Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

A COMBINED DISCRETE-CONTINUOUS SIMULATION MODEL FOR ANALYZING TRAIN-PEDESTRIAN INTERACTIONS

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ABSTRACT

Computer simulation has defined itself as a reliable method for the analysis of stochastic and dynamic complex systems in both academic and practical applications. This is largely attributed to the advent and evolution of several simulation taxonomies, such as, Discrete Event Simulation, Continuous Simulation, System Dynamics, Agent-Based Modeling, and hybrid approaches, e.g., combined discrete-continuous simulation, etc. Each of these simulation methods works best for certain types of problems. In this paper, a discrete-continuous simulation approach is described for studying train and pedestrian traffic interactions for purposes of decision support. A practical operations problem related to commodity train operation within two small towns in Alberta, Canada, is then used to demonstrate the implementation of the approach within the Simphony.NET simulation system. Simulation results generated are presented.

1 INTRODUCTION

Train tracks constructed and operated on grade often intersect with other transportation modes such as vehicular and pedestrian transportation. Vehicular transportation refers to cars, trucks, e.t.c., on roads, while pedestrian transportation refers to people walking or running. Such intersections are typically left uncontrolled until such a time that traffic volumes increase, the nuisance from train whistles is intolerable, or there is an occurrence of incidents. Controls are installed to ensure continued operation of each transportation mode with minimal interference. In both controlled and uncontrolled intersections, higher priority is normally given to the mode which would be affected the most by frequent stops, wait times, etc. For pedestrian-train intersections, trains are prioritized.

Formal studies are inevitable in arriving at the decision that relate to the need to install formal control devices at such intersections because of the capital and running costs involved. Such studies rely on the concept of warrants which is predominantly used in traffic management of intersections (Roess, Prassas, and McShane 2010). Such studies are either carried out empirically, using simulation-based approaches, or using a combination of both. Simulation-based approached or a mixed approach would be considered more favorable because either approach facilitates inexpensive ways of experimenting with different scenarios. Consequently, a combined approach was adapted for the study presented in this paper.

In the mixed approach, i.e., empirical-simulation-based approach, the empirical component was used to ground truth the state of the system being studied through observation of traffic arrival patterns, the geography of the site, etc. Data collected served as basic inputs for the simulation model building process. On the other hand, the simulation component was dedicated to explicitly emulating the traffic interactions within a computer-based virtual environment. Coupling numerical or analytical methods, other than simulation, with empirical studies would have been ineffective because they cannot handle uncertainty and stochasticity as well as simulation-based methods. Constructs in transportation are generally characterized by uncertainty and stochasticity hence the mixed empirical and simulation-based approach was deemed appropriate.

2 COMPUTER SIMULATION

Several taxonomies of computer simulation exist today. This is partly due to the advances made in the computing science domain and the increasing complex nature of problems that have to be analyzed using simulation. Examples of simulation taxonomies include: Monte Carlo simulation, Discrete Event Simulation (DES), Continuous Simulation (CS), System Dynamics (SD), Agent-Based Modeling (ABM), e.t.c. Monte Carlo simulation is a simulation method that to a large extent relies on random deviates drawn from a model, for the performance of computations (Law and Kelton 1991). Most Monte Carlo simulations are static in nature but also dynamic ones exist. Discrete event simulation is a dynamic type of simulation that is used in the emulation of systems through the scheduling and processing of events at specific points in time. On the other hand, in continuous simulation, the system being emulated on computer is scanned every time step (typically each in size) and decisions made on whether events get triggered (Pritsker 1986). In most situations, the state variables of the system are tightly coupled with time and hence continuously change. Finite difference numeric algorithms are utilized in the process of updating these state variables. Examples of continuous simulation languages include: SLAM II (Pritsker 1986), ACSL and CSSL-IV (Pratt 1987), SIMSCRIPT II.5 (Fayek 1988), and SIMAN (Sturrock and Pegden 1989). Contemporary simulation systems that support continuous simulation include: Simphony (Hajjar and AbouRizk 1999), AnyLogic (The AnyLogic Company® 2000), and Vensim (Ventana Systems® 1988), e.t.c.

