Metadata of the chapter that will be visualized online

Chapter Title	Physical Networks' Approach in Train and Tram Systems' Investigation	
Copyright Year	2016	
Copyright Holder	Springer International Publishing Switzerland	
Corresponding Author	Family Name	**Simic**
	Particle	
	Given Name	**Milan**
	Suffix	
	Division	School of Aerospace, Mechanical and Manufacturing Engineering (SAMME)
	Organization	RMIT University
	Address	Bundoora East Campus, Plenty Road, Bundoora, Melbourne, VIC , 3083, Australia
	Email	milan.simic@rmit.edu.au
Abstract	Large vehicles on rail networks are complex, nonlinear, engineering systems that perform translator motion. Apart from system components' nonlinearities, there are environmental influences as well, through railroad characteristics' changes on the long routes. On the one side, we have historical or legacy systems, still in place, and on the other, there are state-of-the-art train compositions that are capable of achieving extremely high ground speeds of transportation. In both cases reliability and safety are the primary objectives in system maintenance and system design. Global physical networks approach is presented here, and applied in this investigation. Physical quantities like speed, force, power, and energy are studied, monitored, and presented. The main contribution of this modeling application is in its capability to obtain various data from any part of the system which could be used for the improvement of overall system safety and reliability.	
Keywords (separated by "-")	Physical network - Network elements - Train - Tram - Composition - Rail network - Traffic safety - System reliability	

Chapter 4
Physical Networks' Approach in Train and Tram Systems' Investigation

Milan Simic

Abstract Large vehicles on rail networks are complex, nonlinear, engineering systems that perform translator motion. Apart from system components' nonlinearities, there are environmental influences as well, through railroad characteristics' changes on the long routes. On the one side, we have historical or legacy systems, still in place, and on the other, there are state-of-the-art train compositions that are capable of achieving extremely high ground speeds of transportation. In both cases reliability and safety are the primary objectives in system maintenance and system design. Global physical networks approach is presented here, and applied in this investigation. Physical quantities like speed, force, power, and energy are studied, monitored, and presented. The main contribution of this modeling application is in its capability to obtain various data from any part of the system which could be used for the improvement of overall system safety and reliability.

AQ1

Keywords Physical network • Network elements • Train • Tram • Composition • Rail network • Traffic safety • System reliability

4.1 Introduction

We could easily say that the train is among the longest, mobile, mechanical engineering systems that humans can build, nowadays. Train compositions, that can stretch few kilometers, usually have distributed power units, i.e., locomotive engines positioned in front of, between wagons, and behind them. Such long and heavy transportation systems express nonlinearities of different types. That also depends heavily on the environment conditions. For example, friction between the rails and the wheels is changing drastically when the weather changes from the very dry and sunny conditions to heavy rain, or snow and ice on the rails. Those conditions are extremely important for the acceleration and braking, having in mind that we perform motion control of the overall mass of few 10^7 kg. There are

AQ2

M. Simic (✉)
School of Aerospace, Mechanical and Manufacturing Engineering (SAMME), RMIT University, Bundoora East Campus, Plenty Road, Bundoora, Melbourne, VIC 3083, Australia
e-mail: milan.simic@rmit.edu.au

R.N. Jazar, L. Dai (eds.), *Nonlinear Approaches in Engineering Applications*,
DOI 10.1007/978-3-319-27055-5_4

various mathematical models and simulations used in the systems' study and design (Ďurica 2015; A mathematical model for a train run). In various large and complex, nonlinear, engineering systems investigation, physical networks approach is one of the valuable tools adapted and already presented (Simic 2015). Application area is now extended and results are presented here. Velocities, forces, displacements, power, and energy have been monitored.

Initially, a physical networks' model of a single wagon is created taking in consideration the mass of the vehicle together with the stiffness and friction components of the interfacing elements between wagons and with the rails. Starting from that basic model, the whole train composition model, as a large network, is set up and simulations performed. Any physical quantity can easily be monitored and displayed. This gives valuable information on the subsystems and system design.

4.2 Physical Networks Approach in Modeling

Physical network is a geometrical structure of interconnected ideal network elements, with two connection points. Network elements represent mathematical relationships between two dependent system variables in the physical system. Engineering systems are built using various sets of elements, specific for the system type. Basic definitions, principles, and rules for solving equations represented by a network are independent of physical system which that network is representing.

Energy through the system is transferred and transformed using two types of system variables. ***Flow, f,*** type system variables are representing physical quantities that are traveling ***through*** the systems elements, and their connections. ***Potential, p,*** type variables are expressing the state established ***across*** the system elements and between any two network points, i.e., nodes. Potential of a point in the network is a relative quantity and depends on the reference point chosen. For example, speed is relative, as we know, and depends on the reference.

A simple physical network example is shown in Fig. 4.1. Looking from the energy point of view, there are passive and active network elements in each network. Generic name for any passive element is impedance, $\boldsymbol{Z}$, or admittance, $\boldsymbol{Y}$, where $\boldsymbol{Z = 1/Y}$. Active elements, or energy suppliers to the system, are ideal flow and potential sources, as well as initial conditions expressed as initial values of the flow through, and potential across network elements.

