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# MATHEMATICAL MODELING OF TRAIN DYNAMICS: A STEP TOWARDS PC TRAIN SIMULATOR

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## Abstract

Training of locomotive engineers (train drivers) is an expensive and a time consuming undertaking. Expertise regarding efficient driving on track with steep grades and curvatures can only be achieved after many years of experience on that particular track. Coupled with this, techniques for minimizing fuel and time, conventional training is provided on the locomotive with some experienced driver. This mode of training is subject to the arability of experienced resource so it can only be carried out for a couple of times in a week. It takes locomotive engineer months to qualify for a specific section of track. A PC based train simulator can accelerate the training process. Although some train simulation games are available in the market, they are not based on the actual physics involved in the train operation. This work explores the mathematical modeling of train dynamics, and based on this model of train; we build a train simulator that can be used by railroad operators as a driver-training tool. This mathematical modeling also include modeling of the Train Air Brakes, Coupler and Wagon connections, Track forces, Dynamics Brakes and Tractive forces. The proposed train simulator provides an accurate and realistic dynamic response of actual train. In this way the transition from simulator to actual train will be much smoother.

**Keywords:** Train Simulator, Train Air Brakes Model, Mathematical Modeling, GUI, Train Dynamics

## 1. Introduction

Advancements in computer software and hardware platforms have led the rail industry to develop computer software, which can simulate the dynamics of train movement. The real challenges associated with train dynamics modeling is to arrive at an optimized model. This optimization should target minimizing complexity while still creating a modeled response that faithfully represents real-world Train response.

Rail industries of North America, Australia, Japan etc…, has been using computer aided vehicles dynamics simulators for the last two decades and these programs have come a long way. Not only do these simulation program serve to accelerate scientific research and development but also help to gain to financial advantages from Railway service industry.

Following list enumerates some advantages that can be gained through train dynamics simulators:

i) Train dynamics simulators are the only way to simulate those scenarios which are impossible to exercise in reality, for example, moving a train through very steep gradient, frequent alteration of throttle positions, sudden application of train brakes etc. The results obtained through this simulation are the source to craft the preventive driving strategies for tough tracks (Rossetti et al., 2009).

ii) Probably one of the most widely accepted advantages of train simulators is driver training program. Without this simulation programs, the operator driving would be a very expensive and dangerous activity. Advanced simulators also provide very immersive graphics to mimic the actual track and train environment. This raises the proficiency and confidence level of new drivers. Quality of mathematical model determines the usability of a train simulator as a high end locomotive engineer certification tool, as a research platform, or just a gaming product (John et al., 1977).

iii) Simulation packages play a vital role in Train Accidents investigations, which include: derailments, brake failures, human errors and accidents pertaining to steep grades and curvatures. Results of these derailments investigation help railroad authorities to develop litigations and operating procedures to prevent accidents in future (Stephen, 2000), (Paetsch et al., 2006).

iv) These simulators serve as an economical tool to develop, design and test new rail equipments. Testing new designs on real trains would be rather expensive and dangerous activity to carry out.

The main objective of this research work is to obtain and document the domain specific knowledge pertinent to train dynamics, and also to translate that knowledge into mathematical representations. Further to develop an integrated train dynamics model based on these mathematical representations and to build an easy-to-use interface to validate and tweak model response.

The domain specific knowledge has been gathered from different textbooks, published research papers and patents filed on this subject. MATLAB Simulink (simulink/index.html) has been used for rapid and iterative prototyping techniques like numerical integration, curve fitting, and parameter estimation, which are extensively used to achieve the acceptable level of accuracy within the model as a result of various iteration and modifications. The MATLAB-Simulink model has been made ready to be translated into software architecture that could be coded in C language. Furthermore to enhance user experience a graphical user interface has been developed in C# to perform validation run on the model.

The rest of the paper is organized as follows: Section 2 provides the introduction of different terms associated with rail domain in detail. Section 3 discusses the overall structure of Train Dynamics. Section 4 and Section 5 present the modeling of Wagon Connection and Track Forces, respectively. The implementation of constituents of Train Dynamics model is presented in Section 6. Section 7 presents the results of validation run perform after integrating all the aforementioned constituents into a single model. Finally, Section 8 concludes the work.

## 2. Taxonomy of Railway Industry

### *2.1 Locomotive and Rolling Stock*

Locomotive refers to active component of freight train. It provides the pulling or pushing power to the whole train. Locomotive usually incorporates diesel electric series motors to provide the traction effort. A train 'consist' may contain one or more locomotives.

Rolling-stock refers to the cars that are connected to the locomotive. They are the passive components as they do not contribute to traction effort provided by the locomotive. Freight trains are relatively lengthier than passenger trains as they might have more than five hundred car connected with them.

### *2.2 Coupler and Draft Gears*

Coupler and Draft Gears together are an assembly to connect to cars of the train. Couplers are made with a slight slack or dead-zone between them (Cole, 2006).

### *2.3 Slack Action*

It is defined as relative displacement among a string of coupled cars as the result of motoring and braking.