System Dynamics is a high level type of simulation that utilizes a continuous simulation implementation scheme together with mathematical modeling techniques. This simulation paradigm was created in the mid-1950s by Professor Jay Forrester while working at MIT Sloan School of Management (Jay 1971; Radzicki and Taylor 2008). System Dynamics is most suitable for problems that are characterized by non-linear interrelations between state variables. Graphical simulation systems that support SD permit the representation of state variables using stocks, flows, and loops (balancing or reinforcing). The stocks and flows emulate the dynamic change in the variables while the loops facilitate explicit representation of feed and feedback behaviors.

Agent-Based modeling is another high level simulation paradigm that is comprised of automatous or semi-autonomous constructs referred to as agents (Wooldridge 1999). These agents have the ability to communicate with each other and their environment, and can behave in unique ways (Mili & Steiner 2008; Kesaniemi and Terziyan 2011). Environments that support this simulation modeling paradigm, typically provide capabilities for modelers to utilize any of the other simulation types described, i.e., DES, CS, SD, etc., in their model development.

3 CONCEPTUAL DESIGN FOR SIMULATING TRAIN-PEDESTRIAN INTERACTIONS

3.1 Formulation and Modeling of Behaviors

In typical transportation studies, all the constructs of interest can be placed into one of two categories, namely: infrastructure, and the users of this infrastructure. For a train-pedestrian interaction study, the infrastructure includes the train tracks for train travel, the space available for pedestrian movement and any control devices that exist. The users include trains and pedestrians.

The behavioral aspects that are important relate to the way the users interact with the infrastructure and themselves. Mobility is one of the important behaviors and is shared amongst users of infrastructure. Parameters that define mobility include: arrival rates, travel direction, maximum/average travel speed, acceleration and deceleration. Other behaviors include halting movements, altering the direction of movement and tolerable wait times. These last three behaviors are best modeled using behavioral rules that have stochasticity embedded within them.

Trains operating in isolation of the pedestrians could behave in one of two ways. The first includes trains traversing the section without stopping while the second involves trains staging at designated locations to make a drop-off or pick up. When the interaction with pedestrians is considered, behavioral ways such as scanning the space around the train track for pedestrians that are close and related interventions become important. First, triggers that prompt the train to commence a scanning session need to be well defined. An example could include the transition of the train into a specific discretized zone and details on this are presented in the following subsection.

3.2 Discretization of the Interaction Space

Space is an important parameter in studies that are concerned with dynamic behaviors of mobile constructs. First, boundaries need to be delineated after which the delineated space is further sub-divided into smaller discrete cells or zones to facilitate dynamic computation and related analysis. The size of the discrete spaces depends on the anticipated computational intensity, and precision desired. Also, the need for natural buffers such as for safety, could influence the discretization process. These zones (Figure 1) facilitated the definition and modeling of the behaviors for trains, pedestrians and their interactions.

A total of four zones were designated for modeling pedestrian behavior. However, only two are shown in Figure 1, i.e., a “pedestrian red zone”, and a “pedestrian yellow zone”. These were defined perpendicular to the track at the point at which pedestrians cross the track. The purpose was to indicate how close the pedestrian is to the track. Although there was no formal built pedestrian crossing facility, the point along the track at which pedestrians frequently crossed was referred to as “pedestrian crossing zone”. The “pedestrian red zone” represents the train track and a space closest to it. Pedestrians within this zone are hit by the train when it gets to the designated “pedestrian crossing zone”. Pedestrians within the “pedestrian yellow zone” are counted as missed incident statistics when a train arrives at the “pedestrian crossing zone”. Those in the “pedestrian red zone” are counted as incidents. The last zone also not presented in Figure 1 is referred to as a “pedestrian green zone”. It was meant to serve as an entry point for pedestrians arriving to the area with the intention of crossing and as an exit for those leaving the area.

Zones designated for modeling train behavior and its interaction with pedestrians included: a “train yellow zone”, “train red zone”. The first two train zones were setup for purposes of triggering a scan of the space of interest so that a train would be able to decide its next course of action while it is in motion. The third train zone was used for purposes of collecting statistics of incidents (pedestrians hit), and missed incidents.

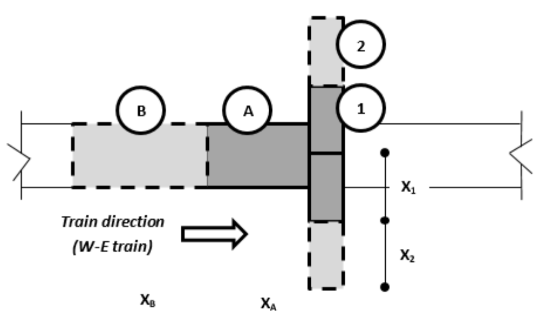

Figure 1: Schematic layout of the “train zone” and “pedestrian zone”.

