

TrainDynamic Simulation – A new Approach

L.Cantone¹, R.Karbstein³, Dr. L.Müller³, D.Negretti², R.Tione², H-J.Geißler⁴
¹University of Tor Vergata, Italy, Rome; ²Faiveley Transport Italia, Italy, Turin;
³DB Systemtechnik (DB AG), ⁴International Union of Railways (UIC)

1 Introduction

Longitudinal Forces have an impact on length, traction and train composition – or in other words - the capacity of Trains. Wrong decisions concerning these Parameters result in accidents due to derailments, damages of wagons and load or even higher maintenance costs and lowered capacity. The parameters which mainly influence these forces are the Braking and Acceleration forces/regimes, brake components including buffers and draw gears and operational strategies to assure optimized train composition.

The UIC has a very long history regarding the development of CAMO-Systems (Computer Aided Modelling of Operation) for the calculation and simulation of longitudinal forces. Now, UIC has gone one step further, not only developing a complete new system with various new features and dimensions, but also offering the industry, the railways and the research institution the possibility to participate in the evolution and modification of the new system directly by obtaining the source code. This is a new approach for all above mentioned institutions; it assures a system which will be able to suit all railway needs worldwide concerning train dynamics due to braking, if the institution is willing to participate and to bring in its own interests.

In 2004 the UIC predicted the need for a new system, due to the fact that the structure of the earlier system was too complex to maintain and to adapt it to new functionalities and requirements. The missing cooperation between all stakeholders led to the situation that no one was willing to finance further development.

From this situation tasks were resulting:

- Establishing a system which is easy to maintain and to modify
- Establishing a legal institution to ensure further evolution of the system where each partner has the same influence
- Allowing all railways worldwide to adapt the system to their requirements
- Assuring a system with a worldwide approval

After intensive investigation, the UIC decided to buy and enhance the **Train Dynamic** (TrainDy) software from Faiveley Transport. TrainDy was developed by Faiveley Transport Italy with a relevant contribution of Tor Vergata University in Rome. To assure the restriction free access, UIC obtained and will spread the source code of the system. TrainDy can be used by every railway operator, infrastructure owner, manufacturer or university worldwide who is willing to enter a TrainDy consortium which offers the opportunity of worldwide standardisation.

2 CAMO-Software development and the new Approach

Regarding Software development, the time between the definition of software requirements and the final product is decreasing more and more. To meet this challenge, enormous capacities are involved in the development of widespread software. The development of CAMO-Systems is very complex, but also limited to a narrow number of users. Older CAMO-Systems were developed by one small company using a very high skilled narrow software development team [5] [6].

This approach causes different problems:

1. The produced software is tested in a narrow number of “test cases”.
2. The amount of money to enhance the software is directly related to the number of members of the development team and of software users. If the amount of one of these numbers decreases, the development finally stops and the software will become useless after a range of one or two years.
3. The capacity of the development team defines the velocity of development.
4. The brain pool stays constant, new ideas are not implemented – innovation is reduced.
5. The software stays national; the possibility of a world wide use is not realistic, due to the different railway requirements (Asia, Europe, Russia, North and South America).

The UIC faced up these problems in 2006 and discussed a new approach to solve them. The gathered solution consists of three different elements:

1. To test and verify the software, an independent Expert Group has to be established, which certifies each software version. To ensure the independency, a legal entity at UIC should be realized. This ensures the quality and reliability of the results of the software calculation.
2. To control the development of the new software versions, a CAMO-Consortium (now TrainDy-Consortium) will be established. Members of this group get access to the software and are allowed to produce new software modules and to publish results, calculated with the software. In return of this, the Consortium members pay an annual fee for these rights, which allows the consortium to develop new features and to certify the software.
3. In order to override the barriers of national railway requirements, to extend the brain pool and to increase the development speed, the source code of the software will be available in the standard programming language MATLAB[®] for the members of the above mentioned consortium in return of a fee.