### *2.4 Coupler Forces*

Coupler forces are due to a combination of steady state forces and transient forces. The steady state forces are due to the resolution of all affecting forces. The transient forces are due to slack action which introduces the relative motion between front and rear cars. This relative motion dictates that both cars are having different values of acceleration. As we know that body experiences acceleration under the action of some force and this force is called coupler force. This force is parallel to the longitudinal axis of the rail vehicle. The coupler force can be classified as (Cole, 2006):

i) Buff force is the compressive coupler force or the force that tends to push the front and rear vehicle together.

ii) Draft force is the tensile coupler force that tends to pull the vehicles apart.

### *2.5 Train Air Brakes*

Train Air Brake System is pneumatic, distributed and fail-safe mechanism. Each car within the train consist has its own local air brake system. A brake pipe travels from locomotive to the last car of the train and connects to each local air brake system. This system is capable of applying, releasing and charging brakes of the car. Air brake system of all the connected cars works in collaboration to constitute train air brake system (Cole, 2006).

### *2.6 Independent Brakes*

Independent brakes are direct air brake system. Despite train air brakes, it is confined to locomotive only. They are mostly used in yards (http://en.wikipedia.org/wiki/Rail_yard) where the speed of the freight train is as low as 15 mph. Application of these brakes at higher speed may result in accident.

### *2.7 Dynamics Brakes*

Like independent brakes, they are confined to locomotive but they are not pneumatic in nature. During the application of these brakes, motors of the locomotive began to act as generators preventing the locomotive to produce more traction effort.

### *2.8 Components of Automatic Brake System*

Automatic Brake System is distributed and fail-safe (http://en.wikipedia.org/wiki/Fail-safe) mechanism. Each car within the train has its own air brake system. For the purpose of clarity; let's call it as the car air brake system. This system is capable of applying, releasing and charging brakes of the car. Air brake system of all the connected cars works in collaboration to constitute train air brake system (Table 1). Some components within the train air brake system are not the part of any car instead they influence and control the operation of all the connected car brakes systems.

Table1: Component of Train Air Brakes and their distribution.

| | |
|---|---|
| Equalizing Reservoir | Locomotive |
| Main reservoir | Locomotive |
| Brake Pipe | Extends throughout train connected to each car's control valve |
| Compressor | Locomotive |
| Control Valve | Every car |
| Auxiliary reservoir | Every car |
| Emergency Reservoir | Every car in conjunction with aux reservoir |
| Brake cylinder | Every car |
| Emergency vent valve | Every car |
| Retainer | Every car |
| Load Empty valve | Every car |
| Angle Cock | End of every car |

### *2.9 Tractive Effort and Dynamic Brakes Modeling*

Force applied and produced by locomotive to move the train is called its tractive effort. In diesel electric locomotives, input fuel is used to derive generators. These generators in-turn derives DC series motors, which pull the train by providing the tractive effort.

The traction control also called as throttle notch control. Notch can be position to provide a set point of traction effort for the system. The positions of Notch varies geographically; In north American railroad total eight positions are provided for Notch while in Australian railroad 31 positions are available.

### *2.10 Throttling*

To manipulate the power or pulling capacity of series motors, the current through diesel electric motors is controlled by throttle control. There are eight position of throttle from 1 to 8.

### *2.11 Track Grade and Curves*

Track gradient is the change in elevation of the track. One percent grade refers to 1 foot change in the elevation of track per 100 feet. Similarly, curvatures within the track are expressed in terms of degree.

### *2.12 Track Profile*

It is profile of grades and curvatures of the track on which simulator has to simulate the dynamics of train.

### *2.13 Train Consist*

Train consist is the collection of number, relative position, lading weight, type of cars attached within the train.

## 3. Classification of Train Dynamics

### *3.1 Lateral and Vertical Train Dynamics*

Lateral and Vertical Train Dynamics refers to evaluation of forces which are responsible for the movement of train in the respective directions. This aspect of train dynamics is beyond the scope of this research work; the study of these aspects of train dynamics are meant to design better railway bogies and to study wheel rail contact and to develop better suspension systems for railway wagons.

### *3.2 Longitudinal Train Dynamics*

Longitudinal train dynamics is defined as the motion of train in the direction of track. It involves the study of all those forces which contributes to the movement of train in the longitudinal direction; these forces include: pneumatic brakes (Air brakes and independent brakes), traction effort, coupler forces, dynamic brakes, grad, curvature forces etc.

The longitudinal dynamic behavior of the train can often be described by the system of differential equations. These equations, for the sake of simplicity, ignore the contributions of all the lateral and vertical forces. This assumption is employed by all the commercial rail simulation packages (Cole, 2006).

### *3.3 Distributed Mass Model*

Distributed mass model produces results that are more accurate by first simulating the dynamics of each car followed by deducing the dynamics of the whole train. The proposed simulator incorporates the dynamics of slack action and the elements of distributed train model used for this simulator are given below:

i) Train Air Brakes Model
ii) Train Dynamic Brakes Model
iii) Train Traction Effort Model
iv) Coupler Model
v) Curvature and Gradient Resistance Model
vi) Data Files

The mathematical modeling of these elements and development of MATLab model is the subject of this research work. The computations for simulation are centered on Newton's Second law of motion. Mathematical model at each time step, evaluates all the resistive and accelerative force acting on each and every car. The net force is obtained by subtracting resistive forces from the accelerative force. The net force is divided by mass of the car to obtain the acceleration produced in the car for the current time step. Simulator repeats this calculation for all the cars to determine the acceleration produced in different parts of the train. The sources of resistive forces are: Train Air brakes, dynamic brakes, independent brakes, curvature resistance, grad resistance (if train is experiencing upgrade); while the sources of accelerative forces are traction effort and grad force (if train is experiencing the down grade).

