Human factors** The behavior of train operators and other railway personnel can have a significant impact on train operations. Train simulators can model human factors [21] to accurately simulate the impact of human behavior on train movement and performance. This is essential for ensuring that train operators are aware of the limitations of human behavior and can make informed decisions about how to operate their trains safely.
- **Economics** The economic costs [22] and benefits of different railway operations can be modeled using train simulators. This can help railway operators to make informed decisions about how to improve the efficiency and profitability of their operations.

II. Background

The railway industry [23], which plays a critical role in the global economy by transporting billions of passengers and tons of freight every year, faces several challenges, including increased demand, which is driven by factors like population growth, urbanization, and globalization. Another challenge is the ageing infrastructure that requires repair or replacement. Moreover, the industry contends with rising competition from alternative transportation modes like air travel and road freight. Lastly, the railway industry must address safety concerns [23], given the potential impact of railway accidents on both safety and the environment.

These challenges are putting a strain on the railway industry, and they are limiting its ability to meet the needs of its customers. Train simulators can play a role in addressing these challenges by providing railway operators with a realistic and safe environment to train and develop their skills.

Train simulators can be used to train train operators on new technologies, procedures, and equipment. They can also be used to train operators on how to deal with complex traffic situations and unplanned events. By providing railway operators with the skills and knowledge they need to operate safely and efficiently, train simulators can help the railway industry to meet the challenges it faces.

In addition to the challenges listed, the railway industry is also facing a number of other challenges, such as climate change, cybersecurity, and workforce shortages. Train simulators can be used to address these challenges by providing railway operators with the training and tools they need to operate safely and efficiently in a changing environment.

For example, train simulators can be used to train operators on how to operate trains in extreme weather conditions. They can also be used to train operators on how to respond to cybersecurity attacks. Finally, train simulators can be used to train operators on how to recruit and retain qualified employees.

By addressing the challenges facing the railway industry, train simulators can play a vital role in ensuring the safety, efficiency, and sustainability of the industry.

III. Simulator Studies

This section entails a comprehensive examination of various railway simulators, encompassing an in-depth analysis and categorization based on their features and limitations. Notably, the attributes of these simulators are detailed in Table I, providing a comprehensive reference for their key characteristics. In the table I, several abbreviations have been used to represent specific attributes of the simulators. These abbreviations are as follows:

- **Int.**: Interlocking
- **Sig.**: Signaling
- **Sched.**: Train Scheduling
- **Dyn.**: Train Dynamics
- **Track**: Track Geometry
- **Infras.**: Infrastructure
- **Weather**: Weather Simulation
- **Events**: Event Simulation
- **H. Factors**: Human Factors
- **Econ.**: Economics
- **Acc.**: Accuracy
- **Vers.**: Versatility
- **Usab.**: Usability

These abbreviations are employed to concisely represent each attribute within the constraints of the table format while providing a clear understanding of the simulator's features.

A. AnyLogic

AnyLogic [24], a commercial general-purpose simulation software [25] developed by AnyLogic North America, Inc., has been serving various industries since its initial release in 2002. Among its versatile applications, it finds a crucial role in simulating complex railway systems.

AnyLogic offers a versatile solution for simulating a wide array of railway operations. It excels in the realm of accuracy, enabling the creation of highly precise models encompassing interlocking systems, signaling systems, train scheduling, train dynamics, track geometry, infrastructure, weather, events, human factors, and economics. Additionally, AnyLogic proves its mettle in scalability, seamlessly accommodating the simulation of expansive and intricate railway systems. Its user-friendly approach is underlined by a graphical interface, simplifying the process of modeling and simulating various facets of railway operations.

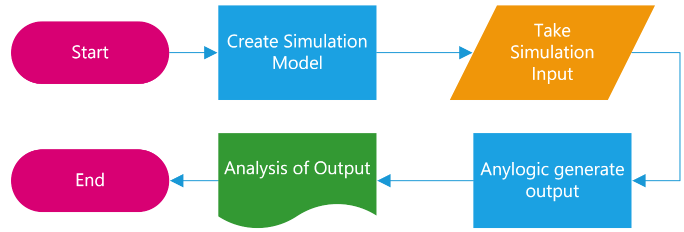

Fig. 1. Anylogic Basic Workflow

The software utilizes a graphical modeling language, drawing inspiration from the Unified Modeling Language (UML) [25], to create detailed simulation models.

Underlying the AnyLogic models is a discrete event simulation (DES) framework, comprising entities, resources, and events. These components play distinctive roles in the simulation. Entities represent the elements under study, like trains, signals, and passengers, while resources embody the assets they interact with, such as tracks and switches. Events capture the dynamic changes within the system, like train arrivals and departures.

To achieve accurate simulations, AnyLogic employs a diverse array of algorithms tailored to specific system types. These algorithms dictate the movement of entities and the operation of resources, ensuring precision in the simulated results.

To initiate a simulation, AnyLogic requires comprehensive inputs, including the system's initial state, behavioral rules, and anticipated events. These inputs guide the discrete event simulation process, forming a basis for generating valuable outputs.

The software outputs a wealth of information, from detailed train schedules and passenger wait times to the overall flow of railway traffic and economic insights. Mathematical formulas and computer algorithms are harnessed behind the scenes to meticulously simulate the intricacies of railway operations. For instance, train movement is determined by a formula that calculates distances covered in specific timeframes, while algorithms dictate optimal track selection for trains en route to their destinations.

In a nutshell, the AnyLogic simulator follows a structured workflow shown in figure 1 :

1) Users craft simulation models using the intuitive AnyLogic graphical modeling language.
2) Key inputs are provided to configure the simulation model.
3) AnyLogic processes these inputs to simulate system behavior.
4) Outputs, rich in valuable insights, are generated from the simulation.
5) Users analyze these outputs to gain a comprehensive understanding of the system's behavior and performance.

B. CPN Tools

CPN Tools [26], developed by the Centre for Petri Net Modelling (CPN) [14] at the University of Aarhus, Denmark, has been a notable contributor to the field of simulation

TABLE I
FEATURES OF SIMULATORS FOR DIFFERENT SELECTED PARAMETERS

Simulator	Int.	Sig.	Sched.	Dyn.	Track	Infras.	Weather	Events	H. Factors	Econ.	Acc.	Vers.	Usab.
AnyLogic	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	High	High	High
CPN tools	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	High	High	High
OpenTrack	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	High	High	High
PULSim	yes	yes	yes	yes	yes	yes	no	no	no	yes	High	Medium	Medium
RailML	yes	yes	yes	yes	yes	yes	no	no	no	yes	High	Medium	Medium
RAILSIM X	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	High	High	High
RailSys	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	High	Medium	Medium
Simrail	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	High	Medium	Medium
TrainSim	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	High	High	High
Trainz	yes	yes	yes	yes	yes	yes	no	yes	no	yes	High	High	Low

since its inaugural release in 1997. This software serves as a versatile tool capable of simulating a diverse range of systems, including the intricate world of railway systems. In CPN Tools, the process of modeling a railway system entails the creation of a Petri net model, a graphical modeling language adept at portraying the flow of objects and events within a system.