The expected goal of the described elements is to ensure a maximum attraction to the new software without any financial industrial interest. Therefore the contractors Faiveley Transport and the UIC agreed on the exchange and widespread of the source code without restriction regarding the access to the consortium. All parties of the railway business like the Industry, Railways, Operators, Consultants and of course Research Institutions are invited to join the consortium and to be part of the further development of TrainDy. The aim of this new approach is reached, when institutions all over the globe are participating in the software development and different railways with their different material and operational conditions use the TrainDy software. The effect will be the harmonisation of rail operation and equipment and also their evaluation. As a consequence, standardisation means also a decreasing price structure for railway components.

3 Algorithms

The TrainDy environment is conceived as an environment for train dynamic computations. In its basic stage it considers the vehicles as rigid masses on a 3D track and it integrates the dynamic equations of motion with variable integration time step [1]. The track is modelled as a series of straight lines, plain curves and parabolic curves, with variable cant, curvature and slope. The vehicles exchange forces via buffers and draw gears, these forces generate six generalized forces acting on each vehicle; so, even with one longitudinal Degree of Freedom (dof) for vehicle (i.e. the middle position of the vehicle on the track) all generalized forces are computed. Moreover, by this way, it is possible to compute the forces on the wheels, approximately, via equilibrium equations. The forces on each vehicle are the

resultants of longitudinal forces and of the track and manoeuvre forces, too. Braking, acceleration, aerodynamic, rolling friction and curving forces are computed. Special attention is focused on the braking forces that are computed by modelling: the main brake pipe during braking and releasing manoeuvres, the master brake valves, the distributors (with accelerating chambers and auxiliary reservoirs) and the brake cylinders (see par. 3.1). Furthermore, by knowing the pressure in brake cylinders, the braking forces are computed considering the data of pneumatic scheme of each vehicle. The pneumatic model, developed using the data of the train brake simulator of Faiveley Transport Italia, is designed to manage any number of driver's brake valves along the brake pipe.

TrainDy is made of two basic modules: the first computes the time evolution of the pressure in braking cylinders, and the second calculates the longitudinal dynamics of the train, using the previously computed pressures. In the following, the description of these modules is provided.

3.1 Pneumatic module

Before computing the time evolution of the pressure in braking cylinders, it is necessary to compute the time evolution of the pressure in the main brake pipe. At this aim, the main brake pipe is modelled by a circular pipe with variable cross section (quasi mono-dimensional model) from which air can be blown in or spilled out and this can happen both from the ends (for example, "end of train" device) and along the pipe through the side wall (useful for distributed braking, as it is long trains with more than one loco), see Fig. 1. The pipe has a constant diameter within each vehicle and a diameter reduction, which simulates the hose couplings between two consecutive vehicles.

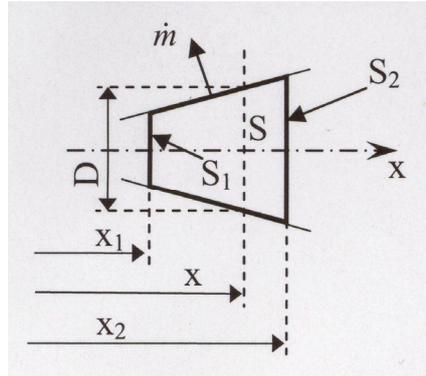


Fig. 1 Variable cross section pipe

From the conservation of mass and energy and the balance of momentum within the above hypotheses the governing equations become:

$$\begin{cases} \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \frac{\rho}{S} \frac{\partial (uS)}{\partial x} = -\frac{\dot{m}}{Sdx} \\ \frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial p}{\partial x} + u \frac{\partial u}{\partial x} = \frac{\tau}{D} + \frac{u}{\rho} \frac{\dot{m}}{Sdx} \\ \frac{\partial q}{\partial t} + u \left(\frac{\partial q}{\partial x} + r \frac{\partial T}{\partial x} \right) + r \frac{T}{\rho S} \frac{\partial (\rho u S)}{\partial x} = 4 \frac{\phi_r}{\rho D} - \frac{\tau u}{D} - \frac{\dot{m}}{Sdx} \frac{1}{\rho} \left[(c_v + r) T_{vc} + \frac{1}{2} u_{vc}^2 - q \right] \end{cases} \quad (1)$$

where ρ is the density, u axial velocity, p pressure, T temperature and all of them must be considered as mean values on the general cross-section S of diameter D and abscissa x ; q is the specific energy, c_v specific heat at constant volume,