## 4. Wagon Connection and Coupler Modeling

A Wagon Connection is established by the combined activity of two auto-couplers. For the purpose of mathematical modeling, a wagon connection is considered instead of individual coupler (Cole, 2006).

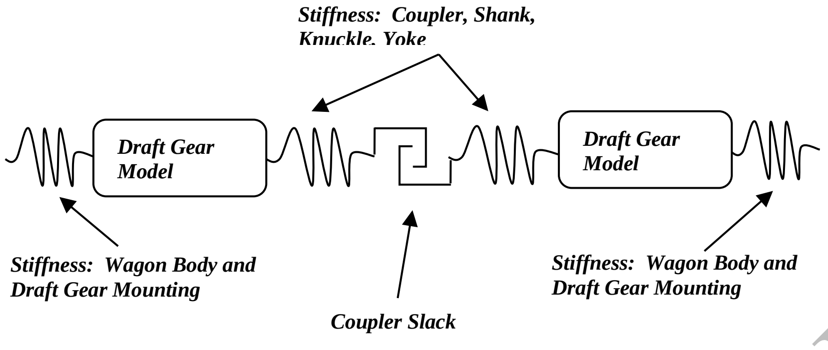

Fig. 1: Components in a Wagon Connection Model (Cole, 2006)

A wagon connection is divided into three components (Fig. 1):

- A dead zone for coupler free slack
- A linear spring for modeling of the locked stiffness. Locked stiffness is the sum of all the stiffness, added in series, which includes the component such as coupler shank, knuckle, yoke and wagon body.
- A model equivalent to two draft gears.

### *4.1 Mathematical Modeling*

To model different aforementioned regions, we have consulted different research materials like (Cole, 2006), (Cole, 1998) by Dr Cole and (Hsu et al., 1977) (by Hsu and Peters). In (Cole, 1998), Cole has suggested to opt for the following mathematical techniques for the modeling of these regions, which are listed in Table 2.

Table2: Modeling of Wagon Connection Behavior Modes (Cole, 2006).

| **Dynamic Behavior** | **Modeling Type** |
|---|---|
| Loading | Velocity and displacement dependent function |
| Locked unloading | Various linear equations |
| Unloading release | Look up table |
| Unloading | Look up table |

### *4.2 Modeling of Loading Region*

Also to model the loading region, we have studied (Cole, 2006), (Cole, 1998). Cole in (Cole, 1998) has suggested the way to improve the existing models by incorporating the role of impact velocity. His improved model of the wagon connection element (the friction wedge model), only adds a velocity function to piece-wise-linear force-displacement model (Cole, 2006). However, in this research work, we focus on the loading curve and provide relationship between force, deflection and velocity. According to (Cole, 1998), (Cole, 2006) the model is as follows:

The friction wedge model simply builds on a piece-wise-linear model of the polymer spring. The friction properties of the wedge are approximated to a function such as:

$$\mathrm{F_f} = \mu_s \mathrm{N} \qquad \text{for } \mathrm{v} = 0$$

$$\mathrm{F_f} = \mu_{(\mathrm{v})} \mathrm{N} \qquad \text{for } 0 < v < \mathrm{v_f}$$

$$F_f = \mu_k N \qquad \text{for } v \geq v_f \tag{1}$$

The force predicted by a piece-wise –linear function is of the form:

$$F = f(x) \tag{2}$$

Where $f_{(x)}$ is a piece-wise-linear function.

The polymer spring therefore can be modeled by this equation. The effect of wedge friction can then be added as follows:

$$F = f(x)\, g(F_f) \tag{3}$$

Where $g(F_f)$ is a geometry function which relates the wedge friction force to the polymer spring force. The model is now non-linear and has two independent variables x and v. In more general term:

$$F = F(x_{iw}\,, v_{iw}) \tag{4}$$

and

$$k = \frac{\delta F}{\delta x_{iw}} \tag{5}$$

As polymer spring is in series with the combined stiffness of other wagon components, the stiffness function can then be made to incorporate these stiffness components.
To model the loading region, we need to have (Hsu et al., 1977), (Cole, 1998):

i) A linear equation that relates the velocity of impact with coefficient of friction. So that we can get the relation of velocity dependent force of friction as shown in Eq. (1).

ii) A piece-wise linear function of force versus displacement.

iii) A geometrical function that relates the frictional force to the spring force.

To fulfill the first requirement, we consulted the Dr Cole's (Cole, 2006), in which a set of equations is derived to describe the phenomenon of loading and unloading. According to (Cole, 2006), these equations can be used as the starting point of the draft gear model, thus

For loading

$$F_c = F_s \tan\phi / [\tan\phi - \mu_2] \tag{6}$$

For unloading

$$F_c = F_s \tan\phi / [\tan\phi + \mu_2] \tag{7}$$

Where,

$\mu_2$ is the coefficient of friction of the wedge surface.

$F_s$ is the spring force.

$F_c$ is the coupler force.