Ideal flow source, shown as $\boldsymbol{F(t)}$ in Fig. 4.1, has infinite internal resistance, called impedance, $\boldsymbol{Z_{in}}$, $\boldsymbol{Z_{in}} \text{->} \infty$ while ideal potential source, $\boldsymbol{P(t)}$, has zero value of the internal impedance, $\boldsymbol{Z_{in} = 0}$. Flows through branches are shown, and labeled as $\boldsymbol{f_1}$ and $\boldsymbol{f_2}$, while the node potentials are marked as $\boldsymbol{p_1}$ and $\boldsymbol{p_2}$. In any physical network, product of instant values of two network variables, flow $\boldsymbol{f(t)}$ and potential $\boldsymbol{p(t)}$, is giving the value of the instant power $\boldsymbol{p(t)}$, that particular network element dissipates or stores, as given by Eq. (4.1).

$$p(t) = f(t) * p(t) \tag{4.1}$$

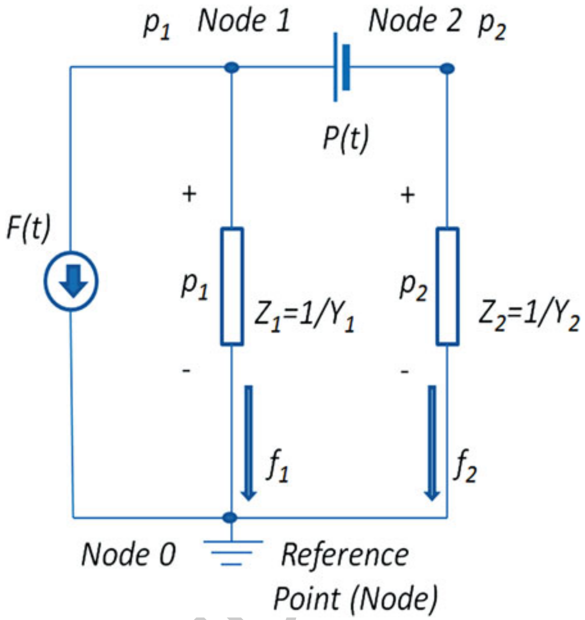


Fig. 4.1 Generic physical network diagram: Ideal flow source is labeled as ***F(t)***, while ideal potential source is labeled as ***P(t)***

The unity of the nature is expressed in the extraordinary analogies of the differential equations used to represent various physical phenomena. The same type of equations, ordinary differential equations (ODE), is used for the study of mechanical systems with translation, mechanical systems with rotation, hydrodynamics, and for the electrical circuits. The theory of turbulence in liquids and the theory of friction in gases show great similarities with the electromagnetic theory. Network elements represent mathematical relationships between two dependent system variables in a physical system. There are three types of relationships: proportionality, differentiation, and integration. For example, in an electrical circuit those basic elements are resistor, capacitor, and the coil. Often, real systems are extremely complex, but they can be simplified, or they may have linear subsystems as their integral parts.

Examples of physical variables in an electric circuit are ***electrical current,*** as a ***through variable***, and ***electrical potential,*** as an ***across variable***. Current, i, through electrical conductors, or a network element, is directly related to the ***mechanical*** flow of electrons, i.e., charge, dq, over time dt, as per Eq. (4.2).

$$i = \frac{dq}{dt} \tag{4.2}$$

The charge of a single electron is $e = -1.602 \times 10^{-19}$ *coulomb*. Following that, the current of *1A* corresponds to the flow of 6.241509×10^{18} electrons per second.

Electrical potential, V_C, for example, is related to the number of accumulated electrons, on capacitor C, plates, as given by Eq. (4.3),

$$V_C = \frac{1}{C}\int_0^T i dt = \frac{1}{C}\int_0^T \frac{dq}{dt} dt = \frac{Q(T)}{C}; \quad \text{if } Q(0) = 0 \tag{4.3}$$

where *Q(T)* refers to the accumulated charge over the period T and initial charge on the capacitor plates, for $t = 0$, was *0 coulomb*. Potential difference between two nodes is called voltage. The universal reference point, in electric circuits, is ground potential of *0 V*.

We have ***force*** and ***velocity*** as network variables in a mechanical system with translation, or ***torque*** and ***angular speed*** in a mechanical system with rotation. In a hydraulic system we have ***flow*** and ***pressure***.

ODE with constant coefficients, A_i, $i = 0 - n$, are used for modeling various physical systems. An ODE, shown by Eq. (4.4), is a relation between two variables: independent variable t and dependent $y = y(t)$, and the derivatives of y as follows $\frac{dy}{dt}, \frac{d^2y}{dt^2}, \ldots, \frac{d^ny}{dt^n}$.

$$A_n \frac{d^n y}{dt^n} + A_{n-1}\frac{d^{n-1}y}{dt^{n-1}} + \cdots + A_1 \frac{dy}{dt} + A_0 y = f(t) \tag{4.4}$$

On the right-hand side, we can have any function of time, *f(t)*. The special case when $f(t) = 0$ is known as homogenous equation. Equation (4.4) is called ordinary because only one independent variable exists, which is usually time. It is linear because only the first exponent of dependent variable, or its derivatives, is present in the expression. Examples of network components in a generic physical network, then in an electrical circuit, mechanical system with translation and mechanical system with rotation, are given in Table 4.1. Equations for the stored energy and power losses are also presented.

In a generic physical system, integration, proportion, and differentiation of network variables are associated with elements labeled as A, B, and C. The general name for all of them is impedance, Z, or admittance Y, as already shown in Fig. 4.1. In an electrical circuit we have inductivity, L, conductivity G, i.e., resistivity, $R = 1/G$, and capacity C. Finally for the translation we have k for stiffness, B for friction, and m for mass of the object. Translator network variables are force, F, and velocity v. There are also other physical systems like thermal and fluids where analogies could easily be established, as given in (de Silva 2005 and Sanford 1965).