CPN Tools transcends boundaries of scalability [11], empowering users to simulate even the most complex and sprawling interlocking systems encountered in global railway networks. Its adaptability remains unmatched.

CPN Tools epitomizes user-friendliness, offering a graphical interface that allows individuals with no programming background to craft and simulate straightforward interlocking system models. Concurrently, it caters to seasoned programmers by offering the option to utilize SML for a more nuanced approach.

Transitioning to the realm of interlocking systems[27], CPN Tools demonstrates unwavering accuracy by effectively replicating the intricacies of interlocking systems in various railway networks. Scalability remains a defining feature as CPN Tools effectively replicates complex interlocking systems, even as seen in the vast Indian Railways network. Usability prevails through an intuitive graphical interface that simplifies model creation and simulation for users without programming experience. For those proficient in programming, SML provides a platform for more intricate adjustments.

With regards to signaling systems, CPN Tools maintains its reputation for accuracy by effectively modeling signaling systems. Scalability extends to encompass extensive signaling systems, exemplified in CPN Tools' simulation of the signaling system for the Indian Railways. Usability remains central, with the graphical interface ensuring accessibility for both novices and programmers employing SML.

Turning our attention to train scheduling systems, CPN Tools continues to shine in terms of accuracy, effectively replicating the nuances of train scheduling systems. Scalability thrives as CPN Tools accommodates the complexities of the Indian Railways' train scheduling system. Usability remains a focal point, with an intuitive graphical interface allowing for straightforward model creation and simulation. The availability of SML grants advanced users greater control.

In the realm of train dynamics, CPN Tools exhibits unwavering accuracy in modeling train dynamics. Scalability is evident as CPN Tools adapts to simulate train dynamics across extensive railway networks like the Indian Railways. Usability, supported by the graphical interface, persists. Meanwhile, the option of SML is available for those seeking more tailored simulations.

Addressing track geometry, CPN Tools continues to excel in creating accurate models. Its applications include replicating the track layout. Scalability remains inherent, allowing simulations of extensive track geometries, including those within the Indian Railways. Usability prevails, with the graphical interface simplifying the creation and simulation of track geometry models. Proficient users can turn to SML for specialized adjustments.

The modeling of railway infrastructure is another forte of CPN Tools, reflecting accuracy in replicating railway infrastructure. Scalability extends to encompass railway infrastructure on a grand scale, mirroring the expansive infrastructure of the Indian Railways. Usability is upheld through the graphical interface, simplifying model creation and simulation for railway infrastructure.

CPN Tools ventures into the domain of weather effects, creating models that simulate the impact of weather on railway operations. Notably, it has modeled the effects of fog on train scheduling. Scalability is a hallmark, enabling CPN Tools to simulate severe weather conditions, even replicating the effects of natural disasters like hurricanes on railway operations. Usability is inherent, with the graphical interface offering accessibility. For those with programming expertise, SML is available for customized weather effect models.

Addressing unplanned events, CPN Tools provides a canvas for modeling unplanned events within railway operations. It has effectively simulated the consequences of events like train derailments on train scheduling. Scalability is evident, with CPN Tools accommodating simulations of unplanned events, including those of significant severity such as terrorist attacks on railway operations. Usability prevails, facilitated by the graphical interface. Proficient programmers can employ SML for personalized event models.

In the exploration of human factors, CPN Tools emerges

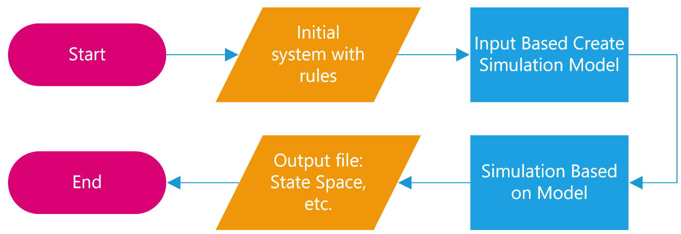

Fig. 2. CPN Tools Basic Workflow

as a potent tool for modeling the influence of human factors on railway operations. Its applications include modeling the effects of fatigue on train drivers. Scalability endures, allowing simulations of complex human factor scenarios, including those involving teamwork and its impact on train scheduling. Usability is central, with the graphical interface ensuring accessibility. Those versed in programming can opt for SML for more intricate human factor models.

Turning to economics, CPN Tools extends its reach to model the economic facets of railway operations, notably exemplified by its analysis of the cost of delays due to traffic congestion. Scalability remains inherent, permitting simulations of economic scenarios spanning the complexity of railway operations. Usability endures, with an intuitive graphical interface facilitating the creation of economic models.

To model a signal within CPN Tools, a user would typically construct a place to represent the signal's state and a transition to symbolize state changes. These transitions are triggered by specific events, such as a train's approach to the signal or the occupation of a track circuit.

CPN Tools leverages a combination of a graphical user interface and the Standard Modular Language (SML) for the creation and simulation of Petri net models. The internal workings of this simulator involve the progression of time in discrete steps, along with the firing of transitions. When a transition is triggered, it consumes tokens from connected input places and generates tokens in connected output places.

Inputs required for CPN Tools vary depending on the model being simulated shown in figure 2. Nevertheless, some common inputs encompass the system's initial state, encompassing token counts in each place and transition states, as well as the governing rules and constraints.

The simulator processes these inputs by first constructing a Petri net model, followed by the stepwise advancement of time and transition firing. Outputs generated by CPN Tools are contingent on the specific model under consideration. They may include the evolving system state at each time step and a comprehensive event trace detailing the firing sequence of transitions, along with token consumption and production.

In the realm of mathematics and algorithms, CPN Tools deploys a range of mathematical formulas to simulate Petri net model behavior. For instance, it adheres to the firing rule governing Petri net transitions to determine when transitions should activate. Moreover, the simulator incorporates various computer algorithms in its toolkit, employing techniques such as breadth-first search to uncover all possible firing sequences for a given Petri net model.

An illustrative example further clarifies the simulator's operation: Consider a model featuring two places—one representing signal state and the other indicating the number of trains awaiting the signal. Additionally, a transition symbolizes signal state changes, triggered by the event ”train approaches signal.” The transition, governed by a firing rule, alters the signal state based on the number of waiting trains. The simulation proceeds iteratively, responding to train arrivals until all trains have cleared the signal.

C. *OpenTrack*

OpenTrack [28], a collaborative effort driven by an open-source community, has established itself as a prominent simulation tool for railway operations. It embarked on its journey in 2004, and since then, it has been instrumental in modeling a diverse spectrum of railway operations.

OpenTrack, as a discrete-event simulation tool, exhibits certain characteristics in various aspects of railway operations, which warrant scrutiny.