$\tau = -\text{sgn}(u) \cdot \left(f + K \cdot \frac{D}{dx} \right) \cdot \frac{u^2}{2}$ takes into account for dissipative sources (there, f is

the distributed coefficient of pressure loss, K concentrated coefficient of pressure loss and $\text{sgn}(\square)$ sign function); ϕ_r is the exchanged thermal flux, r gas constant, \dot{m} in-

flow or out-flow mass flux; subscript l refers to lateral quantities, which has to be determined by imposing the right boundary conditions and, finally, subscript vc refers to “vena contracta” conditions of the equivalent lateral nozzles.

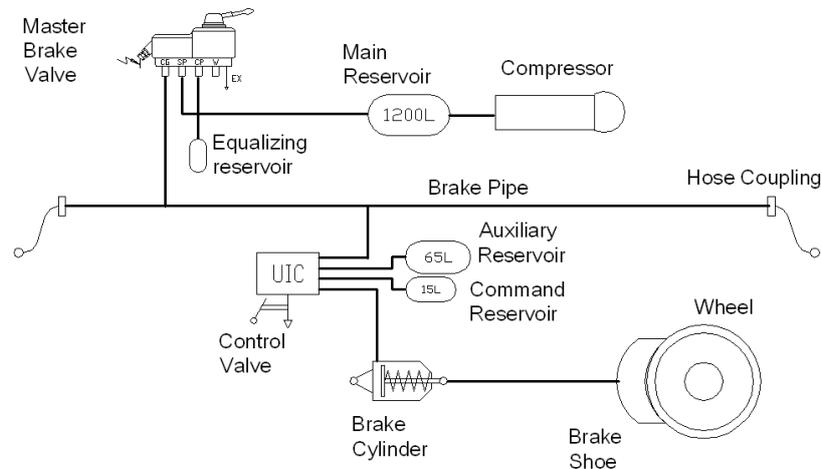


Fig. 2 Sketch of the train pneumatic system

The integration of (1) needs both suitable boundary conditions and initial conditions for all the components (accelerating chambers, driver’s brake valve and auxiliary reservoirs) since, all of them, determine some of the source terms of (1). In the pneumatic module of TrainDy, the “real” pneumatic braking system of a train (Fig. 2) is modelled as a variable cross-section pipe with some lateral nozzles.

The driver’s brake valve is modelled as a nozzle with an equivalent diameter, tuned on experimental data. During a braking, the upstream pressure of the nozzle is the pressure of the brake pipe, while its downstream pressure is either the atmospheric pressure, for an emergency braking, or, for a service braking, the pressure of the pilot chamber of the driver’s brake valve. In the latter case, the downstream pressure is time-variable, according to a law provided by the constructor of the valve. On the other hand, during a releasing, the upstream pressure of the nozzle is the pressure of the pilot chamber, yet provided by the valve constructor, whereas the downstream pressure is the pressure of the brake pipe. Since the real pneumatic circuits used for the three previous manoeuvres are different, there are also three equivalent diameters of the nozzle that simulates the same driver’s brake valve; fortunately these diameters need to be determined only one time and they do not depend on the length of the train. All the above considerations, along with the classical equations of a nozzle [2], make easy to compute the mass flux terms of equations (1), corresponding to the sections $S(x)$ where the driver’s brake valves are located.