4.3 Mechanical System with Translation: Basic Model

Let us consider a mechanical system with translation. Two approaches in modeling of a basic network, which includes all three passive network elements and a power source, are presented here. Passive network elements are mass, ***m***, expressing

Table 4.1 Various physical network components

	Description	Prototype	Electrical	Translation	Rotation
t3.1	Through variable	***Flow - f***	***Current - i***	***Force - F***	***Torque, or Momentum - M***
t3.2	Across variable	***Potential - p***	***Voltage - u***	***Velocity - v***	***Angular Velocity - w***
t3.3	Element integration	Generic Element A $f = A\int pdt$	Inductivity L $i = \frac{1}{L}\int udt$	Stiffness k $F = k\int vdt$	Rotational Stiffness k $M = k\int wdt$
t3.4	Accumulated energy	$\frac{f^2}{2A}$	$\frac{Li^2}{2}$	$\frac{F^2}{2k} = k\frac{x^2}{2}$ $x =$ distance	$\frac{M^2}{2k}$
t3.5	Element proportion	Generic element B $f = Bp$	Conductivity G/Resistivity R $i = Gu = \frac{1}{R}u$	Damping constant B $F = Bv$	Angular damping D $M = Dw$
t3.6	Power dissipation	$fp = \frac{f^2}{B} = p^2B$	$iu = i^2R = \frac{u^2}{R}$	$Fv = \frac{F^2}{B} = v^2B$	$Mw = \frac{M^2}{D} = w^2D$
t3.7	Element differentiation	Generic element C $f = C\frac{dp}{dt}$	Capacity C $i = C\frac{du}{dt}$	Mass m $F = m\frac{dv}{dt}$	Moment of Inertia $F = M\frac{dw}{dt}$
t3.8	Accumulated energy	$\frac{Cp^2}{2}$	$\frac{Cu^2}{2}$	$\frac{mv^2}{2}$	$\frac{Mw^2}{2}$

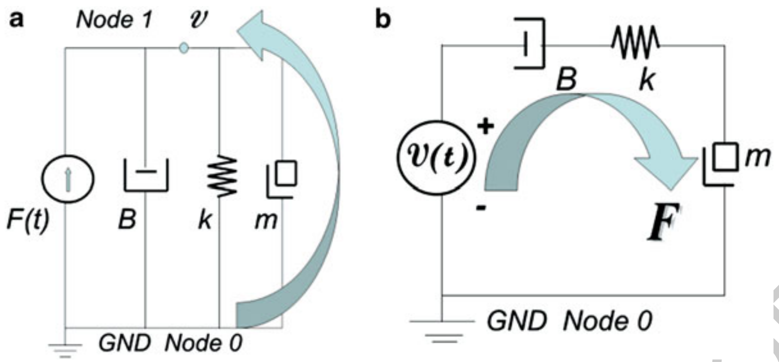


Fig. 4.2 (**a**) Basic mechanical network model with ideal force power source ***F(t)***. (**b**) Basic mechanical network model with ideal velocity power source ***V(t)***

inertia, spring element with its stiffness, ***k***, and damping element, ***B.*** Active elements, presented here, are an ideal force source, ***F(t)***, as shown in the first layout, Fig. 4.2a, and an ideal velocity source, ***V(t),*** as shown in the second layout, Fig. 4.2b.

Basic translational motion mechanical network with ideal force source ***F(t)*** can be expressed with Eq. (4.5), i.e., Eq. (4.6) as follows:

$$Bv + m\frac{dv}{dt} + k\int v dt = F \tag{4.5}$$

or in an operator form

$$\left(B + m\frac{d}{dt} + k\int dt\right) v = F \tag{4.6}$$

On the other side, basic translational motion mechanical network with ideal velocity source ***V(t)*** can be expressed with Eq. (4.7), i.e., Eq. (4.8) as follows:

$$\frac{F}{B} + \frac{1}{k}\frac{dF}{dt} + \frac{1}{m}\int F dt = v \tag{4.7}$$

or in an operator form

$$\left(\frac{1}{B} + \frac{1}{k}\frac{d}{dt} + \frac{1}{m}\int dt\right) F = v \tag{4.8}$$

In Fig. 4.2a the same velocity, *v*, is measured across all network elements as it is an ***across variable***. Since there are no initial condition shown, the sum of forces through passive elements equals the force supplied by ideal force source ***F(t).*** Analogue story is for the network shown in Fig. 4.2b, where the same force is measured ***through*** all network elements. In this case the sum of all velocities measured ***across*** all passive elements equals to the velocity supplied by the ideal velocity source ***V(t).***

4.4 Modeling a Single Wagon

We will now consider a single wagon model. Vehicle has four pairs of wheels that support the body by springs and dry friction dampers. A wagon is shown in Figs. 4.3a and 4.4, while connection interface can be seen from Fig. 4.3b. Initial model design would include basic sub-networks as already shown in Fig. 4.2a, just without force power source component. We have eight sub-models, each with all three basic network elements. Since the velocity is same, in the node 1, we can use equivalent representation. Following that, in the next step of modeling we will represent the system with just two support points which very much correspond to the mechanical design. The system is nonlinear and multidimensional, but motion and vibrations along other axes might be subject of another investigation, since we now just consider the motion along the line connecting two points on the railroad. We will neglect gravitational stiffness since we will consider just one dimensional problem of translation along x axis.