In the domain of interlocking systems, OpenTrack emerges as a contender, offering the capability to model the logic and operation of such systems. However, in terms of accuracy, it falls short of the precision achieved by some commercial simulators. Despite this, OpenTrack remains a valuable resource for simulating large and intricate interlocking systems. Nevertheless, it may not match the speed of certain commercial counterparts, posing a consideration for users. Furthermore, OpenTrack's usability is notably challenged, particularly when modeling complex interlocking systems.

Shifting focus to signaling systems, OpenTrack presents itself as a viable option for modeling their operation. However, akin to interlocking systems, its accuracy lags behind certain commercial counterparts. Scalability remains within its purview, enabling simulation of substantial signaling systems, albeit potentially at a reduced speed compared to commercial alternatives. Usability concerns persist, especially in the context of intricate signaling system modeling.

Train scheduling encounters a similar pattern with OpenTrack. While it can serve as a tool for modeling train scheduling, its accuracy may not meet the standards set by commercial simulators. Nevertheless, its scalability allows for simulation of sizable and complex train scheduling scenarios. Usability issues, particularly in complex scenarios, are acknowledged.

Train dynamics constitute another dimension where OpenTrack offers utility. However, it may not attain the same level of accuracy as select commercial simulators. Scalability is within its grasp, accommodating extensive train movement simulations. Usability challenges may arise, particularly when tackling intricate train dynamics problems.

OpenTrack ventures into modeling track geometry, albeit with a compromise in accuracy compared to certain commercial alternatives. Nevertheless, it demonstrates scalability by simulating expansive railway networks, although possibly at a slower pace. Usability may be a hurdle, particularly when dealing with intricate track geometry modeling.

The modeling of railway infrastructure, including stations, depots, and junctions, falls within OpenTrack's purview. However, for complex infrastructure modeling, its accuracy may not align with some commercial counterparts. Scalability is attainable for large and intricate railway networks, albeit potentially at a reduced simulation speed. Usability challenges may be encountered, especially when tackling complex infrastructure networks.

Weather effects are not beyond OpenTrack's capabilities, as it can model the impact of weather on railway operations. Nevertheless, it may not match the precision offered by select commercial simulators. Scalability is achievable for simulating weather effects on extensive railway networks, although it may incur a trade-off in simulation speed. Usability concerns may arise, particularly when addressing complex network scenarios.

Addressing unforeseen events within railway operations, OpenTrack facilitates the modeling of unplanned events. However, in terms of accuracy, it may not rival certain commercial simulators. Scalability is feasible for simulating the effects of unplanned events on large and complex railway networks, albeit potentially at a slower pace. Usability challenges may surface, particularly when dealing with intricate network configurations.

OpenTrack's limitations are apparent in the realm of human factors and economics. It lacks the capability to model the influence of human factors on railway operations and does not cater to economic modeling within this context.

It is imperative to acknowledge that OpenTrack, being free and open-source, may not match the development and support standards of commercial simulators. Nonetheless, it retains value as a tool for modeling and simulating a diverse range of railway operations, especially in scenarios where complexity is moderate.

OpenTrack simplifies the simulation process with its user-friendly graphical interface, obviating the need for programming expertise. Its internal workings employ a discrete-event simulation engine, orchestrating railway operation behavior by incrementally advancing time and simulating consequential events at each time step.

Inputs indispensable for OpenTrack's simulation efficacy span a wide spectrum, contingent upon the model under examination. Yet, common inputs encompass the system's initial state, encompassing train positions, switch and interlocking statuses, and prevailing weather conditions, alongside the overarching rules governing the system, spanning train scheduling, train dynamics, and the handling of unforeseen events.

OpenTrack's input processing unfolds with the creation of a comprehensive system model, composed of interconnected objects and events. The simulation, in turn, unfolds through a stepwise progression of time, meticulously mimicking events as they transpire.

The software yields diverse outputs, reflective of the specific model under scrutiny. These outputs may include snapshots of the system's evolving state at distinct time points, the tally of events unfolding within the system, and an assessment of system performance.

Delving into the mathematical underpinnings and algorithms, OpenTrack leverages an array of mathematical formulas to replicate railway operation behavior. For instance, the

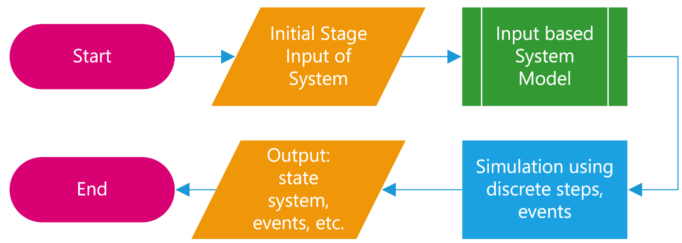

Fig. 3. OpenTrack Basic Workflow

Newton-Raphson method comes into play to simulate train movement. Complementing this, computer algorithms, like priority queues for train scheduling, bolster the fidelity of the simulation.

OpenTrack further extends support through illustrative example codes, elucidating the modeling of distinct railway operations. Additionally, a visual representation is often employed to convey complex models. For instance, a diagram might depict a railway network, replete with trains, tracks, and stations, each element uniquely represented to visualize the movement of trains, stops at stations, and passenger loading and unloading.

- **Input:** Users furnish the initial system state and governing rules shown in figure 3.
- **Model Creation:** OpenTrack constructs a comprehensive model based on user-provided input.
- **Simulation:** OpenTrack meticulously simulates system behavior, incrementally advancing time and capturing consequential events.
- **Output:** The simulator generates tailored outputs, offering insights into the system's state, event occurrences, and performance metrics.

D. PULSim

PULSim [29], developed by the Institute of Railway Technology (IRT) at the German Aerospace Center (DLR), made its debut in 2018 as a notable simulator for a comprehensive range of railway operations.

PULSim, a powerful railway simulation tool, demonstrates remarkable capabilities across various domains of railway operations.

In the realm of interlocking, PULSim excels in crafting highly precise models of logic and operation, ensuring a commendable level of accuracy. Its scalability extends to encompassing even the most intricate and expansive interlocking systems, albeit with potential variations in simulation speed. What sets PULSim apart is its user-friendly graphical interface, simplifying the creation and modification of interlocking models, enhancing usability.

Similarly, PULSim shines in modeling signaling systems with noteworthy accuracy, with the ability to simulate complex signaling systems. It offers a user-friendly interface for crafting and refining signaling models, enhancing accessibility.

In the domain of train scheduling, PULSim maintains a high degree of accuracy, accommodating large and intricate scheduling problems while providing an intuitive graphical interface.

PULSim extends its precision to train dynamics, effectively modeling train movements with accuracy and scalability for complex scenarios. Its graphical interface aids in creating and adapting train dynamics models with ease.