The development for the behavioral rule specifications were based on the discretization process described in this sub-section. These behavioral rules for trains and pedestrians are discussed in the next subsection.

3.3 Zone-Based Behavioral Rules

When trains or pedestrians are not in a stationary state, their default behavior is to continue moving in the direction of their planned destination. This default behavior is altered when anticipation is made of likely interference to this motion. In order to model the behaviors of trains and pedestrians, a critical analysis of their interaction was considered inevitable. This was adapted as a first step so that the master and slave configuration would be setup adequately. In this context, the master was setup to initiate the interaction communications. All other constructs were considered slaves, i.e., only respond to messages received. In order to minimize communication conflicts, trains were considered masters while pedestrians were taken as slaves.

3.3.1 Train Behavioral Rules

Communication was initiated every time a train transitioned into a designated zone. The train was setup to operate across three designated zones (also described in the previous sub-section). The zones were ordered as follows: first zone - "train yellow zone", second zone - "train red zone", and third zone - "pedestrian crossing zone". A transition into the "train yellow zone" was meant to trigger the first train scan session. If the scan results revealed a presence of pedestrians (approaching track or in close proximity to the track), then train would whistle and continue motion. A second scan of the train track space would be triggered as soon as the train transitions into the "train red zone". The train would be compelled to whistle and then decelerate to a complete stop if a presence of pedestrians was revealed for this second scan. When an emergency stop is triggered, the train scans for pedestrians that are on the track or close to the track, i.e., the "pedestrian red zone" when the train arrives at the designated "pedestrian crossing zone". If there is atleast one pedestrians within the "pedestrian yellow zone", a count is made for a missed incident. Both the first and second scan sessions were mandatory for all trains regardless of pedestrian presence or absence. The acceleration and deceleration of trains was modeled explicitly for situations involving trains stoppage and start-up. Train emergency stops due to incidents were assumed to result in delays that are longer than emergency stops due to missed incidents.

There was one other type of stop referred to as a scheduled stop, which was explicitly modeled. Scheduled stops were meant to facilitate train drop-off and pick-up operations. The delay associated with this type of stop varies depending on the reason for stopping and the nature of the consignment being handled. Statistical distributions were used to represent the uncertainty associated with this delay. The train behavior described was applied to every train that was within the study area. The fact that it is a single carriage way train track facilitates this. In the case of pedestrians, many of them can simultaneously use the right of way. The train behavior described is summarized in a state machine chart presented is Figure 2. The concept of state machine charts used here was adapted from the Systems Modeling Language (SysML) domain.

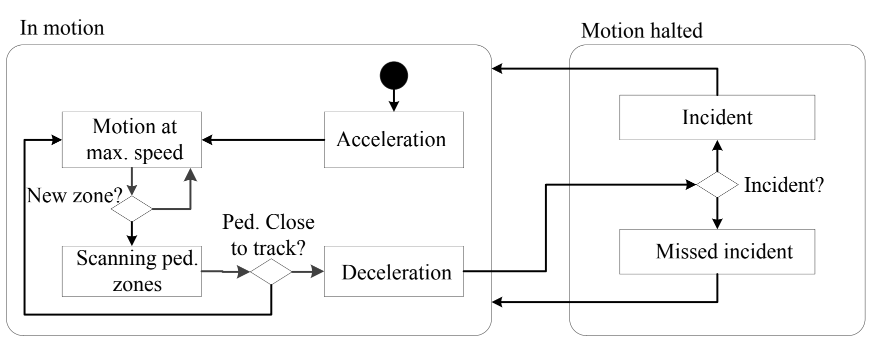

Figure 2: Schematic summarizing train behavior.

3.3.2 Pedestrian Behavioral Rules

Given that pedestrians were setup as slave constructs; alterations to their default behavior were implemented only when they receive a train whistle signal. In reality, it is difficult to estimate the rate at which pedestrians accelerate and decelerate, consequently these aspects of their motion behavior were ignored in subsequent formulations and modeling. Pedestrian motion behavior is unique to an individual and varies across individuals. Explicit representation of this unique individual behavior can result in significant computation overhead. Consequently, pedestrians were clustered and behaviors defined based on these clusters. The clusters included: 1) pedestrians with reduced mobility, i.e., persons over 65 years, children with an adult, and persons with disabilities (cluster 1), and 2) pedestrians with normal mobility (cluster 2). Arrival rates, movement characteristics and other behavioral patterns were uniquely defined for each cluster.