Fig. 4.3 (**a**) A single wagon as an example for basic tram/train elements modeling; (**b**) Connection interface that will be modeled as a spring

Fig. 4.4 A standard wagon with four sets of wheels

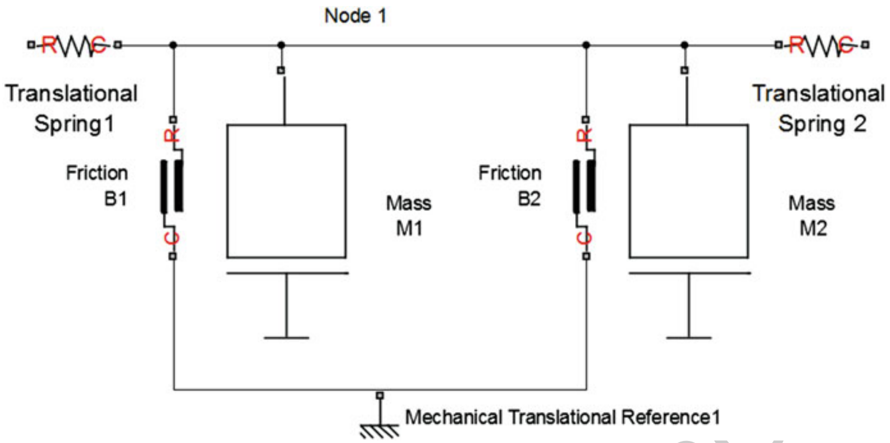


Fig. 4.5 A Simulink model of a single wagon with 2 support points and connection interface

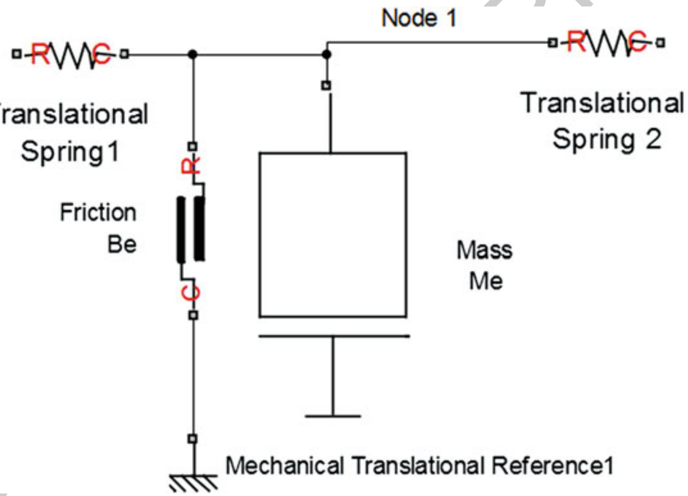


Fig. 4.6 Final Simulink model of a single wagon with connection interface

Two support points model designed in Simulink is shown in Fig. 4.5. Connection interface is presented by translational springs. Further simplification of the model is shown in Fig. 4.6. Once again, since the velocity in the node 1 is applied ***across*** all network elements we can represent the network from Fig. 4.5 with the equivalent one given in Fig. 4.6. Total equivalent mass *Me* is the sum of M1 and M2, while the *Be* is the sum of B1 and B2. Comparing translational mechanical system to an electrical system, we can see that the ***mass*** of an object shows analogy with the ***capacity*** while the ***friction*** is similar to the ***conductivity***, i.e., reciprocal to the resistivity, $\boldsymbol{G = 1/R}$.

4.5 System of Two Wagons

Let us now consider the process of joining two wagons. One of them is in stationary state while the other one is approaching with the speed of $v_0 = 2$ m/s. Using the equivalent wagon model presented in Fig. 4.6 we have designed system's model of two wagons as shown in Fig. 4.7. The presented model is ready to run, but we should be able to monitor changes in the network variables. In our case, basic physical variables of interest are speed and force. Position, power, and energy could be monitored as well, based on the set of Eqs. (4.9), (4.10), and (4.11).

$$\text{Position} = \int_0^T v(t)dt \tag{4.9}$$

$$\text{Power} = p(t) = F(t) * v(t) \tag{4.10}$$

$$\text{Energy} = E = \int_0^T p(t)dt = \int_0^T F(t) * v(t) \tag{4.11}$$

In order to monitor physical quantities as mentioned above we need to introduce sensors and display devices. While measuring velocity as an ***across variable*** we have to place the sensor ***across*** network element. Our Ideal Translational Motion Sensor, as defined in Simulink environment, has to be placed across measurement node and the Mechanical Translational Reference, which is equivalent to mechanical