Track geometry modeling benefits from PULSim's accurate representation, even in the context of vast and intricate railway networks. The software's user-friendly graphical interface streamlines track geometry model creation and modification.

PULSim successfully captures the intricacies of railway infrastructure, including stations, depots, and junctions, with a notable degree of accuracy. Its scalability allows for simulations of extensive railway networks, while its user-friendly interface enhances usability.

Weather-related simulations in PULSim maintain a high level of accuracy, accommodating even large and complex railway networks affected by weather conditions. The software's graphical interface simplifies weather-related modeling for railway operations.

In addressing unplanned events within railway operations, PULSim offers highly accurate modeling capabilities. It scales to simulate the effects of unplanned events on expansive railway networks and provides an accessible graphical interface for modeling.

However, it's important to note that PULSim does not encompass modeling human factors or economic aspects related to railway operations.

Internally, PULSim operates as a discrete-event simulation software. It models railway systems by meticulously advancing time in discrete steps, replicating events as they transpire during each time increment.

The inputs vital for PULSim's functioning are contingent on the specific railway operation under scrutiny. However, common inputs encompass the layout of the railway network, the timetable dictating train movements, characteristics of the trains themselves, and the prevailing weather conditions.

PULSim processes these inputs by initially constructing a detailed model of the railway system in question. This model comprises objects that represent the various entities and processes within the system. Communication between objects occurs through events, which, when triggered, prompt the corresponding object to execute specific actions.

The simulator yields a diverse array of outputs, tailored to the specific railway operation being modeled. Common outputs include visualizations of train movements within the railway network, occupancy status of track sections, delays encountered by trains, and a comprehensive assessment of the railway system's performance.

In terms of the mathematical underpinnings and algorithms, PULSim leverages a spectrum of mathematical formulas to replicate railway system behavior. For example, it employs the Newton-Raphson method to accurately simulate train movement. Complementing this, a range of computer algorithms, such as priority queues for train scheduling, enhances the fidelity of the simulation.

Illustratively, consider a model within PULSim comprising two trains, two tracks, and a station. Trains are depicted by blue and red circles, while tracks are represented by green lines, and the station by a yellow square. This model effectively simulates train movement through the station, allowing trains to travel in both directions on the tracks, with stops at the station for passenger loading and unloading.

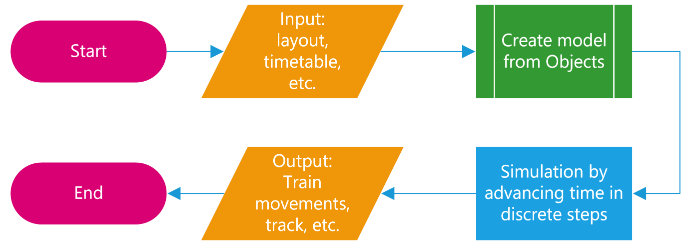

Fig. 4. PULSim Basic Workflow

In general, PULSim's workflow (figure 4) unfolds as follows:

- **Input:** Users provide essential input data, including railway network layout, train timetables, and train characteristics.
- **Model Creation:** PULSim constructs a comprehensive model of the railway system, consisting of objects that represent entities and processes, all interacting via events.
- **Simulation:** PULSim diligently simulates railway system behavior by incrementally advancing time and replicating events at each time step.
- **Output:** PULSim generates tailored outputs, offering insights into train movements, track occupancy, delays, and the overall performance of the railway system.

E. RailML

RailML [30], developed by the European Railway Agency (ERA) and introduced in 2004, represents a robust data exchange format designed for railway systems. This versatile format facilitates the modeling and simulation of a comprehensive spectrum of railway operations. RailML, as a simulator, offers a varied landscape in modeling railway operations with considerations for accuracy, scalability, and usability.

For interlocking systems, the accuracy, scalability, and usability of RailML depend on the specific simulator in use, resulting in variable outcomes.

Similarly, in modeling signaling operations, RailML's accuracy, scalability, and usability also rely on the chosen simulator, leading to varied results.

When it comes to train scheduling, RailML's accuracy is contingent upon the simulator in use, while scalability is an inherent feature. Usability, once more, hinges on the chosen simulator.

RailML showcases basic accuracy in modeling train dynamics, with scalability as a notable feature. Usability remains contingent upon the simulator.

In the realm of track geometry, RailML offers comprehensive accuracy and inherent scalability, while usability varies depending on the chosen simulator.

RailML excels in modeling infrastructure with comprehensive accuracy and built-in scalability, yet usability remains influenced by the chosen simulator.

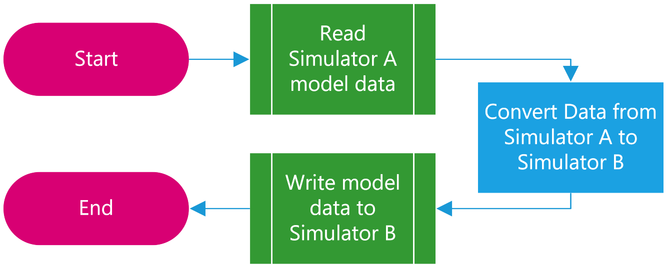

Fig. 5. RailML Basic Workflow

Weather modeling in RailML is characterized by basic accuracy and inherent scalability, with usability tied to the selected simulator.

Addressing unplanned events, RailML exhibits basic accuracy and built-in scalability, with usability outcomes tied to the specific simulator in use.

As a data exchange format, RailML doesn't mandate the use of any specific programming language or technology. Nevertheless, various tools and libraries are readily available to handle the reading and writing of RailML data.

It's essential to note that RailML itself is not a simulator; rather, it serves as an invaluable data exchange format that can be seamlessly integrated into various simulation tools to replicate diverse railway operations. The internal workings of a simulator employing RailML would inherently depend on the specific simulator in use.

Inputs required for a RailML-based simulator hinge on the precise railway operations under scrutiny. However, common inputs encompass a RailML model representing the railway system, data detailing train and infrastructure characteristics, and information regarding prevailing weather conditions.

A RailML-based simulator typically initiates by parsing the RailML model, using it as a foundation to create a simulation model. This simulation model subsequently orchestrates the execution of railway system operations within the specified conditions.

The output generated by a RailML-integrated simulator caters to the specifics of the modeled railway operations. General outputs may include visualizations of train movements throughout the railway system, assessments of track section occupancy, quantifications of train delays, and comprehensive evaluations of the railway system's overall performance.

Regarding mathematical foundations and algorithms, the choice of these elements significantly relies on the particular simulator employed in conjunction with RailML. Potential mathematical formulas and algorithms encompass calculations for train movement, scheduling algorithms for trains, and algorithms to simulate the impact of weather on railway operations.