During a braking, the accelerating chambers of the control valves are modelled as lateral small volumes connected to the brake pipe by means of nozzles of equivalent constant diameters. The pressure of the air in these volumes changes according to the inflow flux mass, holding constant, for hypothesis, the temperature of the air in the volume of the accelerating chamber. In this case, the upstream pressure of the nozzle is the pressure in the brake pipe and the downstream pressure is the pressure of the air in the small volume; after a certain time period, the pressure of the air in the small volume is bigger than the pressure in the brake pipe and the air goes back, from the small volume to the brake pipe. By this way it is easy to compute the mass flux terms of equations (1), corresponding to the sections $S(x)$ where the accelerating chambers are located. Both the nozzle diameter and the capacity of the lateral volume are tuned on experimental measurements, fortunately, this tuning occurs only one time and it neither depends on the manoeuvre (emergency or service braking) nor on the train length.

The auxiliary reservoirs are modelled as lateral big volumes connected to the brake pipe by means of a nozzle with variable diameter [3] and they communicate with the

brake pipe only during a releasing. From the modelling point of view, the auxiliary reservoirs are similar to the accelerating chambers except that their initial pressure depends on the previous braking, because the air in the auxiliary reservoirs has been used to fill the braking cylinders.

Moreover, in order to integrate the equations (1), also the concentrated loss pressure factors K (in the expression of the dissipative source τ) must be determined by a matching with the experimental measurements.

The computation of the mass flux and the “vena contracta” conditions corresponding to the different equivalent nozzles are, by this way, easily computed.

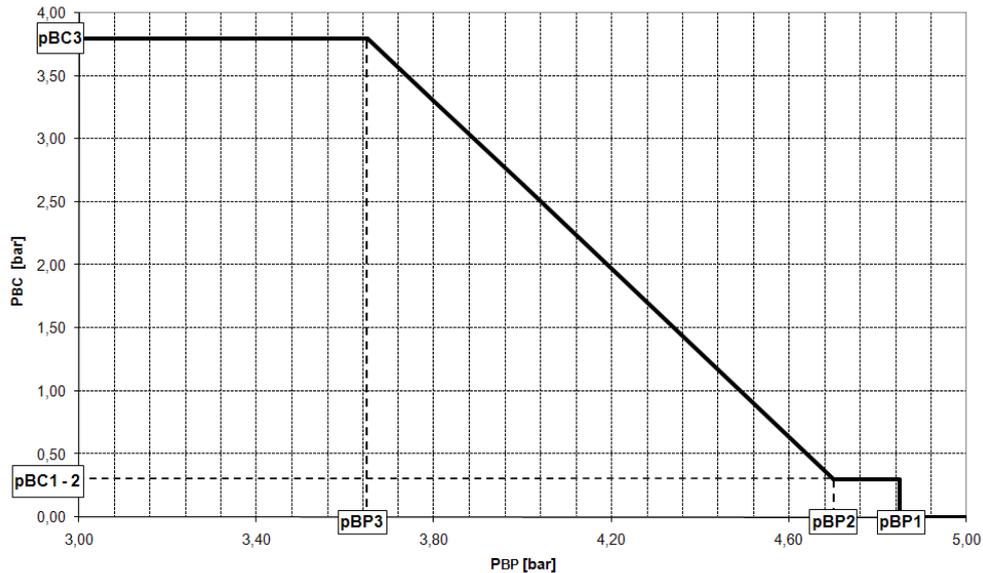


Fig. 3 Example of control valve transfer function

Once computed the pressure in the main brake pipe, the control valve transfer function (Fig. 3 shows an example) along with the limiting curve of the braking cylinders (Fig. 4 shows an example) are used in order to calculate the time evolution of the pressure in the braking cylinders.