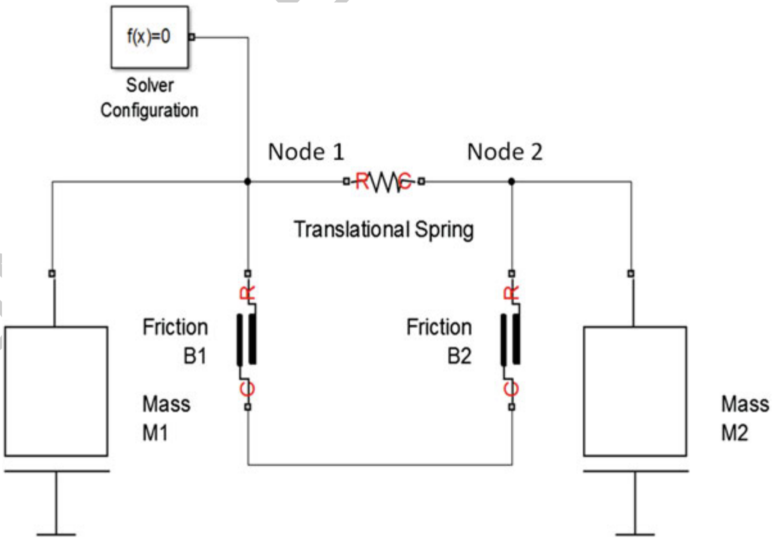


Fig. 4.7 A Simulink model of two wagons

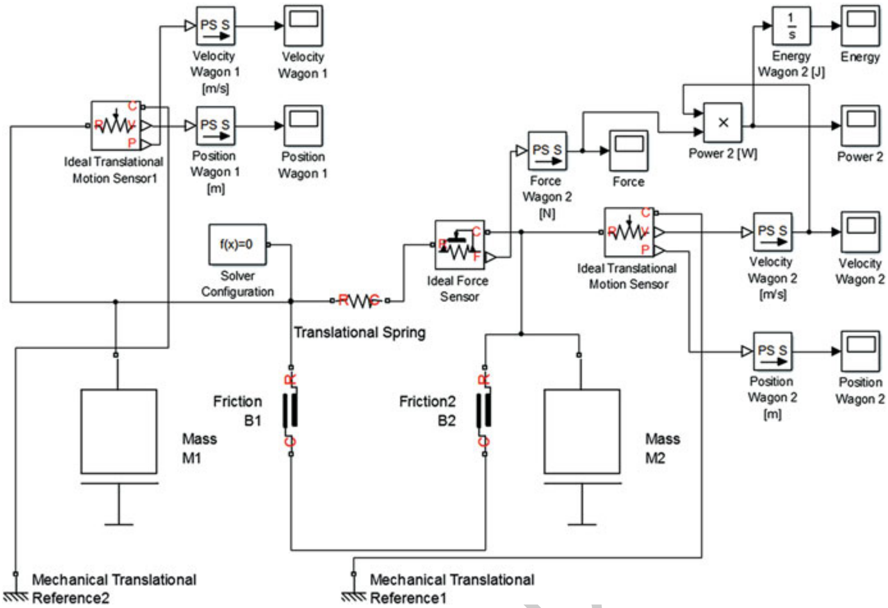


Fig. 4.8 Final Simulink model of two wagons with sensors and monitors

motion ground, i.e., $V_{\mathrm{GND}} = 0$ m/s. Opposite to that, measurement of a through variable, such as force in our case, requires placement of the sensor in the network. According to this a new simulation model is designed and presented in Fig. 4.8. Simulation results for the wagon one velocity, wagon two velocity, path traveled, i.e., position and force at the wagon two, are presented in Fig. 4.9.

We can see that the speed of the first wagon is going down from the initial value of $v_0 = 2$ m/s to 0.64 m/s, oscillating and then stabilizing at the value of 1 m/s as expected.

Similarly, after the impact, the speed of the second wagon is increasing from 0 m/s to 1.36 m/s, oscillating and then stabilizing at 1 m/s. The force is maximum just after the contact and then oscillating and going down to zero. The power diagram is shown in Fig. 4.10. Variables are expressed in SI systems units [W]. SI units are used in the whole paper. Finally energy carried by wagon 2 is shown in Fig. 4.11.

Since the friction elements are involved, we have inelastic collision of two masses, where one of them was stationary. Assumption was made that the masses are the same. Inelastic collisions do not conserve kinetic energy, but the conservation of moment is in place. After the collision two masses are joined together and travel in the same direction. In Eq. (4.12) speed is shown as a vector quantity. We can see that in the particular case of inelastic collision, as simulated by our model, expected

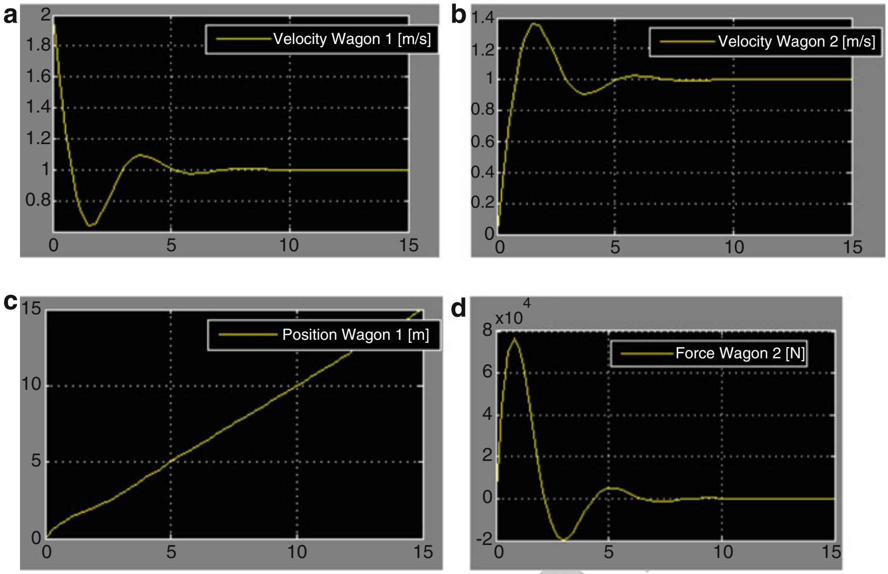
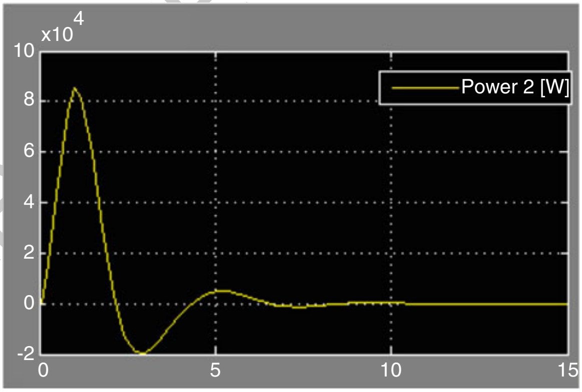


Fig. 4.9 (**a**) Wagon 1 velocity. (**b**) Wagon 2 velocity. (**c**) Path traveled. (**d**) Force at wagon 2 node