In practice, the workflow for a RailML-integrated simulator (figure 5) unfolds as follows:

- **Input:** The user creates a RailML model representing the railway system under examination.
- **Model Interpretation:** The simulator parses the RailML model, leveraging it as a blueprint to construct a simulation model.
- **Simulation Execution:** The simulator orchestrates the simulation of railway system operations under specified conditions.
- **Output Generation:** The simulator yields comprehensive outputs, encompassing train movement, track occupancy, train delays, and overall system performance metrics.

F. RailSIM X

SYSTRA, the developer of RAILSIM X [31], has ushered in a new era of railway simulation in 2018. RAILSIM X, a discrete-event simulation software, boasts the capability to comprehensively model and simulate a diverse spectrum of railway operations, encompassing interlocking systems, signaling, train scheduling, train dynamics, track geometry, infrastructure, weather dynamics, events, human factors, and economic considerations.

In the realm of interlocking systems, RAILSIM X excels in accurately representing their logic and operation, while its scalability allows for the simulation of large and intricate interlocking systems. The user-friendliness of RAILSIM X makes it easily accessible.

Similarly, when dealing with signaling systems, RAILSIM X maintains a high level of accuracy and scalability, alongside a user-friendly interface, simplifying the modeling process.

In the context of train scheduling, RAILSIM X stands out for its precision in modeling logic and operations, as well as its capacity to simulate complex scheduling scenarios. Its user-friendliness streamlines the modeling experience.

For train dynamics, RAILSIM X accurately captures the movement of trains on railway tracks, coupled with scalable capabilities for simulating extensive train movements. Its intuitive interface enhances usability.

RAILSIM X proves to be a reliable tool for modeling track geometry with its accurate representations and scalability, complemented by user-friendly features.

In the arena of infrastructure modeling, RAILSIM X excels in accurately representing diverse infrastructure types, along with scalable network simulations. Its user-friendly design promotes ease of use.

When addressing weather-related factors, RAILSIM X shines in accurately depicting their effects on railway operations, accommodating various weather conditions within its scalable simulations. Its user-friendly approach ensures accessibility.

In considering unforeseen events, RAILSIM X delivers precision in representing their impacts on railway operations, paired with scalability to model diverse scenarios. Its user-friendly interface simplifies the modeling process.

RAILSIM X leverages a diverse repertoire of mathematical formulas and computer algorithms to faithfully replicate the intricate behavior of railway systems. For instance, it employs the Newton-Raphson method to meticulously simulate train movements. Moreover, the software employs an array of algorithms to efficiently schedule trains and faithfully replicate the influence of weather and unforeseen events.

Internally, RAILSIM X operates by first constructing a meticulous model of the railway system under scrutiny. This

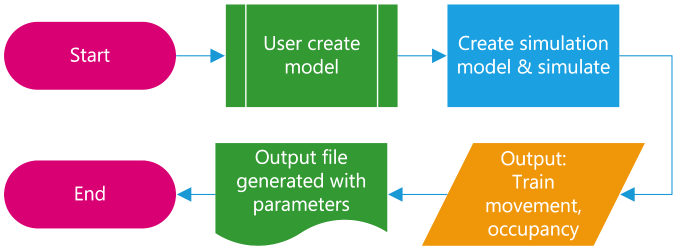

Fig. 6. RAILSIM X Basic Workflow

model comprises a multitude of objects, each representing entities and processes intrinsic to the railway system. These objects communicate seamlessly through a web of events, with each event triggering corresponding actions within the system.

The simulator proceeds to replicate the behavior of the railway system by incrementally advancing time in discrete steps and faithfully reproducing the events that transpire at each juncture. The outcome is an array of outputs that illuminate critical facets of railway operations, encompassing train movements, track occupancy status, train delay quantifications, and holistic assessments of the railway system's performance.

Inputs necessary for RAILSIM X to function effectively vary contingent on the specifics of the operations in focus. However, common inputs often include data encapsulating the railway network's layout, train timetables, train characteristics, and prevailing meteorological conditions.

RAILSIM X efficiently processes these inputs by interpreting and utilizing them to craft a precise model of the targeted railway system. Subsequently, it proceeds to simulate the system's behavior methodically, culminating in a wealth of informative outputs.

The foundation of RAILSIM X's operational prowess lies in an arsenal of mathematical formulas and computer algorithms. These encompass the aforementioned Newton-Raphson method for train movement simulation, sophisticated scheduling algorithms, and algorithms tailored to capture the multifaceted effects of weather and unexpected events.

A typical workflow for RAILSIM X transpires (shown in figure 6) as follows:

- **User Model Creation:** Users commence by constructing a model that accurately represents the railway system of interest.
- **Model Interpretation:** RAILSIM X ingests the user-created model and transforms it into a detailed simulation model.
- **Simulation Execution:** The simulator propels the simulation, meticulously reproducing railway system behavior within the predefined parameters.
- **Output Generation:** RAILSIM X delivers comprehensive outputs, ranging from intricate train movement details to occupancy status of track sections, train delay analytics, and overarching system performance evaluations.

G. RailSys

RailSys [32], a creation of the Institute of Railway Technology (IRT) at the German Aerospace Center (DLR), made its debut in 2000. Functioning as a discrete-event simulator, RailSys stands as a versatile tool for modeling and simulating an expansive spectrum of railway operations, offering precision and scalability across various aspects of railway operations modeling.

In the domain of interlocking systems, RailSys excels in delivering a detailed and accurate simulation, capturing the intricate logic and operation of interlocking elements. Its scalability allows for the simulation of large and complex systems. RailSys ensures accessibility through a user-friendly graphical interface, eliminating the need for programming expertise.

For signaling systems, RailSys maintains a high level of fidelity, meticulously representing the logic and operation of signaling elements. Its scalability accommodates the simulation of expansive and intricate signaling systems. The user-friendly graphical interface simplifies model creation and modification.

In the realm of train scheduling, RailSys offers high-fidelity simulations, encompassing diverse train schedules and priority rules. It readily handles the complexities of large-scale train scheduling problems. RailSys's user-friendly interface streamlines model development without requiring programming skills.

Train dynamics modeling with RailSys captures the nuances of forces acting on trains, such as gravity, friction, and aerodynamic drag, ensuring a high degree of fidelity. Its scalability extends to modeling extensive train movements, while the user-friendly interface simplifies model adjustments.

In the area of track geometry, RailSys provides high-fidelity simulations, depicting various track elements and their interactions accurately. Scalability is evident in the simulation of extensive railway networks. The user-friendly graphical interface enhances ease of model creation and modification.

RailSys offers high-fidelity simulations of diverse railway infrastructure elements, including stations, depots, and junctions. Its scalability encompasses complex railway networks with versatile infrastructure. The user-friendly interface simplifies infrastructure model development.

When addressing weather-related factors, RailSys provides precise simulations, capturing the effects of different weather conditions on railway operations. Scalability extends to modeling diverse weather scenarios, while the user-friendly interface facilitates weather model creation and adjustments.