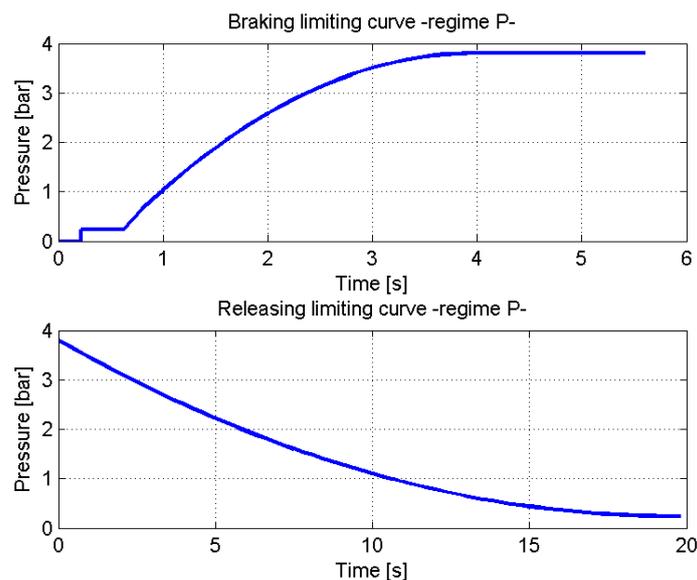


Fig. 4 Example of limiting curve.

In the very beginning of the braking phase, the filling of the braking cylinders is performed only mathematically because, according to [4], it does not depend on the “braking regime”; then, the pressure in the braking cylinders is controlled in time and depends, not only on the pressure in the brake pipe but also on the limiting curve. Practically this implies that the pressure in the braking cylinder is, respectively, the minimum or the maximum between the limiting curve and the transfer function for braking or releasing manoeuvres.

Once computed the pressure of the air in the braking cylinders, the main “source” of the longitudinal dynamic behaviour of the train is determined.

3.2 Dynamic module

In its basic modelling, a train is regarded as series of masses connected by non linear springs; a typical force-stroke characteristic of these springs is shown in Fig. 5.

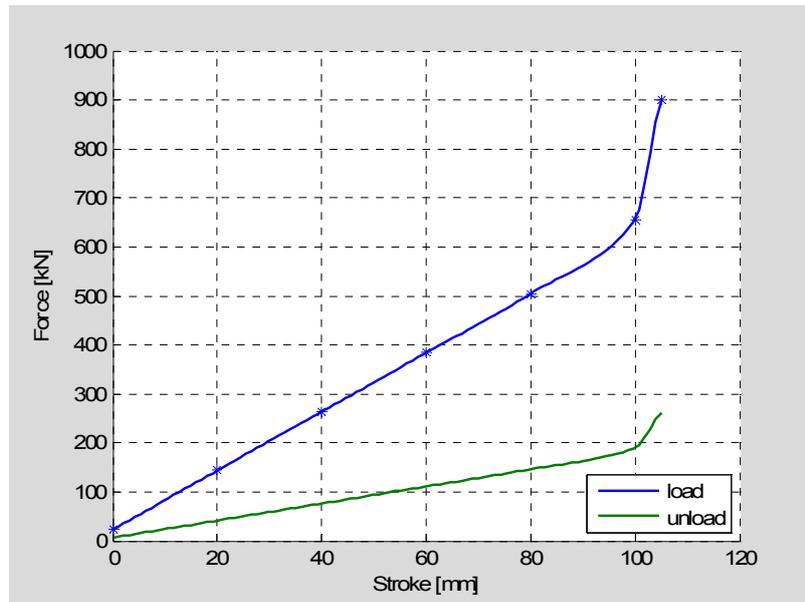


Fig. 5 Example of buffer force-stroke characteristic.

The model is similar to [5]: the force-stroke characteristic can be provided in two different ways: a) giving the damping and some points of the loading curve; b) providing points both of loading and of unloading curve; in both cases, the limiting speeds of loading and unloading must be given. TrainDy uses a cubic piecewise interpolation of the input data, which assures slope continuity, in order to prevent numerical errors of integration. When the relative speed is among the loading and unloading limiting speeds, the force provided by the coupling is computed as:

$$F(x, v) = c(v) \cdot F_{un-load}(x) + [1 - c(v)] \cdot F_{load}(x);$$

the coefficient $c(v)$ is plotted in Fig. 6 in the case of loading speed 0 m/s and unloading speed 0.1 m/s. This means that if the relative speed is among 0 and 0.1 the loading and unloading force are computed for the given relative approach x , and the actual force exchanged by the wagons is calculated as above.