Fig. 4.10 Power measured at the wagon 2 node



final velocity should be half of the initial velocity. That can easily be verified by looking at Fig. 4.9a, b.

$$M1 = M2 = m,$$

$$m\mathbf{v}_0 = m\boldsymbol{v}_f + m\boldsymbol{v}_f = 2m\boldsymbol{v}_f$$

$$\boldsymbol{v}_f = \frac{1}{2}\mathbf{v}_0 \tag{4.12}$$

Fig. 4.11 Kinetic energy carried by the wagon 2

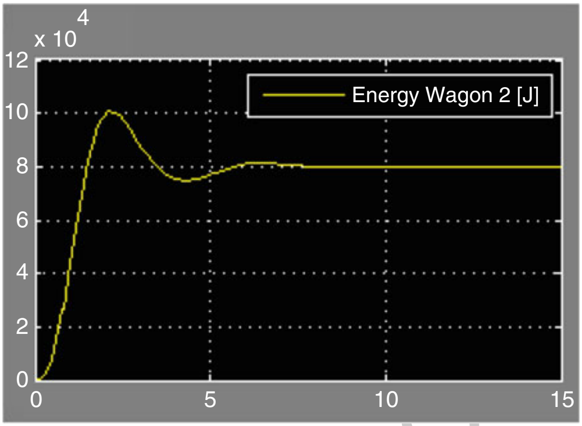
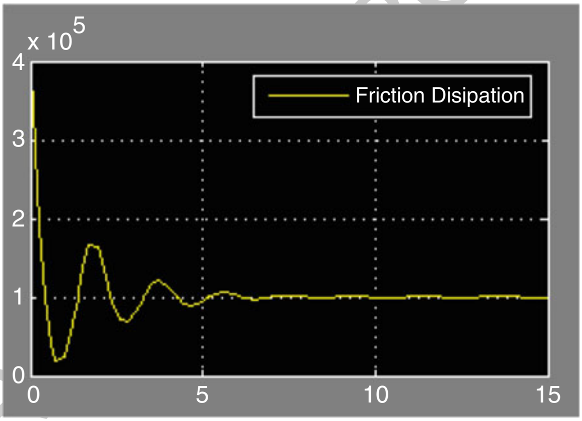


Fig. 4.12 Energy dissipation in friction element



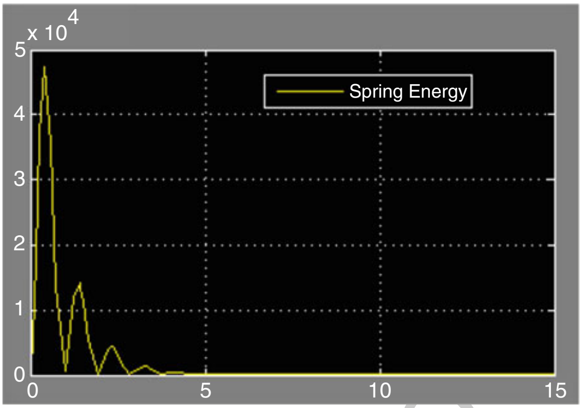
In Eq. (4.12) $\boldsymbol{v_0}$ is an initial velocity of the wagon 1, as already given, while $\boldsymbol{v_f}$ is the final value of the joint system velocity. We assumed that wagons have the same mass. Energy losses through one of the equivalent friction elements are calculated using expression $E = v^2 B$, as given in Table 4.1. Graph representing simulation results is given in Fig. 4.12.

The spring interfacing element is accumulating and releasing energy as per equation $E = k\frac{x^2}{2}$. Spring energy graph is given in Fig. 4.13.

Figure 4.14 shows distribution of kinetic and spring energy measured at the node 2, as labeled in Fig. 4.7.

Figure 4.15 presents final model of the systems with all sensors, calculations, and monitors shown.

Fig. 4.13 Spring energy



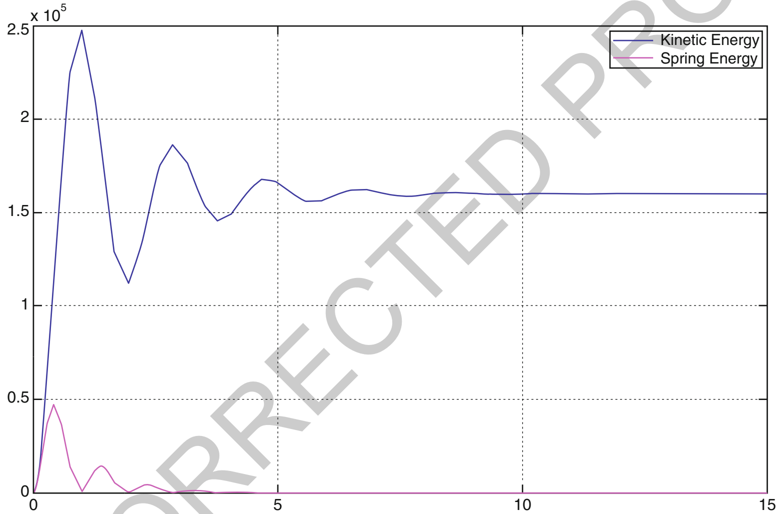


Fig. 4.14 Kinetic and spring energy distribution measured at the node 2

4.6 Train Composition Model

We are now going to simulate whole train composition as shown in Fig. 4.16. The only difference now, comparing to previous modeling, is the way how we supply the energy to the system. Locomotive is simulated as a velocity source as shown in Fig. 4.17. The next Fig. 4.18 shows velocity pattern generated by the locomotive.

As with the previous model, we could add sensors, calculators, and monitors to trace changes in the physical quantities, in the various parts of this complex system.