$\Phi$ is the wedge angle.

Dr Cole further relates the coefficient of friction with the impact velocity.

$$\mu = \mu_s \qquad \text{for } v = 0$$

$$\mu = \mu_{(v)} \qquad \text{for } 0 < v < v_f$$

$$\mu = \mu_k \qquad \text{for } v \geq v_f$$

Where $\mu_s$ is the coefficient of static friction and $\mu_k$ is coefficient of kinetic friction.

This set of equations dictates that μ is equal to $\mu_s$, if the velocity of impact is zero and μ has the constant value if the velocity of impact is greater than certain final velocity $v_f$ between zero and $v_f$, μ is function of the velocity of impact. He assumed a piece-wise linear function.

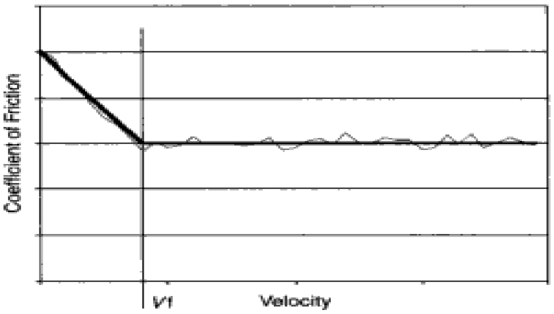

Fig. 2: Piece-wise linear approximation of wedge friction coefficient (Cole, 2006), (Hsu et al., 1977)

By visual inspection (Fig. 2), we have derived the following piece-wise linear function for velocity dependent coefficient of friction.

$$\mu = \mu_s \qquad v = 0$$

$$\mu = \frac{(\mu_k - \mu_s)}{v_f} \times v + \mu_s \qquad 0 < v < v_f$$

$$\mu = \mu_k \qquad v \geq v_f$$

Where v is the velocity of impact.

If we compare Eq. (4) of Cole's proposed model with Eq. (6) or Eq. (7), we can say that

$$g(F_f) = \tan\Phi \,/\, (\tan\Phi - \mu)$$

and

$$f(x) = F_s$$

Where $F_s$ is determined from the Fig. 3 (Cole, 2006) as it is not explicitly given in (Cole, 2006) or in (Cole, 1998).

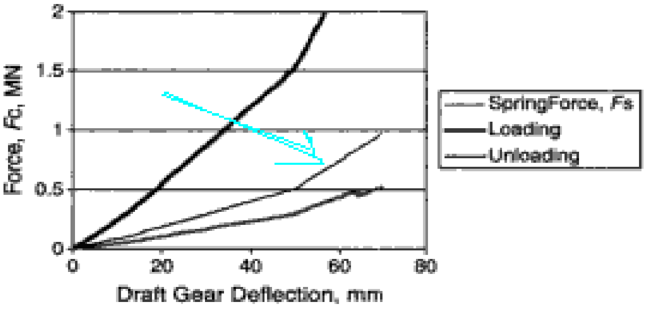

Fig. 3: Sample draft gear wedge model output (Cole, 2006)

From Fig. 3, we have concluded the following set of piece-wise linear equations for spring force $F_s$.

$$F_s = 10 * d \qquad 0 < d <= 50 \qquad (8)$$

$$F_s = 25 * (d - 50) + 500 \qquad 50 < d \qquad (9)$$

Where, $F_s$ is in KN and d is in mm

## 5. Modeling of Track Forces

Track geometry contributes to longitudinal train dynamics. Track is characterized by Curvatures and Gradient. Train dynamics simulator needs a complete profile of Track for simulation. Values of curvature and gradients are stored against at each feet distance down the track. The simulator that is designed stores the track profile in CSV format.

At each step, simulator finds the value of acceleration; integrate it twice to compute the current displacement of the train. This displacement is mapped to the current train position on the track. Simulator inquires track profile data file to find the value of curvature and gradient for currently computed train position. These curvature and gradient values are then used to compute the curvature and gradient forces that are to be used to compute the acceleration for the next simulation step.

### *5.1 Gradient*

Gradient is stated by means of feet of rise 100/feet of horizontal distance; two e.g., – A track if rises 3-feet over a distance of 100-feet, the gradient treated as "3 percent; and considered as grade of "3.5 percent if the rise of 3 and-a-half feet. Highest acceptable value for the North American Railroad is 4 percent. Gradient can be uphill or downhill.

### *5.2 Curvature*

Curvature is stated by means of the no. of degrees traversed by 100-feet of track. e.g., a curve of 5-degree encompass 5-degree of a circle for each 100-feet of track, a sharper 16-degrees curve covers 16-degree in each 100-feet (Durali et al., 2004).

### *5.3 Grade Force*

The force due to track grade is determined from the following Eq. (10) (TFRA-USA, 2009):

$$F_{GRD} = 20 \times W \times G \tag{10}$$

Where G is average percent grade under the train. The average percent grade under the train is determined by the following Eq. (11):

$$G = \frac{E_{HE} - E_{TE}}{L} \times 100 \tag{11}$$

L is the length of the train.

Where $E_{HE}$ is the elevation at the head end

$E_{TE}$ is the elevation at the tail end

The elevations are determined by referencing the head and tail-end positions with the data in the track profile data file, where the tail end position is the difference between the head end position and the train length. It should be noted that this method is only accurate for trains with a uniform mass distribution, and therefore some assumption will cause some errors to appear in end results.