In handling unplanned events, RailSys proves its versatility by modeling and simulating their impacts on railway operations accurately. Scalability allows for the simulation of a wide range of unplanned events in complex railway networks. The user-friendly graphical interface ensures ease of model development.

The inner workings of RailSys draw upon an array of mathematical formulas and computer algorithms to faithfully replicate the intricate dance of railway systems. A notable example is its use of the Newton-Raphson method to precisely emulate train movements. RailSys also deploys various algorithms to orchestrate train schedules and simulate the influence of weather and unexpected events.

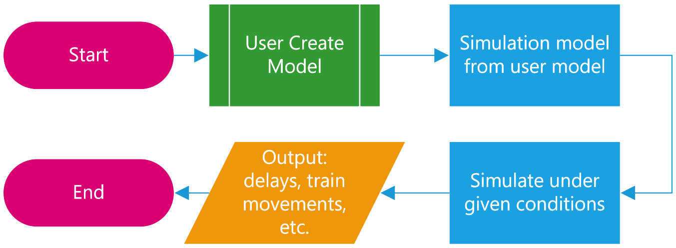

Fig. 7. RailSys Basic Workflow

Internally, RailSys commences its simulation journey by meticulously constructing a model of the target railway system. This model is an amalgamation of objects, each representing entities and processes inherent to the railway system. These objects communicate seamlessly through a web of events, with each event triggering the corresponding object to undertake specified actions.

The simulator then embarks on a journey to replicate the intricate behavior of the railway system. It accomplishes this by systematically advancing time in discrete increments and meticulously reproducing the events that transpire at each juncture. The outcome is an array of outputs that provide valuable insights into railway operations, spanning train movements, track section occupancy, train delay metrics, and holistic system performance assessments.

The inputs required for RailSys to function optimally vary depending on the specific operations under scrutiny. However, common inputs typically encompass data detailing the railway network's layout, train timetables, train characteristics, and prevailing meteorological conditions.

RailSys adeptly processes these inputs by interpreting and employing them to create a precise model of the targeted railway system. Subsequently, it proceeds to simulate the system's behavior methodically, culminating in a wealth of informative outputs.

At the core of RailSys' operational prowess lies an arsenal of mathematical formulas and computer algorithms. These include the Newton-Raphson method for simulating train movements, sophisticated scheduling algorithms, and algorithms tailored to replicate the multifaceted impacts of weather and unexpected events.

The typical workflow for RailSys (figure 7) unfolds as follows:

- **User Model Creation:** Users commence by constructing a model that faithfully encapsulates the railway system of interest.
- **Model Interpretation:** RailSys ingests the user-created model and transforms it into a detailed simulation model.
- **Simulation Execution:** The simulator propels the simulation, meticulously reproducing railway system behavior within predefined parameters.
- **Output Generation:** RailSys delivers comprehensive outputs, spanning intricate train movement details, track section occupancy status, train delay analytics, and overarching system performance evaluations.

H. Simrail

Simrail [33], a discrete-event simulator meticulously crafted by the Railway Technology Institute (RTI) at the University of Stuttgart, stands as a formidable and versatile instrument. It empowers users to model and simulate an expansive spectrum of railway operations, it excels in offering high-fidelity simulations across various facets of railway operations modeling.

In the domain of interlocking systems, Simrail delivers a meticulous and detailed simulation, capturing the intricate logic and operation of interlocking elements with precision. Its scalability enables the simulation of expansive and complex interlocking systems. Simrail prioritizes accessibility, providing a user-friendly graphical interface tailored for non-programmers, facilitating the creation and modification of interlocking models.

For signaling systems, Simrail maintains a high level of fidelity, comprehensively representing the logic and operation of signaling elements. Its scalability extends to modeling extensive and intricate signaling systems. Simrail's user-friendly graphical interface simplifies model development for those without programming expertise.

In the realm of train scheduling, Simrail offers high-fidelity simulations, encompassing various train schedules and priority rules. It readily handles large-scale train scheduling problems and offers a user-friendly interface for model creation and adjustment, even for non-programmers.

Train dynamics modeling with Simrail captures the complexities of forces acting on trains, including gravity, friction, and aerodynamic drag, ensuring a high degree of fidelity. Its scalability extends to modeling extensive train movements. The user-friendly interface simplifies model development, making it accessible to non-programmers.

In the area of track geometry, Simrail provides high-fidelity simulations, depicting various track elements and their interactions with accuracy. Scalability is evident in the simulation of extensive railway networks. The user-friendly graphical interface enhances ease of model creation and modification for non-programmers.

Simrail excels in offering high-fidelity simulations of diverse railway infrastructure elements, including stations, depots, and junctions. Its scalability encompasses complex railway networks with versatile infrastructure. The user-friendly interface simplifies infrastructure model development, ensuring accessibility to non-programmers.

When addressing weather-related factors, Simrail provides precise simulations, capturing the effects of different weather conditions on railway operations. Scalability extends to modeling diverse weather scenarios. The user-friendly interface facilitates weather model creation and adjustments for non-programmers.

In handling unplanned events, Simrail proves its versatility by modeling and simulating their impacts on railway operations accurately. Scalability allows for the simulation of a wide range of unplanned events in complex railway networks. The user-friendly graphical interface ensures ease of model development, even for non-programmers.

Simrail's capabilities extend to modeling and simulating the effects of human factors on railway operations, such as human error and fatigue, with accuracy. It readily handles large and complex railway networks considering various human factors. The user-friendly interface simplifies model development for non-programmers.

Furthermore, Simrail can be effectively utilized to model and simulate the financial consequences of different railway operations and scenarios, demonstrating versatility in economic modeling. Its scalability extends to simulating large and complex railway networks considering various economic factors. The user-friendly graphical interface facilitates economic model creation and modification, even for non-programmers.

To manifest the intricacies of railway systems, Simrail deftly employs an array of mathematical formulas and computer algorithms. For instance, it leverages the Newton-Raphson method to replicate the intricate choreography of train movements. Simrail harnesses scheduling algorithms to orchestrate the movement of trains across the network. Moreover, it relies on specialized algorithms to emulate the multifaceted impacts of weather and unforeseen events while also capturing the dynamics of human involvement.

Despite its complexity, Simrail boasts an extensive and well-documented user manual, complemented by a plethora of tutorials and online examples. These resources collectively ensure that mastering the simulator is an attainable goal, fostering a user-friendly experience.

Simrail has etched its presence in diverse research endeavors and practical applications. Noteworthy applications include its role in scrutinizing the performance implications of various interlocking system designs, evaluating the efficacy of distinct train scheduling algorithms, and assessing risk factors associated with human interactions within railway operations.

For individuals seeking to model and simulate railway operations comprehensively, Simrail emerges as an indispensable tool. Its versatility and potency empower users to scrutinize a wide gamut of railway systems and their operational intricacies.