Simulation events were scheduled and processed to emulate the motion of the pedestrian across each zone. When a train sends a whistle signal, pedestrians behave in one of two ways. The first involves a pedestrian proceeding undeterred in motion, after hearing the train whistle. This option accounts for pedestrians in a real life situation who may not hear the whistle, for example because they have a distracting device plugged in their ears, as well as pedestrians that are high risk takers - proceed towards the track with the hope that they will make it past the track before the train arrives. The second pedestrian behavior that is likely to be displayed after a train whistles, involves the pedestrian coming to a complete stop. There are further behavioral possibilities associated with this option. The first involves the pedestrian waiting until their right of way is cleared, i.e., the train leaves or passes by the “pedestrian crossing zone”. The other behavior involves the pedestrian waiting for only a predefined amount of time after which they leave in the opposite direction that they were initially travelling because the train took long to clear that pedestrian’s right of way.

The described behavioral rules served as a basis for modeling pedestrians in the simulation model. Each pedestrian category was assigned unique behavioral pattern based on the rules/options discussed. Probabilities were used to create variation in pedestrian behavior hence emulating the uniqueness that exists in reality. The schematic layout shown in Figure 3 summarized the pedestrian behavioral options discussed above.

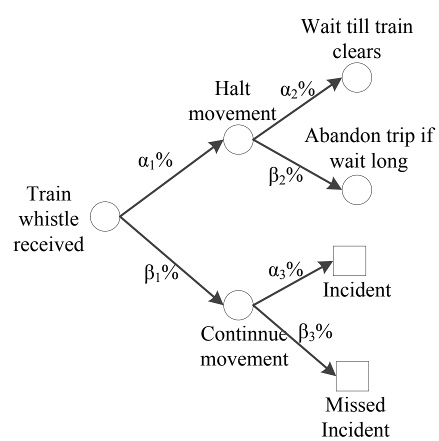

Figure 3: Schematic layout summarizing possible pedestrian behavior.

4 METHODOLOGY

Most studies have a data collection component within them; this study was no exception. Data was required to serve as input for the simulation model and for validation purposes. This data was collected in the following ways: 1) through structured interviews with operators of the train, their supervisors, the people that live in the vicinity of the study area, 2) through observations of the site, behavioral patterns, and direct measurement.

The simulation environment chosen for the implementation of the presented designs was Simphony.NET. The choice was influenced by the facts that Simphony.NET is free software for research purposes and also, two of the authors of this paper are involved in its creation and maintenance. However, Simphony.NET has not yet got the services to facilitate agent-based modeling, a simulation modeling paradigm that would have been a natural choice for this type of study. Consequently, a combined discrete-continuous simulation approach was adapted as the second best option. The modeling approach adapted in Simphony.NET to implement the designs has already been discussed.

The continuous portion as dedicated to the implementation of sub-models that emulate the train travel, its transition between zones and the related scanning operations. Distance parameters are used to represent the extents of the designated zones along the train track. Then, zone distances are represented as stocks in the continuous sub-models which get scanned by watch modeling elements to determine when predefined thresholds are crossed, i.e., when the train transitions from one zone to another. This setup facilitated the trigger of state events that emulate the train scanning for pedestrians on or close to the tracks and subsequent whistles or stoppage. The discrete event portion was used to emulate the travel of pedestrians. On entry into a zone, a simulation event was scheduled which signaled the exit of the pedestrian from the zone. This scheduled event would be suspended for the time that the pedestrian has to halt their motion, before it is resumed. Scheduling of pedestrian travel events were accomplished through the use of Task modeling elements while the suspension and resumption of events was accomplished through the use of code snippets within a formula editor.

5 DESIGN IMPLEMENTATION

The implementation of the design described was be elaborated through a real project that was done for a Canadian-based company which operates a large fleet of cargo trains. This project is referred to as a case study for the sake of this paper. This section of the paper is organized as follows. First, an overview of the project is presented along with details of the site layout. Thereafter, the data that was collected from the field and experts at this company is summarized. This data served as inputs to the simulation models that were created to emulate the train and pedestrian mobility and behaviors. These simulation models are also presented and then used to experiment with multiple scenarios. Finally results of this experimentation are presented.

