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# A GENERAL RAPID TRANSIT SIMULATION MODEL WITH BOTH AUTOMATIC AND MANUAL TRAIN CONTROL

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## ABSTRACT

This paper summarizes the design and application of a general discrete-event simulation model of a rapid transit system. The model incorporates features of both 3-aspect, manual control and automatic train control. We discuss the model architecture and validation, and its application. The model has been applied to several systems, including one in Atlanta having automatic train control and one in Toronto that is manually controlled. The model has been used to investigate a number of operational and scheduling issues.

## 1 INTRODUCTION

In this paper we present a general model of a rapid transit system that has been used to address a number of complex issues arising in the operation and scheduling of vehicles in a rapid transit system. The model has been used to analyze schedules, signaling design, block design, single tracking, and temporary speed restrictions. It has been used on both existing and proposed systems.

We discuss model objectives, input data requirements, model architecture, model outputs, and verification. Certain unique and interesting features of the model architecture are discussed in detail.

Finally, we briefly discuss the model's application to the Metropolitan Atlanta Rapid Transit Authority (MARTA) system and the Toronto Transit Commission (TTC) system. MARTA is a modern system having automatic train control (ATC), while TTC is an older manually controlled system based on a 3-aspect signaling system.

## 2 THE MODEL

### 2.1 History and Current Status

The model was developed jointly combining the simulation expertise of Carson/Banks & Associates and the train control expertise of Parsons Brinckerhoff Quade & Douglas (PBQ&D). It was initially developed for MARTA, a system incorporating automatic train control. At a later date, it was expanded to incorporate features of manual systems.

At present the model consists of a number of re-usable modules that can be combined and customized for a particular application. In each project it is further expanded to incorporate new features. The model has been applied to MARTA, TTC and a number of other systems.

### 2.2 Model Objectives

The rapid transit simulation model gives PBQ&D engineers the capability to:

- Run multi-train, multi-station simulations in realistic detail
- Perform operational analysis at interlockings and branching points
- Analyze single tracking operation during periods of track maintenance
- Analyze the effect of temporary speed restrictions
- Analyze train schedules, headway and dispatching under various scenarios

### 2.3 Model Inputs

Our goal has been to have all user-changeable input data in an understandable format in input data files. The input data files include the following:

- A head table, giving block lengths, connectivity, and control line speeds
- A mid table, giving grade change points and platform dwell locations
- A schedule file, giving dispatch time and location for both terminals and intermediate headway control points
- Tables for tractive effort (acceleration)
- Tables for braking profiles

The names "head table" and "mid table" refer to model events, discussed in section 2.4, that affect the head and midpoint of a train, respectively. The contents of the head and mid tables are discussed in more detail in the following sections.

Additional inputs include formulas that account for grade in the computations for acceleration and braking.

### 2.4 Simulation Language and Animator

The model was developed using the general purpose simulation language GPSS/H Professional$_{TM}$ and the post-processing animator Proof Animation$_{TM}$, both from Wolverine Software Corporation. GPSS/H is widely used for industrial simulations and had been found suitable for transit simulations in a number of previous studies. (See Brunner and Crain, 1991.)

Characteristics of GPSS/H that proved beneficial include its speed, flexibility and power. We used the Professional version which is based on a 32-bit DOS extender that allows it to run on a 386-class PC under DOS, Windows 3.0 or OS/2 2.0. The 32-bit DOS extended environment allows models of virtually unlimited size, a distinct advantage for detailed transit models that need large quantities of input data. The detailed modeling of acceleration and braking also requires large amounts of computational power, which GPSS/H provides as well as or better than most other simulation languages because it is a compiled rather than interpreted language.

Proof Animation (Brunner, Earle and Henriksen, 1991) allows a post-processed animation of train movement over the track layout, plus depiction of a train graph (distance versus time string line) produced by the model. The DOS version, limited to 640 KB of RAM, can animate fairly large systems, depending on the number of signal or circuit blocks and other factors. Proof Professional, a 32-bit DOS extended version, essentially removes all memory limitations, allowing animations of very large systems and depiction of train graphs over long intervals of time.

The current version of Proof Animation does not allow concurrent simulation and animation. Although post processing has definite advantages in terms of presentation characteristics (smooth, fluid motion) and portability, concurrency also has definite advantages in terms of using a combined simulation and animation for training purposes and interactive what-if analysis.

One major advantage of Proof Animation is that it allows animation of very large drawings typical of a rapid transit system that stretches over many miles with hundreds of signal or circuit blocks and dozens of interlockings (combinations of switches and crossings for changing tracks). With its CAD-like, vector-based geometry, Proof allows zooming and panning without loss of resolution to bring any portion of the track layout into view. Although the trains become tiny dots, it is also possible to view a complete system to, for example, detect congestion points.