I. TrainSim

TrainSim [34], a commercial train simulator meticulously crafted by Dovetail Games, stands as a testament to the fusion of physics-based realism and stunning graphics. With its unwavering focus on authentic driving physics and lifelike visuals, TrainSim delivers an immersive experience that transports users into the world of railway operations. The simulator accommodates a diverse array of operations, encompassing:

- Guiding trains along a diverse tapestry of railway lines, including mainlines, branch lines, and bustling urban railways.
- Navigating trains through various environments, from challenging mountainous terrains to bustling urban landscapes and serene rural expanses.
- Managing a rich spectrum of train types, spanning passenger locomotives, cargo haulers, and lightning-fast high-speed trains.

TrainSim, a commercial train simulator, primarily focuses on realistic driving physics and graphics, with limited coverage of railway operations aspects.

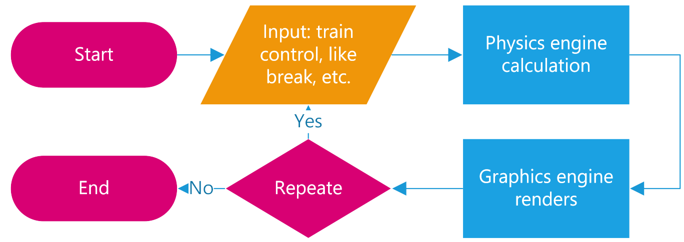

Fig. 8. TrainSim Basic Workflow

In terms of interlocking systems, TrainSim lacks a dedicated model, and it does not offer scalability or usability features in this regard.

Similarly, for signaling systems, TrainSim lacks a dedicated model, with no scalability or usability considerations.

Regarding train scheduling, TrainSim does not provide a dedicated model and lacks scalability and usability features in this domain.

However, TrainSim shines in the realm of train dynamics with a high-fidelity model. It offers scalability for simulating large and complex railway networks. Moreover, TrainSim is user-friendly, catering even to users with no prior experience in train simulation.

Train geometry is another area where TrainSim excels with a high-fidelity model. It supports scalability for simulating expansive railway networks and boasts user-friendliness.

In the domain of infrastructure, TrainSim offers a high-fidelity model, encompassing various elements like stations, depots, and junctions. It is scalable to simulate extensive railway networks and remains accessible to users with no prior train simulation experience.

TrainSim provides a basic model for weather effects, including rain and snow. It scales to accommodate different weather conditions and maintains a user-friendly interface.

However, TrainSim lacks dedicated models for unplanned events, human factors, and economics, with no scalability or usability considerations in these areas.

Underpinning TrainSim's authenticity is its proprietary physics engine, a masterful conductor of the intricate dance of trains and objects on the railway network. This engine accounts for an exhaustive array of factors, including gravitational forces, friction, aerodynamic drag, the unique weight and dimensions of each train, the nuances of the terrain, and the velocity at which the train hurtles along the tracks.

To further elevate the experience, TrainSim employs a proprietary graphics engine, crafting picturesque scenes that mirror reality. This engine is replete with high-resolution textures, lifelike lighting and shadows, and dynamic weather effects that bring the railway network and trains to life.

TrainSim ensures accessibility by accommodating an array of input devices, from keyboards and mice to joysticks and steering wheels. It also offers a diverse range of control schemes, allowing users to choose between manual and automatic driving modes.

The operational workflow of TrainSim (figure 8) unfolds as follows:

- The user deftly issues commands to govern the train's behavior, deftly controlling acceleration, deceleration, and changes in direction.
- The physics engine works its magic, meticulously calculating the train's new position and velocity based on user input and the intricate web of forces influencing the locomotive.
- The graphics engine steps in, painting a fresh, vivid image of the train and the sprawling railway network, accurately reflecting the train's altered position and speed.
- This loop of realism and engagement persists until the user chooses to conclude the simulation.

TrainSim enjoys a wide and diverse user base, catering to a spectrum of purposes. Train enthusiasts revel in the opportunity to experience the exhilaration of operating a train. Railway engineers harness TrainSim as a training ground for real-world scenarios. Game developers leverage its capabilities to craft captivating and true-to-life train simulations.

In essence, TrainSim emerges as an invaluable tool, whether for those keen to delve into the intricacies of train operations, yearning to savor the thrill of train driving, or aspiring railway engineers preparing for the challenges of real-world railway operations. TrainSim primarily serves as a valuable training and educational tool for driving trains, offering realism in physics and graphics. It should be noted that TrainSim is not intended for comprehensive railway operations simulation. It lacks models for interlocking systems, signaling systems, train scheduling, human factors, and economics. Nevertheless, it remains useful for training railway engineers and enthusiasts in various driving scenarios and conditions.

J. Trainz

Trainz [35], developed by Auran (now N3V Games) in 1995, is a commercial train simulator renowned for its comprehensive railway network simulations and realistic train movements. This simulator employs a multifaceted approach to recreate the intricacies of train operations and the railway environment.

To simulate train movements, Trainz employs a sophisticated physics engine, enabling it to mimic the complex dynamics and interactions of trains on the railway network. Additionally, it utilizes a robust graphics engine to render lifelike visuals of the railway infrastructure and the trains themselves.

Trainz is a train simulator that offers varying levels of accuracy, scalability, and usability across different aspects of railway operations.

In the realm of interlocking systems, Trainz lacks a dedicated model, offering neither scalability nor usability features.

For signaling systems, Trainz provides a basic model capable of simulating different signal types, though it falls short in accurately representing complex interlocking systems. However, it does offer scalability for diverse railway networks, and its signaling model is relatively user-friendly.

Trainz does not encompass a model for train scheduling, and it lacks scalability and usability in this domain.

In contrast, Trainz excels in train dynamics with a high-fidelity model that can simulate train movement on various track types, accounting for factors like friction, aerodynamic drag, and inertia. It scales well for complex railway networks and maintains a user-friendly interface.

The track geometry model in Trainz is high-fidelity, encompassing different track elements and considering track curvature and elevation. It offers scalability for diverse railway networks and is user-friendly.

Trainz also boasts a high-fidelity model for railway infrastructure, covering stations, depots, junctions, and level crossings. It scales for large and complex railway networks and is relatively user-friendly.

Regarding weather effects, Trainz provides a basic model for rain and snow impacts on train movement. While it supports scalability for diverse weather conditions, it may not be as accurate as some other simulators. Usability remains relatively straightforward.

In the realm of unplanned events and human factors, Trainz lacks dedicated models, offering neither scalability nor usability features.

Similarly, Trainz does not model economics and lacks scalability and usability considerations in this area.

Trainz stands out for its adaptability, accommodating various input devices and control schemes. Furthermore, it provides scripting capabilities through programming languages like Python and Lua, enhancing its versatility.

Internally, Trainz operates on a modular architecture, dividing the simulation into distinct modules, each responsible for specific tasks, such as train movement simulation, rendering the railway network, or handling user inputs. The simulator functions by progressing through time in discrete steps. During each step, it updates the state of the railway network and trains, diligently scrutinizing for any collisions or noteworthy events.