5.1 An Overview of the Case Study

A simulation project recently consulted on for a rail company is used as a case study. The interest of the company was to gain insights into their operations in two small towns, i.e., Camrose and Ervick, in Alberta, Canada. Trains operated by the company in this area were categorized into two: “Through Trains” – travel without stopping, and “Staging Trains” – stop to make a drop off or pick up. The current state of practice is for “Staging Trains” to stage at the location at which pedestrians cross the track. However, the rail company wanted to quantify the effect of changing the staging location to Ervick. The section of train track within the study area runs in an east-west direction. Details of the study area are presented in Figure 4. The illustrated section of the study area (Figures 1 and 4) at which pedestrians cross was zoned along and perpendicular to the train track according to the dimensions summarized in Table 1.

The simulation model created was setup to generate the following information:

- The nuisance level from train whistles, quantified in this study as count statistics.
- The number of train-pedestrian incidents.
- The number of missed train-pedestrian incidents.
- The pedestrian wait times resulting from staging trains blocking the pedestrian right of way.

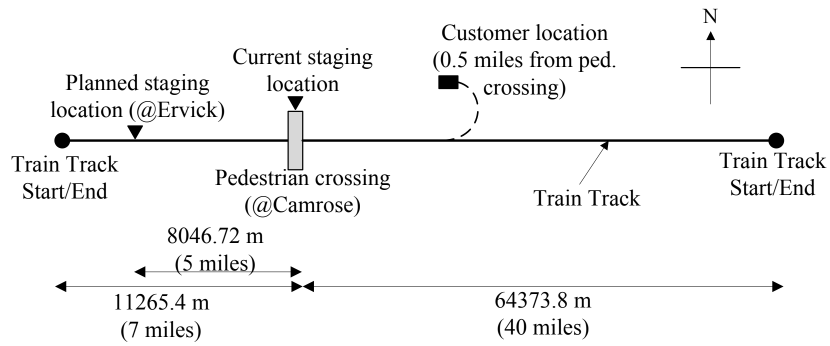

Figure 4: Schematic layout of the study area.

Table 1: Train and pedestrian zone details.

Label (in Figure 1)	Zone	Zone Size	Description
A	Train red zone	X_A = 50 meters	Section in which an approaching train will whistle and make an emergency stop if there is a pedestrian in the vicinity of the track.
B	Train yellow zone	X_A+ X_B= 400 meters	Section in which an approaching train will whistle but continue in motion if there are pedestrians in the vicinity of the track.
1	Pedestrian red zone	X_1 = 2.44 meters	Pedestrians in this zone are considered part of an incident at the time the train gets to the pedestrian crossing.
2	Pedestrian yellow zone	X_1+ X_2 = 7.62 meters	Pedestrians in this zone are considered part of missed incidents at the time the train gets to the pedestrian crossing.

These metrics were conveniently selected so that inferences could be drawn about the impact of the rail company's operations or changes that are proposed to these operations. Beyond understanding the current situation, the rail company was interested in obtaining insights into likely impacts of having higher pedestrian volumes than those experienced at present, and higher train frequencies. Simulation experiments were setup to investigate some of these scenarios. The following sub-sections present the simulation sub-models developed, the behavioral rules that the sub-models were based on, and the input data that they used.

5.2 Simulation Model(s)

5.2.1 Pedestrian Sub-Model(s)

In order to facilitate the simulation modeling process, pedestrians were clustered into two – those with a reduced mobility and those with a normal mobility. In the same spirit, pedestrians were further sub-divided based on their direction of travel. Data on the walk speeds are summarized from Gates, Noyce, Bill, and Van (2006) in Table 2. Observed pedestrian inter-arrival rates are also summarized in Table 3.

Table 2: Walk speeds for the different types of pedestrians.

Pedestrian Category	Walk Speed (m/s)
Cluster 1 (Over 65 years, Child with Adult & Disabled)	1.00 – 1.36

Cluster 2 (Under 30 & 30-60 years)	1.42 – 1.49

Table 3: Pedestrian inter-arrival times.