System model is shown in Fig. 4.19. It can be loaded with more sensors and calculators for monitoring purposes.

this figure will be printed in b/w

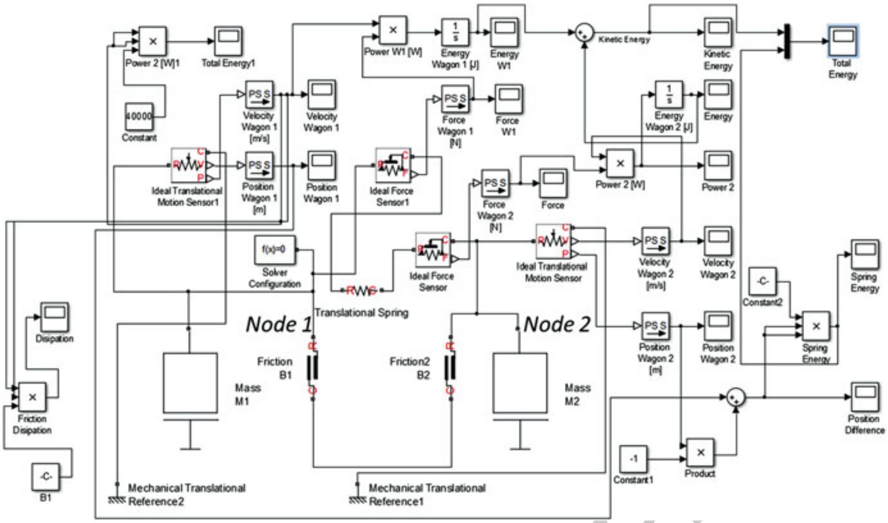


Fig. 4.15 Two wagon model with sensors, calculators, and monitors attached

this figure will be printed in b/w

Fig. 4.16 An ordinary train composition subject to simulation

As examples, forces and velocities in few network nodes are presented in Figs. 4.20 and 4.21.

Other physical quantities can easily be monitored, as already shown in the investigation of the less comprehensive system model, with two wagons and initial conditions present.

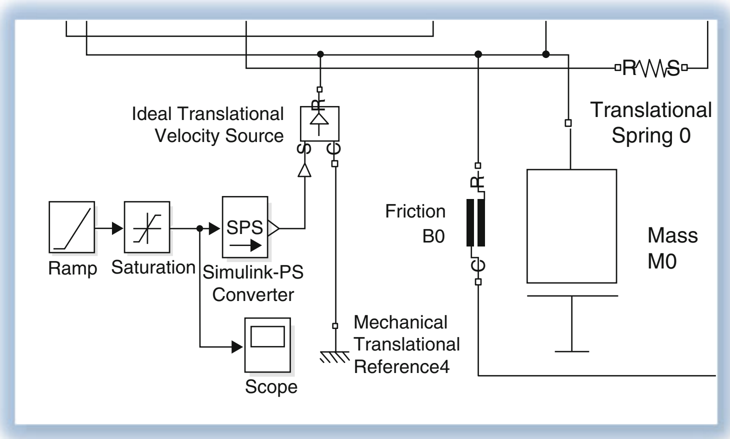


Fig. 4.17 Velocity driving source

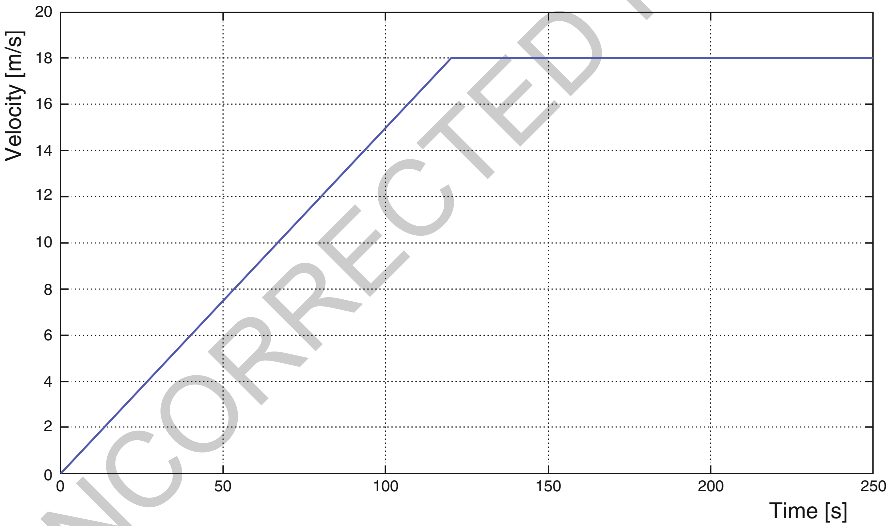


Fig. 4.18 Velocity pattern

4.7 Conclusion

Based on ODE, which are a common way to express various physical systems, physical networks approach is a comprehensive and global tool to model and simulate all sorts of engineering systems. We can perform modeling of mechanical, electrical, or hydro systems easily. Using this approach we simply manage issues