For Trainz to function optimally, several inputs are imperative(figure 9), including a railway network definition file outlining network layout and track characteristics, and a train definition file specifying train attributes such as length, weight, and maximum speed. User input, consisting of commands to initiate, halt, or adjust train speeds, is also pivotal.

The simulator adeptly processes these inputs, using them to refine the state of the railway network and the trains, and simultaneously conducts checks for potential collisions and other critical events.

Trainz yields various outputs, comprising a graphical representation of the railway network and train positions. It also generates log files, documenting the evolving states of the network and trains at each time step. Additionally, the simulator provides an array of data, including performance metrics and fuel consumption statistics.

Mathematically, Trainz employs formulas to calculate train acceleration, incorporating factors like force and mass. For instance, it employs the formula: acceleration = force / mass, with acceleration denoting train acceleration in meters per second squared, force signifying the acting force in Newtons, and mass representing the train's mass in kilograms. Moreover, Trainz employs computer algorithms, such as collision detection algorithms, to prevent train and object collisions.

In a simplified workflow, Trainz commences with user input, enabling commands for train initiation, cessation, and

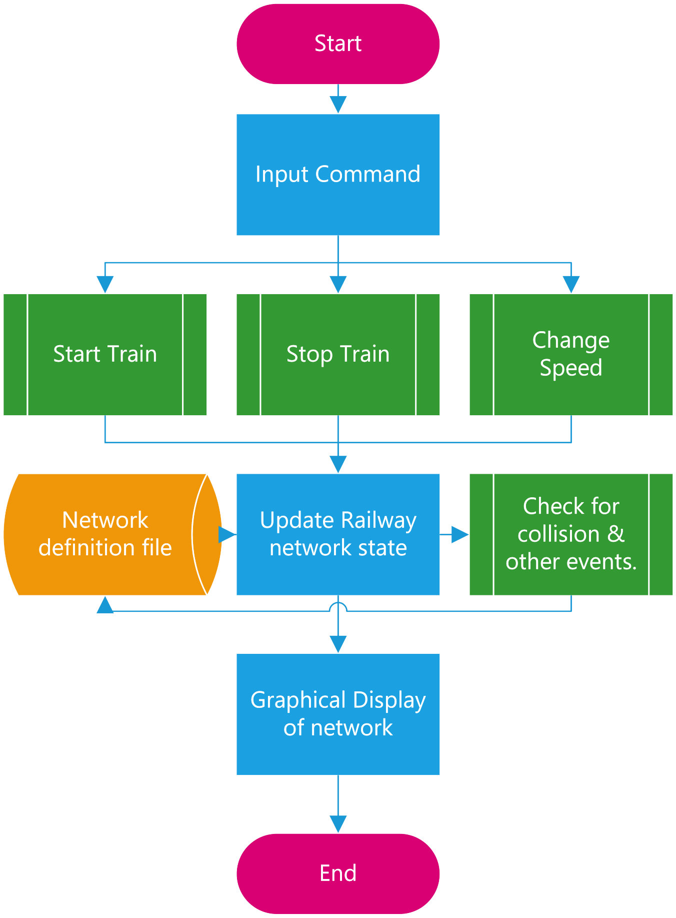

Fig. 9. Trainz Basic Workflow

speed adjustments. Subsequently, the simulator updates the railway network and train states, guided by user input and network definitions. Vigilant checks for collisions and other events are then performed. Finally, Trainz furnishes a graphical representation of the railway network and trains, alongside a detailed log file encapsulating the evolving state of the system at each time step.

IV. Implication, Limitation and Future Scope

The availability of a wide range of railway transportation simulators with varying capabilities holds significant implications for the planning, creation, and administration of efficient train operations, offering valuable tools for various purposes.

Firstly, they enable the thorough testing and evaluation of new railway systems and procedures even before they are put into practice. This proactive approach helps identify and address potential issues, ensuring both safety and operational efficiency. Moreover, simulators play a crucial role in training railway personnel in the use of new procedures and technologies. This training takes place within a controlled environment, enhancing safety and efficiency while reducing the risk of accidents. Additionally, simulators have the capability to simulate and analyze the impact of different events on railway operations. This function proves invaluable in developing contingency plans and fortifying the resilience of railway systems against disruptions and unforeseen challenges. In essence, these simulators serve as indispensable tools in the realm of railway transportation planning and administration.

This study has several limitations that warrant acknowledgment. Firstly, the survey was conducted with a limited sample size, potentially constraining the generalizability of the findings. Secondly, the survey omitted the collection of data on the specific capabilities of each simulator, thus hindering the ability to make meaningful comparisons between them. Thirdly, the study did not assess the effectiveness of the simulators in terms of their capacity to achieve desired outcomes. These limitations underscore potential avenues for future research. Despite these limitations, the study offers valuable insights into the current state of railway transportation simulators and their potential applications. It also highlights several areas for future research, including the development of more sophisticated and accurate models of railway systems, the creation of more user-friendly simulators to widen accessibility, and the expansion of simulator capabilities for training railway personnel in a broader range of skills to enhance safety and efficiency in the industry.

To address the limitations of railway transportation simulators, several strategies can be employed. This includes developing improved models of railway systems using richer data sources and advanced mathematical and computational techniques. Additionally, enhancing user-friendliness through comprehensive documentation and intuitive user interfaces can mitigate these limitations. Furthermore, efforts to make simulators more cost-effective through the development of efficient software and the utilization of open-source software components can also play a pivotal role. These measures collectively aim to enhance the value and utility of railway transportation simulators in the planning, creation, and administration of effective train operations.

V. Conclusion

The comparative study reveals a range of capabilities and strengths inherent in railway operation simulators, covering a wide array of parameters, although with varying levels of detail and model accuracy. Table I provides a numerical summary of the supported parameters, indicating that ten simulators are equipped to handle most of the selected parameters, while some simulators offer partial implementation of economics. This diversity ensures the availability of an appropriate simulator for a broad spectrum of needs, ranging from basic train dynamics simulations to complex simulations of entire railway networks.

More specifically, all ten simulators support the following parameters: Interlocking, Signaling, Train scheduling, Train dynamics, Track geometry, Infrastructure, and Economics (with partial implementation).

When it comes to Weather, seven of the simulators incorporate this parameter into their simulations, and eight simulators account for Events. However, only four simulators consider Human factors within their simulations.

Simulators offer versatile practical applications, including training railway personnel in new procedures and technologies, assessing new railway systems and procedures before implementation, and simulating and analyzing the impact of various events on railway operations.

The results of this study underscore the existence of a diverse array of railway operation simulators, each with distinct capabilities and strengths. This diversity ensures the availability of a suitable simulator for a wide range of needs, spanning from basic train dynamics simulations to intricate simulations of entire railway networks.

Compliance with Ethical Standards

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Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

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