Time of Day	Inter-arrivals (Hrs.)	
	North Bound	South Bound
6am to 10pm	0.35 – 0.40	0.30 – 0.45
10pm to 6am	0.80 – 1.60	0.70 – 1.50

Pedestrians were modeled to exhibit different behaviors as a train approaches depending on the zone that they are in, the zone that the train is in, and the type of person that they are. These behaviors were represented using probabilities. Behavioral rules used in modeling are summarized in Table 4.

Table 4: Probabilities used to model pedestrian behavioral rules.

Pedestrian behavior	Pedestrian in yellow zone	Pedestrian in red zone
Train in zone yellow	• 5% proceed to the red zone • 80% stop in the yellow zone • 5% move to the green zone	• 49% return to the yellow zone • 49% continue to the yellow zone • 2% stop in the red zone
Train in zone red	• 5% proceed to the red zone • 95% stop in the yellow zone	• 49% return to the yellow zone • 49% continue to the yellow zone • 2% stop in the red zone

Pedestrians were modeled using a pure discrete event simulation approach. The Simphony model layout represented (see Figure 5) in the paper was used to mimic the mobility and behavior of pedestrians moving in the north to south direction. There were detailed sub-models encapsulated within the Composite modeling elements to perform specific functions. A similar model layout was used to mimic pedestrians travelling in a south-north direction.

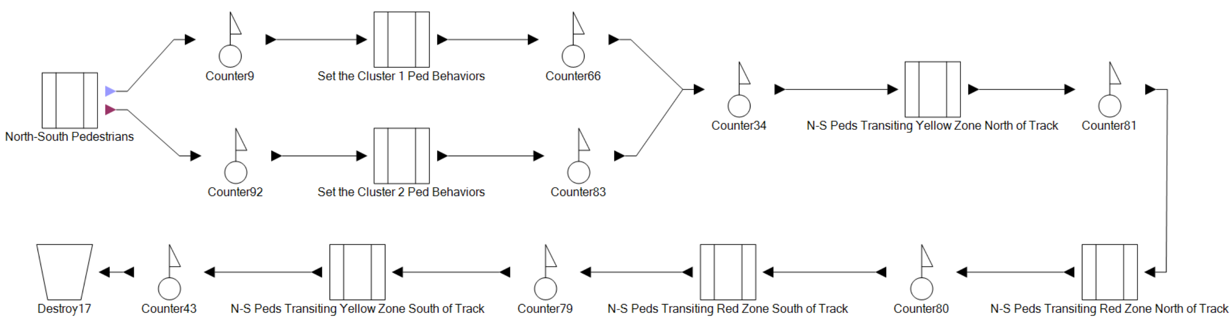

Figure 5: Discrete event model layout for south bound pedestrians.

5.2.2 Train Sub-Model(s)

Details of the train inter-arrivals at the study area for the current situation are presented in Table 5. Data on the maximum speed, acceleration, and deceleration were also provided in Table 6 to facilitate modeling of train motion, especially staging trains.

Table 5: Train arrival frequencies.

Train Type	Arrival Frequency
“Through” Train	5 per day
“Staging” Train	2 per day

Table 6: Kinematic data for trains.

Metric	Value
Maximum Train Speed (m/s)	Constant(11.18)
Train Acceleration/Deceleration (m/s^2)	Uniform(186.26, 372.53)

Table 7 summarizes the behavior responses of the train operator as soon as the train transitions into its yellow or red zone when there are pedestrians present in the pedestrian yellow or red zone.

Table 7: Details of train behavior and delays following an emergency stop.

Train behavior	Pedestrian in yellow zone	Pedestrian in red zone
Train in zone yellow	Record whistle	Record whistle
Train in zone red	• Record whistle for pedestrians that stop moving in their yellow zone. • Train brakes if there are pedestrians in this zone.	• Train brakes: No incident - 0.5 - 0.75 hours delay before motion resumes • Train brakes: Incident - 2-5 hours delay before motion resumes

The train was represented using a discrete event and continuous sub-models. The two main sub-model Simphony layouts are presented in Figures 6 and 7 because of limited space. Other sub-models not presented are those that watch the continuous sub-model state variables and respond to their state events.