## 6. Implementation of Train Dynamics Simulator

This section describes the implementation of Train Dynamics simulator in C programming language. In this context, following items has been documented:

i) Description of different C code software modules and how the function as cohesive whole.

ii) Software architecture of simulation environment that has been developed to execute the mathematics of train dynamics.

iii) Various input and output files which are needed by simulator to perform and manifest its functionality.

For the convenience of reviewer and reader, different terms appeared in this section are described here:

*Simulation Engine:* Simulation Engine refers to the module that executes the simulation logic by integrating functions from Mathematical Library.

*Mathematical Library:* It is the collection of mathematical functions that are to be used as the building blocks of simulation logic

*Simulator Interface:* It is the mean by which Simulator can communicate with other applications.

*Post Simulation:* Phase followed by the expiry of simulation run. It includes archiving output data in the file or rendering this data to GUI Application.

### *6.1 Simulator Architecture*

This section is intended to provide the detailed description of design and Implementation of Train Dynamics simulator in C. The architecture of the simulator can be described by design entities:

i) Simulation Configuration File
ii) Dynamic Parameter File
iii) Track Profile
iv) Simulation Engine
v) Mathematical Library Functions

On the other hand, functionality of the simulator is described by its phases of its execution:

i) Initialization
ii) Simulation Run
iii) Post Simulation

### *6.1.1 Simulation Configuration File*

This is intended to be a (.INI) file which is the de facto standard for the configuration files. The purpose of this file is to provide the simulator with user defined configuration parameters as given in Table 3. These configuration parameters include:

i) Simulation configuration parameters
ii) Configuration parameters specific to train dynamics
iii) Paths of input/output files such as, Train Consist, Track Profile in the Local File system

Table3: Configuration Parameters.

| | |
|---|---|
| 1 | Memory Allocation |
| 2 | Simulation Time |
| 3 | Step Size |
| 4 | Distance Limit |
| 5 | Gross Braking Ratio |
| 6 | Mu |
| 7 | Brake Ragging |
| 8 | Wind Resistance Drag Coefficient |
| 9 | Rolling Friction Coefficient |
| 10 | Train Consist Path |
| 11 | Track Profile Path |
| 12 | Dynamic Parameters Path |

### *6.1.2 Dynamic Parameter File*

This is intended to be a (.CSV) file having name DynamicParameter.csv. This file includes some user defined parameters which are intended to specify the state of different train controls and their corresponding time stamps.

User define parameters/train control are listed below.

i) Notch values

ii) Brake Pipe Pressure reduction command, also include the specification of emergency/full service or release states

iii) Dynamic brake commands

*Dynamic Parameter File Format/Sample:* Format of data within the file is given in the Table 4.

Table4: Dynamic Parameters Sample.

| Time | Notch | Brake Pipe Pressure | Dynamic Brake |
|---|---|---|---|
| 0.0 | 1 | 10.0 | 15 |
| 5.5 | 3 | Charge | 25 |
| 50.5 | 6 | Uc (Unchanged) | 20 |
| 150.3 | 4 | Full Service | 18 |
| 200.0 | 5 | Charge | 25 |
| 300 | 6 | Emergency | 10 |

### *6.1.3 Track Profile*

This is intended to be a (.CSV) file having name TrackProfile.csv. The purpose of this file is to provide simulator with track information. Track information contain track grade and track curvature data. This information is included in file on per feet basis. Data included in this file is listed below:

i) Distance in feet

ii) Track Grade in Percentage

iii) Track Curvature in percentage

Format of the data on file is given in the Table 5.

Table5: Track Profile Data Format.

| Start Point (feet) | End Point (feet) | Track Element | Value |
|---|---|---|---|
| 1 | 3000 | Grade | 1 % |
| 1500 | 2500 | Curve | 1 Deg |
| 3001 | 3999 | Grade | 1% |
| 4000 | 4500 | Curve | 2 Deg |
| 4600 | 4700 | Grade | 4% |

## 7. Experimental Results

This section describes the results of simulator. A lightweight GUI application has been created so that user can interact and view the results of the simulator. Results are displayed against following contents of input files.

### *7.1 Inputs for the Experiment*

*Track Profile:* Table 6 shows the data for the sample track profile:

Table6: Sample Track Profile data.

| Start Point (feet) | End Point (feet) | Track Element | Value |
|---|---|---|---|
| 1 | 3000 | Grade | 1 % |
| 1500 | 2500 | Curve | 1 Deg |
| 3001 | 3999 | Grade | 1% |
| 4000 | 4500 | Curve | 2 Deg |
| 4600 | 4700 | Grade | 4% |

*Train Consist:*

One Locomotive and five (5) connected cars are included for this experiment. Actual Contents of Train consist are omitted for the sake of clarity and conciseness.