this figure will be printed in b/w

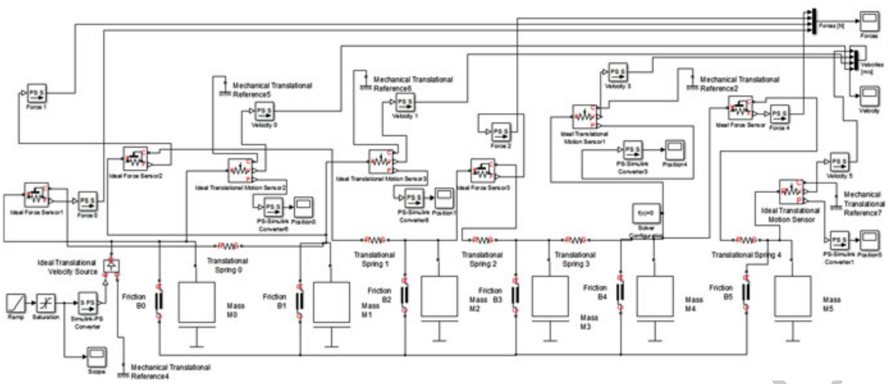


Fig. 4.19 Basic Simulink model of a train composition as shown in Fig. 4.16

this figure will be printed in b/w

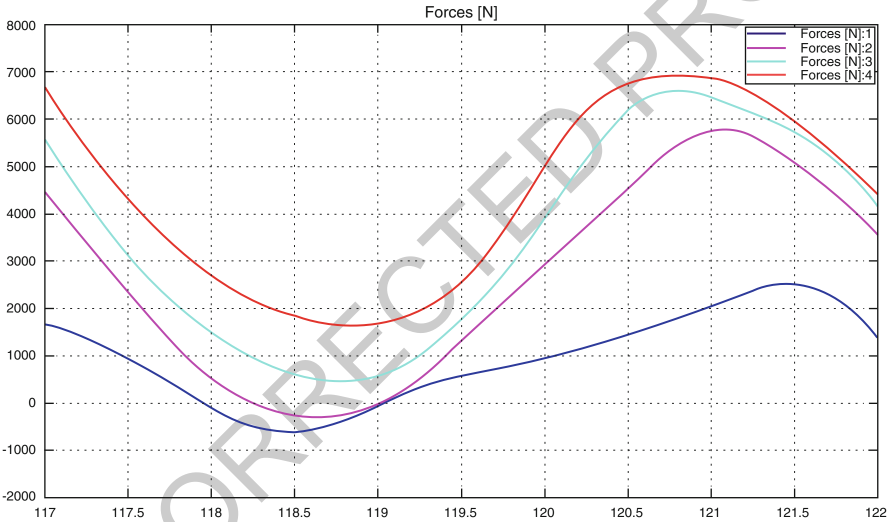


Fig. 4.20 Forces in the different parts of the train composition system

with energy conversions, from one to another system. In each system two basic types of physical quantities exist, while energy conversions are conducted using various sensors and actuators.

As good examples of mechanical systems that conduct translation motion, train and tram systems were modeled using this approach. Train composition is an extremely nonlinear and multidimensional system. Modeling and simulation is presented in just one dimension, as per translation motion vector directions. It is shown how key quantities and performances of the system can be monitored. Motion in other directions, then vibrations and other phenomena, can also be investigated with more comprehensive modeling and simulations. That will be subject to the future physical network applications and presentations.

this figure will be printed in b/w

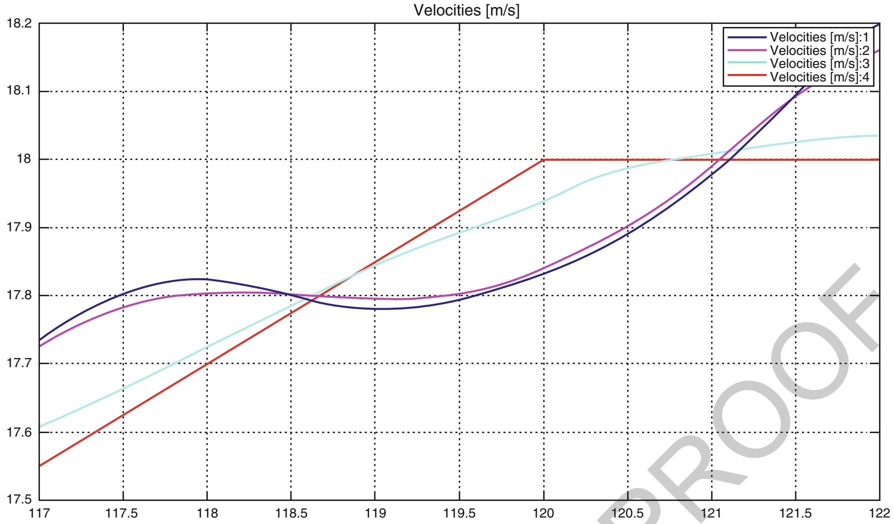


Fig. 4.21 Velocities of the different parts of the train composition system

References

A mathematical model for a train run. Available: http://diplom.utc.sk/wan/1881.pdf.

AQ3 de Silva, C. W. (2005). *Mechatronics an integrated approach*. Boca Raton, FL: CRC Press LLC.

Ďurica, M. (2015). A train run simulation with the aid of the EMTP–ATP programme. In A. Abraham, P. Krömer, & V. Snasel (Eds.), *Afro-European conference for industrial advancement* (vol. 334, pp. 99–107). Switzerland: Springer.

Sanford, R. S. (1965). *Physical networks*. Prentice-Hall.

AQ4 Simic, M. (2015). Exhaust system acoustic modeling. In L. Dai & R. N. Jazar (Eds.), *Nonlinear approaches in engineering applications*. Springer, pp. 235–249.

AUTHOR QUERIES

AQ1. Abstracts are provided twice in this book for every chapter (i.e., “abstracts in chapter file” and “abstracts in main file- front maters and abstracts.pdf” in FM elements). Please check.
AQ2. Please check whether the affiliation is ok as typeset.
AQ3. Please check the inserted publisher location for reference “de Silva 2005”.
AQ4. Please provide the location details for reference “Simic 2015 and Sanford 1965“.