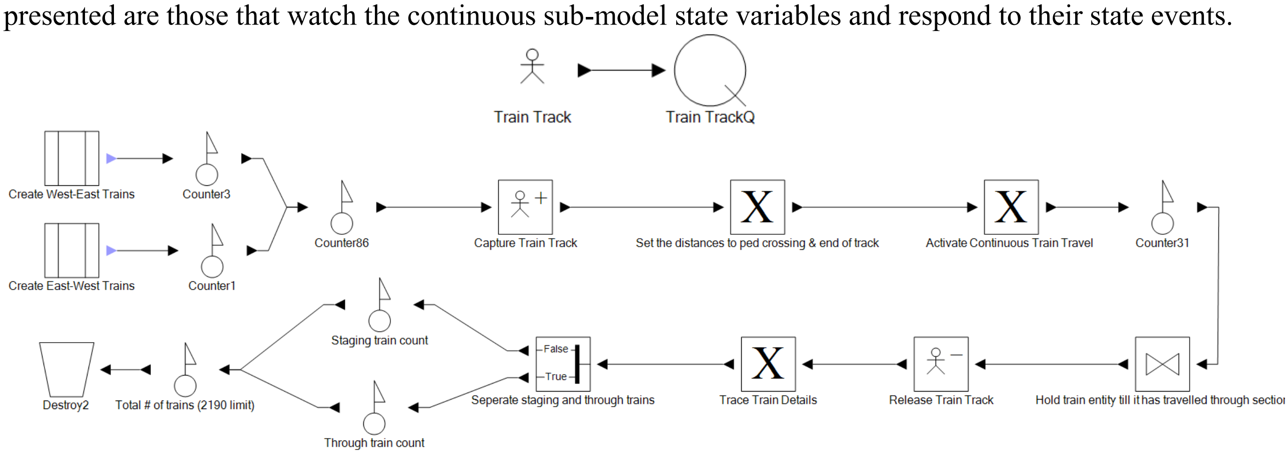

Figure 6: Discrete event model layout for the train.

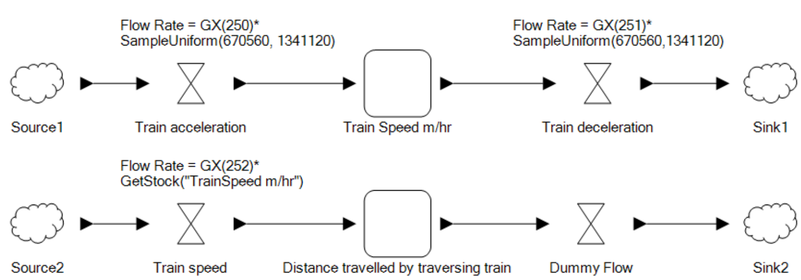

Figure 7: Continuous model for emulating train acceleration, deceleration, and travel distance.

6 VERIFICATION AND VALIDATION OF SIMULATION MODEL(S)

6.1 Model Verification

In most simulation studies, a number of steps are undertaken to confirm that simulation models are created and behave in the way that was intended. These steps typically vary from one simulation language and environment to another but there are some that are crosscutting. For the case study implemented in this paper, the following verification steps were undertaken. Counters were strategically positioned within both discrete and continuous sub-models. The counters in the discrete event portion were used to confirm that the expected number of entities were realized at those specific parts of the model at different points in time. In the continuous sub-model, counters gave information about the number of state events that occurred during the simulation and the times at which they occurred. Another verification strategy applied for both the discrete and continuous sub-models, was the generation of a trace log of simulation events as they evolved. Traces were checked to make sure that modeling constraints such as train speed limits were achieved and adhered to. Also, the sequence of events, e.g., train arrival at track section, entry into the section of track if it is available, travel, stoppage if necessary, and departure, were reviewed and found to be logical.

6.2 Model Validation

The first step undertaken in solving a real world problem is the choice of the method to be adopted in the solution. Serious consideration needs to be given to this step because an error in judgement at this early stage could render all other efforts useless since the work that follows would be regarded as invalid. The problem in the case study presented in this paper was characterized by stochastic and dynamic behaviors and processes. Consequently, adopting computer simulation methods for its solution was regarded as valid. The choice of simulation modeling paradigm is another important decision that could either validate or invalidate a simulation solution. In the case study, a combined discrete-continuous simulation modeling approach was chosen. Discrete event was used to model aspects that only change state at specific points in time, while continuous simulation was used to model aspects of the problem with state variables that continuously vary with time. For example, the mobility of trains was modeled as continuous for reasons already stated. The choice of a discrete approach for modeling the mobility and behavior of pedestrians has also been explained. Although an agent-based modeling approach would have made the process easier and would have resulted in a more elegant model, it was not adopted because the simulation system that was used for modeling did not support this modeling paradigm at that time. Nonetheless, this does not imply that the simulation model presented in this paper is invalid. The design patterns and specifications adopted in this study were valid because they facilitated the creation of a simulation model whose results were considered reasonable by those that are in the neighborhood of the study area and by the management of the rail company.