*Dynamics Parameters:*

Following are the contents of Dynamics Parameter file (Table 7):

Table7: Sample Dynamic Parameter Data.

| **Time instant (sec)** | **Throttle Noch** | **Automatic Braking (psi)** | **Dynamic Braking Notch** |
|---|---|---|---|
| 0 | 1 | Charge | 0 |
| 30 | 2 | Charge | 0 |
| 60 | 3 | Charge | 0 |
| 80 | 3 | 7 | 0 |
| 100 | 0 | 15 | 0 |

## 7.2 Simulation Configuration File

Following are the contents of Simulation Configuration file:

```
State vector size   =   20000
Simulation time   =   150.0 sec
Step size   =   0.005sec
Coupler hard limit   =   0.4 m
First stage loading   =   6000.0 n/mm
Second stage loading   =   17000.0 n/mm
Locked stiffness   =   600000.0 n/mm
Relaxing stiffness   =   600.0 n/mm
Slack region width   =   0.1 m
Kinetic fric coff   =   0.2
Static fric coff   =   0.4
Wedge angle   =   35.0 degree
Cut of cars   =   5
```

### 7.3 Experimental Results

*Train Speed:*

Speed curves are shown (Fig. 5) for three cars of the train makeup- see section 7.1.2 and 7.1.4- at each throttle change speed shoots till he point when brakes of 7psi are applied. At 100 sec the train brakes of 15 psi bring the speed for all the cars down to zero as shown in Fig. 5.

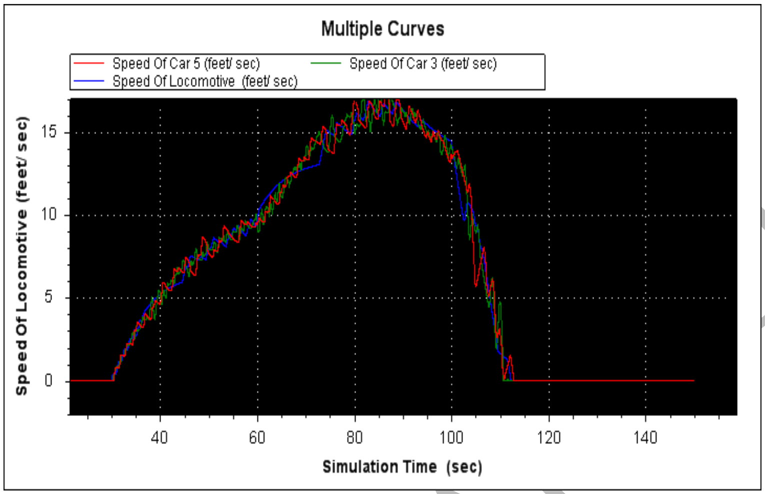

Fig. 5: Speed Curves

*Locomotive Tractive Effort:*

The locomotive tractive effort is shown which is indicative of variations whenever throttle is changed. At 100 second tractive effort reduces down to zero (as shown in Fig. 6) due to the fact that throttle is positioned at zero.

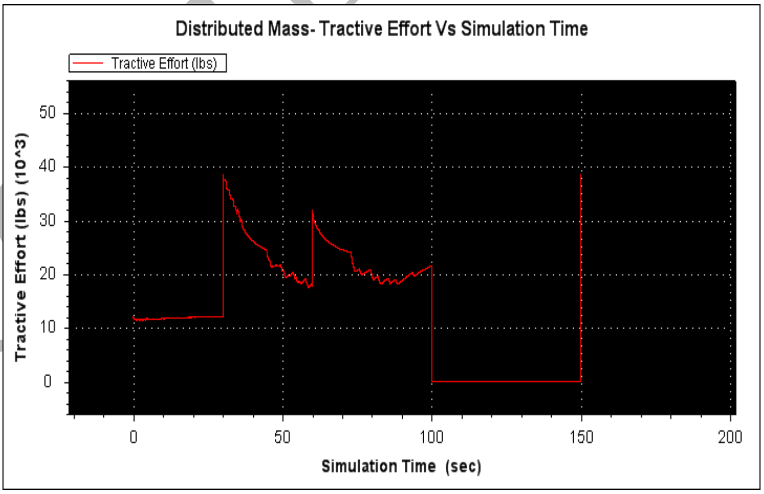

Fig. 6: Tractive Effort

*Train Acceleration:*

The Fig. 7 represents the acceleration curve for the locomotive for the entire simulation span. Each throttle change is causing the transients in the signal.

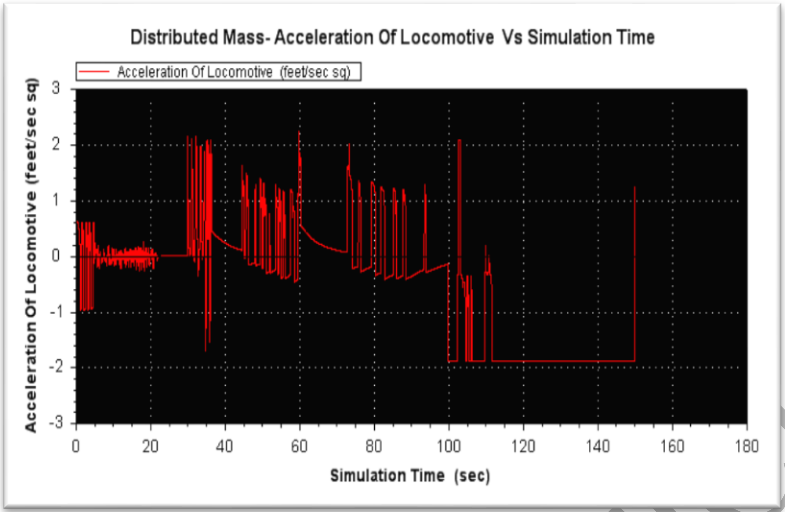

Fig. 7: Acceleration Curve

*Brake Cylinder Pressure:*

The Fig. 8 represents the brake cylinder pressure buildup for two cars. As automatic braking of 7 and 15 psi are applied at 80 and 100 sec. The respective build-up can be seen at these points (Refer to 7.1.3 for current train controls setting supplied to simulator).