### 2.5 Model Architecture

#### 2.5.1 The Track Layout and Speed Control

The track network consists of straight track having a normal and reverse direction, and interlockings such as single and double crossovers, half- and full-pocket track, and diverges to a branch line or a yard. Trains stop and dwell at station platforms for passengers to alight and board. Sometimes, trains may deadhead from an origination point (e.g. a yard or terminal) to its first platform for alighting and boarding passengers, passing other platforms on the way without stopping. Upon completion of service or otherwise following a schedule, a train may deadhead from its last station to a yard. For modeling purposes, a yard is simply a switch for a merging or diverging move at the train magically appears or disappears. We do not model the yard itself.

Trains traverse the track layout and may turn back or "disappear" at a terminal station or internal turnback location. Terminal stations and other turnback locations must have appropriate trackage (e.g. a double crossover in front or a pocket in back of the station) to allow the train to cross to the opposite track and change direction.

When a new train first appears in the dispatching schedule, the model allows a train to initially appear either at a yard and deadhead to its first platform, or to "magically" appear at a terminal or other turnback location.

For controlling the speed of trains, manual systems are divided into signal blocks, each guarded by a 3-aspect (red, yellow, green) or other more complex type of signal. Automatic train control systems are divided into circuit blocks, essentially the equivalent of a signal block but usually without the corresponding visual signal. The signal or circuit blocks, their lengths, and their connectivity (next block) are represented in the head table mentioned in Section 2.3.

The speed of a train is primarily controlled via "control lines", which give the allowed speed of a train depending on the number of unoccupied blocks between its head and the tail of the train immediately ahead of it. In addition, manual systems may have grade-timed or station-timed blocks, namely, a specified minimum time for traversing a given block.

Both manual and ATC systems require a stopping profile for trains entering a station and stopping to dwell at a platform. In the manual system, the stopping profile is pre-computed for each platform based on the desired braking rate and the actual grade(s) preceding the platform. Basically, it gives speed as a function of distance-to-go. The profile covers a distance preceding each platform sufficient to allow a train to stop at its maximum allowed control line speed. When a train is subject to more than one speed indication (such as a profile speed and a control line speed), it always obeys the lower speed.

For ATC systems, the stopping profile is a user input and the train alternately brakes and cruises to follow the profile into the station so that the midpoint of the train stops at a designated point on the platform. Otherwise, the rules for following profile speeds are similar for manual and ATC systems.

One major difference between manual and ATC systems revolves around anticipation of upcoming speed changes. In an ATC system, not counting a stop at a station, a train receives a command to decrease speed or stop only when its head crosses a block boundary or it falls under a profile. At that point, it begins decelerating. In contrast, in a manual system, the driver is expected to see a yellow or red signal ahead and to anticipate the speed required, decelerating ahead of time in order to be at the desired speed when the head of the train reaches the signal. (The red or yellow signal, plus posted speed limits and grade-time or station-timed signals, is a visual indicator to the driver for the control line speed that appears on engineering drawings and is used in the model.) In order to anticipate this speed decrease (depending on conditions ahead), we pre-compute stopping and/or slowing profiles for the end of each signal block.

As the head and mid tables plus the profile speed tables represent a massive amount of data, one requirement for any simulation language used is the capability to utilize all memory available on a modern 386 PC or to have efficient access to a database. Of course, with the data in memory versus in a database, a model will run considerably faster. We chose to have all data in memory; typical models require from 3 to 8 MB of RAM.

### 2.5.2 Model of the Train

Each train is modeled as a dynamic entity (GPSS Transaction) with numerous attributes, including the number of vehicles or cars in the train, the current signal or circuit block of the head of the train and the midpoint of the train, its current speed and its command speed, and its destination. The model explicitly tracks the head, midpoint and tail of each train. For animation purposes, the model may also track the head of each individual vehicle in a train.

Each train maintains a list of distance-related events that will affect train speed at some future time. These events are called head events, mid events or tail events, and are defined by the head, midpoint or tail of the train, respectively, hitting a certain node or point of the track network.

For example, whenever the head of a train passes a block boundary, its command speed may change. Therefore, the head of a train hitting a block boundary is a so-called "head event". Similarly, whenever the tail of a train hits a block boundary, a "tail event" occurs since the command speed of the following train may change, and in addition, if the tail is exiting a block having a look-back speed, it's own command speed may change.

The train is modeled as a one-point mass at its midpoint. Although in reality, grade changes gradually and continuously over a so-called vertical curve, we modeled it more simply as a discrete point change at the grade points defined in the mid table referred to in section 2.3. A grade change is a "mid event".

The weight of the train may have an effect upon its acceleration and braking characteristics, especially through the grade component. Typically, acceleration is defined in a table as a function of velocity at an assumed zero grade; for any other grade, an equation is used to adjust the acceleration as a function of the tabled value and the grade. Similarly, the braking rate may be defined as a constant (for example, 2.8 MPH per second) or by a table as a function of velocity.