7 SIMULATION RESULTS AND DISCUSSION

After the simulation model was created and debugged, it was configured to run a number of scenarios. These scenarios were setup in consultation with the rail company. They included:

- ***Scenario 1.1:*** 7 trains (1/7 staging) per day; train staging at pedestrian crossing in Camrose; 20% pedestrian cluster 1 & 80% pedestrian cluster 2; 30-50 pedestrians per day
- ***Scenario 1.2:*** 7 trains (1/7 staging) per day; train staging at Ervick (5 miles west); 50% pedestrian cluster 1 & 50% pedestrian cluster 2; 150-250 pedestrians per day
- ***Scenario 2.1:*** 11 trains (3/11 staging) per day; train staging at pedestrian crossing in Camrose; 20% pedestrian cluster 1 & 80% pedestrian cluster 2; 30-50 pedestrians per day
- ***Scenario 2.2:*** 11 trains (3/11 staging) per day; train staging at Ervick (5 miles west); 50% Pedestrian cluster 1 & 50% pedestrian cluster 2; 150-250 pedestrians per day

The results presented in Table 8 confirm the correctness of the created simulation model. For example, there were fewer “Staging Trains” created in all scenarios compared to “Through Trains”. Also, a higher number of trains were created for the 3rd and 4th scenarios compared to the 1st and 2nd scenario, a result that is realistic given the train arrival frequencies specified.

Table 8: Total number of trains that passed the junction.

Train Type	Scenario 1.1	Scenario 1.2	Scenario 2.1	Scenario 2.2
“Staging Trains”	730	730	1094	988
“Through Trains”	1460	1460	2191	1980
Both types of Trains	2190	2190	3285	2968

Results on the number of times that trains whistled and came to a complete stop are summarized in Table 9. These results show that an increase in the pedestrian arrival frequency has a higher impact on the number of times that trains have to stop due to pedestrian-train interactions, compared to an increase in train arrival frequency at that location. There were also fewer train stoppages, whistles, and incidents when the train staged at the pedestrian crossing compared to when the train staged away from the pedestrian crossing at Ervick (5 miles west of the pedestrian crossing). This result could be a consequence of having fewer trains running along the train track past the pedestrian crossing location in the scenarios in which the train staged at the pedestrian crossing. When the train arrival frequency was kept the same and that of pedestrians was increased, the total number of train stoppages, incidents, and train whistles increased.

Table 9: Number of train whistles and brakes.

Parameter	Scenario 1.1	Scenario 1.2	Scenario 2.1	Scenario 2.2
Total times train braked	9	74	20	75
Number of incidents	2	51	2	74
Whistles (Train in yellow zone)	38	170	65	236
Whistles (Train in red zone)	67	236	84	349
Total number of train whistles	105	406	149	585

8 CONCLUSIONS

The problem of simulating train-pedestrian interactions was well formulated in a generic fashion that is transferable to other studies involving traffic interactions experienced within the same transportation mode or across different modes. Examples of these transferable design patterns include: 1) concepts of space discretization, and 2) master-slave communication/interaction configurations.

The design formulations were successfully used as a basis for developing a simulation model for train-pedestrian interactions. A combined discrete-continuous approach facilitated modeling train and pedestrian behaviors in a fashion that would be extremely challenging to realize if a pure discrete event simulation approach was utilized, especially the train-pedestrian interactions. Also, the verification process revealed that the process of debugging combined simulation models is significantly more complex compared to debugging pure discrete models. This could be attributed to the fact that to a large extent the continuous portion does not contain flow entities, which are easy to track, for example by using counters, but instead entails solving differential equations numerically. In addition, the discrete-continuous communications are not easy to track.

Simulation experiments were run using the created model and it’s results were found to be satisfactory. This demonstrated that simulation can be used in a practical setting to generate results that can be used to support decision making processes. For the case study, results were tracked on useful metrics which the rail company management could make use of in conjunction with jurisdiction by-laws and other warrants to make rational decisions regarding the operation of their trains and the need for a pedestrian crossing. If no formal crossing is to be provided, results show that it is better for trains to stage at the pedestrian crossing.

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