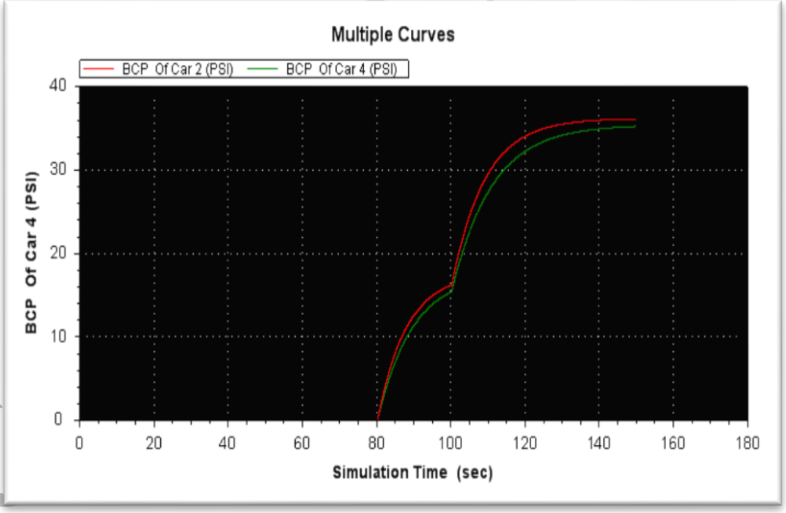

Fig. 8: Brake Cylinder Pressure Curves

**Coupler Forces:**

The Fig. 9 represents the displacement to coupler force graph of the coupler that connects the 3rd and the 4th car together. The buff forces and draft forces are shown on the same displacement axis with sign changed.

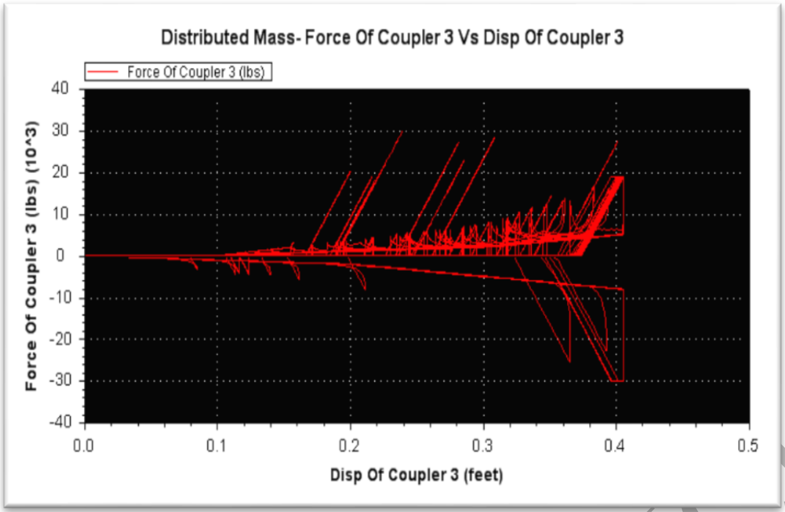

Fig. 9: Coupler forces Curves

*Relative Position Change:*

The Fig. 10 represents the change in the position of the cars as the train moves. Simulator, by taking into account the length and number of cars connected together within the train consist; determine the initial positions of each car. Subsequently, it records the change in position of each car.

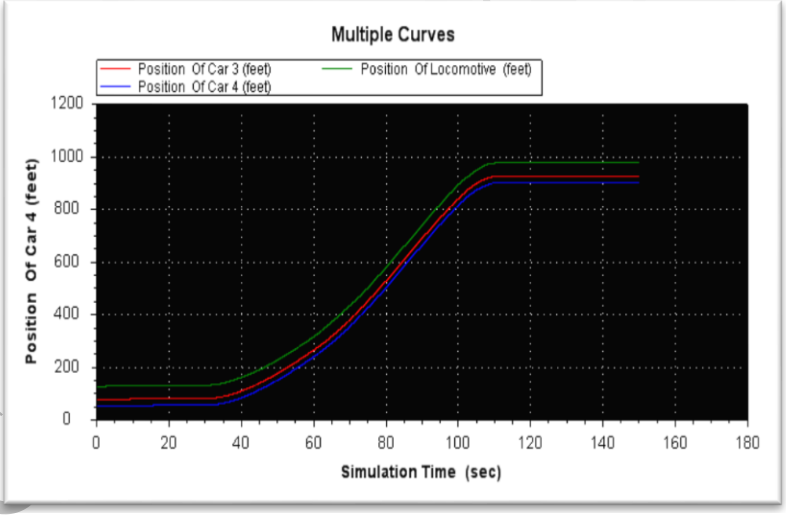

Fig. 10: Variation in Position

## 8. Conclusion and Future Work

This research work attempts to transform the industrial experience of the author with train dynamics, available research material and textbooks into mathematical representations and subsequently into software artifact. Simulator that is developed as the result of this research activity serve as a way to simulate those scenarios which are next to impossible to exercise on actual infrastructure, for example, train movement on steep spiral track, sudden alteration of throttle positions by defying the train handling rules, sudden application of train brakes etc. The results obtained through this simulation are the source to craft the preventive driving strategies for tough tracks.