In summary, a train is affected by the following events:

| | |
|---|---|
| Head events: | Head of train crosses a block boundary |
| | Head of train hits approach to an interlocking |
| Mid events: | Midpoint of train hits a grade change point |
| | Midpoint of train stops at station platform |
| Tail event: | Tail of train crosses a block boundary |

As discussed, some of these events affect the given train, while others may affect the following train. Note also that tail events occur at the same points as head events, thus all tail events are implicitly defined by the head table.

For each distance-related event, the train entity maintains a distance-to-go until that event occurs. At any point in simulated time, the train need only consider its next (or imminent) distance-related event. The time until this event will occur cannot always be computed ahead of time because, among other things, the location and movement of other trains affect the allowed speed of this train. (Note the analogy between this local list of distance events for each train and the typical time-based event list in simulation languages.)

Each train is modeled through both time and distance. At any given time, a train is either accelerating, cruising (speed maintaining), or braking, depending on whether its command speed is greater than, equal to, or less than its actual speed, and also depending on whether or not the train is under a stopping profile. (At present, we do not model coasting, namely, a train moving without applying either an acceleration or braking force.)

For acceleration and braking, the model uses a time and distance step equivalent to a change in velocity of 1 foot per second. If a step of 1 foot/sec will take the train past its imminent distance event, then this value is reduced proportionately and the next step takes the train to its imminent event. At each such event, the allowed speed of the train or the immediately following train may change.

## 2.6 Model Outputs

Model outputs fall into four major categories:

- Run time tables
- Train graph
- Animation
- Other tables for specialized outputs such as signal clearance times

Typical run time tables contain, for each train at each platform, its arrival and departure times at the platform, its scheduled departure time (if any), and the computed headway between trains in a given service or on a given route. From the run time table, a transit engineer can analyze train delays and recovery time for delays of various types and duration.

A train graph is a distance-time diagram representing all trains through the system over a period of time. It generally ignores acceleration and braking, representing train movement by horizontal lines for dwell times and lines of constant slope for movement between two adjacent stations.

As we previously discussed in Section 2.4, we used Proof Animation to animate train movement over the track layout. The model generates a trace file that drives the animation over a pre-drawn layout. The bulk of the layout file is drawn using a CAD system and translated into Proof layout format. The animation depicts moving trains as one object, or optionally each vehicle in a train may be depicted. It also displays the trains current control line speed. Currently, it does not display signal aspect (red, yellow or green) for manual systems because of DOS memory limitations; a later model version may use the 32-bit DOS extended version of Proof and show signal aspects.

The Proof layout may or may not be drawn to scale. For animation purposes, the model tracks actual length versus drawn length of each block, so that the head of the train is always in the "correct" (i.e., proportionate) position on screen. Since the vehicles are drawn to scale, this means that for blocks not drawn to scale that the tail of a train may apparently be in the wrong position; however, in the model, both the head and tail are at their correct position. The major consequences are that (1) a control speed may change before or after the animated tail crosses a block boundary, or worse, (2) if one or more adjacent blocks are drawn shorter than actual length, two animated trains may overlap when in the simulation they are maintaining their proper distance. The solution to the second problem is to draw blocks close to scale or longer than scale.

There are virtually no outputs of the Rapid Transit Simulator of a statistical nature that are of interest to transportation engineers. Rather, they are interested in what happens to particular trains on particular schedules, and how operational characteristics or schedules can be changed to avoid delays.

# 3 APPLICATIONS OF THE MODEL

The model has been used to simulate the MARTA ATC system and the manual TTC system. Model output has been verified by comparing model generated station to station and terminal to terminal run times with actual times.

For MARTA, the model was used to investigate the effect of single tracking (two-way traffic on a portion of track) during certain non-peak hours scheduled for track maintenance. The model is used to test different schedules to minimize or eliminate a train having to stop for another train at a single tracking zone. The MARTA model was also used to study various service possibilities and train dispatching for the new under-construction Georgia 400 branch line.

The TTC model was used to compare train delay and system capacity before and after the addition of a proposed connector that would transform the existing U-shaped network into a loop, allowing trains to circle as well as turn back.

## 4 CONCLUSIONS

The model is currently being extended for application to the Market St Elevated line on the SEPTA system in Philadelphia. This system is a manual system with numerous interlocking types different than those previously modeled. In addition, a number of other features are being added to accommodate characteristics of the SEPTA line, including multiple (versus only one) single tracking zone, more complex routings at terminals, and random or specified perturbations (delays due to numerous, un-specified causes).

The Rapid Transit Simulator provides Parson Brinckerhoff engineers and their clients with a tool for detailed analysis of track layouts, block and signal designs, schedules and dispatching, single tracking segments, and other operational and structural characteristics.

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