In this research work, different components for longitudinal train dynamics model are identified and studied. With the aid of available research and development, mathematical model (Daeki et al., 2007) of these components are developed. Simulink has been used for rapid prototyping of the component. Subsequently, by making use of principles of Newtonian physics, these component are wired together in order to retrieve useful data like speed, distance and brake forces, The Simulink model is then codified in C language and GUI is developed so that model can be used in personal computer.

GUI developed along with model is designed in such a way that it provides the user with ease to simulate train dynamics on any user defined track A study has been made to develop a model of track. All the parameters are made configurable so that user can tune the model according to track geometry and train consists.

This research work also explores various areas where improvements can be made to increase the efficiency of the model. The key areas includes but not limited to: model tuning, runtime parameter estimation, adaptive software configuration, modeling of brake pipe leakage, modeling of longitudinal vibrations. Software has been developed in a modular fashion so the models of these aforementioned concepts can easily be incorporated.

Lack of aggregate real train data is one the biggest challenge for the validation and verification of train simulator. Author has attempted to gather it—as much as he can— from engineers working with train automation, textbooks and research material.

- Another usage of this HIL simulation is to use them to develop Automatic Train Control System in which, except for an independent system to detect and handle anomaly, driver is completely replaced with simulators.
- One of the profitable aspects of train dynamics simulators, that is beyond the scope of current research work, is to measure the stopping distances, i.e., quantification of distance train can possibly travel before arriving to stand-still when one or combination of these types of brakes application are performed: Zero-Stop, Full Service and Emergency Service. This measurement helps trainee and drivers to anticipate the how or when to apply brakes effectively on the given route in order to minimize the chances of accidents (James et al., 2005).
- Mathematical models presented within this research work can be useful to develop algorithms to design train control operations in such a way that usage of fuel could be minimized. These algorithms would take the advantage of the fact that existing train dynamics mathematical models depends of track geometry. As described in Chapter 4. So a track awareness algorithm can be developed that try to produce the profile of train control positions for entire duration of train movement with the goal to achieve fuel efficiency.

## References

Cole, C., (1998), Improvement to wagon connection modeling for longitudinal train simulation. Proc., Conf. on Railway Engineering: Engineering Innovation for a Competitive Edge, Institute of Engineers, pp. 187–194, Rockhampton, Australia.

Cole, C., (2006), Chapter 9: Longitudinal Train Dynamics, A Handbook of Railway Vehicle Dynamics, pp. 240-277, Edited by Simon Iwnicki, Print ISBN: 978-0-8493-3321-7, CRC Press.

Daeki, H., Hyeongcheol, L., and Jaeho, K., (2007), Development of a Mathematical Model of a Train in the Energy Point of View, In Proceedings of International Conference on Control, Automation and Systems (ICCAS 2007), Seoul , Korea.

Development of an Adaptive Predictive Braking Enforcement Algorithm U.S. Department of Transportation Federal Railroad Administration, June 2009.

Durali, M., Mehdi Jalili Eahabadi, M., (2004), Investigation of Train Dynamics In Passing Through Curves Using a Full Model”, In Proceedings of the 2004 ASME/IEEE Joint Rail Conference, Baltimore, Maryland, USA, April 6-8.

Hsu, T. K. and Peters, D. A., (1978), A Simple Dynamic Model for Simulating Draft-Gear Behavior in Rail-Car Impacts, Journal of Engineering for Industry, Vol. 100, No. 2, pp. 492–496, November.

James, R. L., William G. J., Bernard S. A., (2005), Train Accident Reconstruction and FELA and Railroad Litigation By Published by Lawyers & Judges Publishing Company, ISBN 1930056931, 9781930056930.

John, E. Mosier, Duncan Okla, (1977), Railway Train Control Simulator, US Patent Number 4041283.

Paetsch, C.R., and Jeong, D.Y., (2006), Dynamic Simulation of Train Derailments”, Massachusetts, USA.

Railroad engineering, Volume 1, By William Walter Hay (2005).

Rossetti, M.D., Hill, R.R., Johansson, B., Dunkin, A., and Ingalls, R.G., (2009), YARDSIM: A rail yard simulation framework and its implementation in a major railroad in the U.S. Edward Lin and Clark Cheng Norfolk Southern Corporation, In Proceedings of the Winter Simulation Conference, May.

Stephen, K. Nickles, (2000), A Method of Optimizing Train Operation and Training, US Patent Number-6144901.

http://en.wikipedia.org/wiki/Fail-safe (Dec, 2011)

http://en.wikipedia.org/wiki/Rail_yard (Jun, 2011)

http://www.mathworks.com/products/simulink/index.html (Dec, 2011)