The laws of the friction coefficient implemented in TrainDy are described in [6]; moreover, a friction coefficient law, that considers the effects of specific pressure (among shoe and wheel) and of the running speed, has been implemented, considering Trenitalia experimental test data.

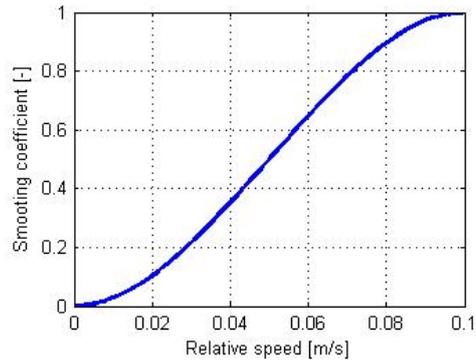


Fig. 6 Example of smoothing function.

4 Validation

The TrainDy algorithms have been fully validated for the pneumatic part and dynamic part. The pneumatic validation took into account 28 simulations and Test runs delivered by DB, SNCF and Trenitalia: 14 in service braking and 14 in emergency braking condition. The pneumatic module has been validated in traditional conditions (loco at the head of the train) and also in distributed braking conditions (more than one braking loco along the train).

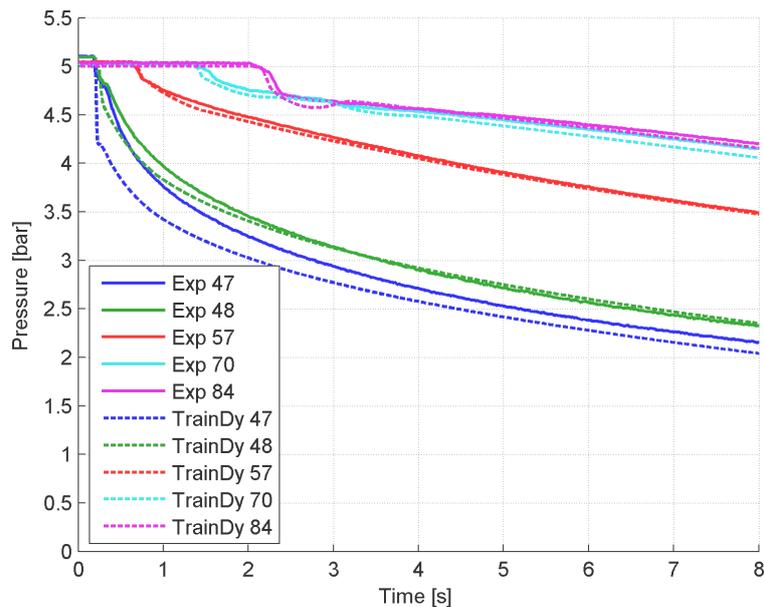


Fig. 7 Pressure in brake pipe

The first certificates of the UIC validation process of TrainDy contained already the most used braking devices. For each device, a set of “good” and “standard” parameters has been identified (the diameter of the equivalent nozzle that models the accelerating chamber is an example of parameter): the good parameters were those ones, adapted as close as possible to the reality of one specific test run. The standard parameters are equal for all the test runs and represent the harmonized average to be used. These standard parameters can be used by the engineers of the railways operators as a good starting point in order to carry out the simulations.

Fig. 8 shows the corresponding longitudinal forces for a starting speed of 20 km/h. The agreement is satisfactory both for the maximum values of the longitudinal forces and for their shape; even the stopping time demonstrates the very good agreement with experimental data: simulated 8 s, experimental 7.8 s. The small differences can

be explained considering that, at the beginning of the braking, the experimental data have a small residual of traction longitudinal force and this can affect the following longitudinal dynamic behaviour.

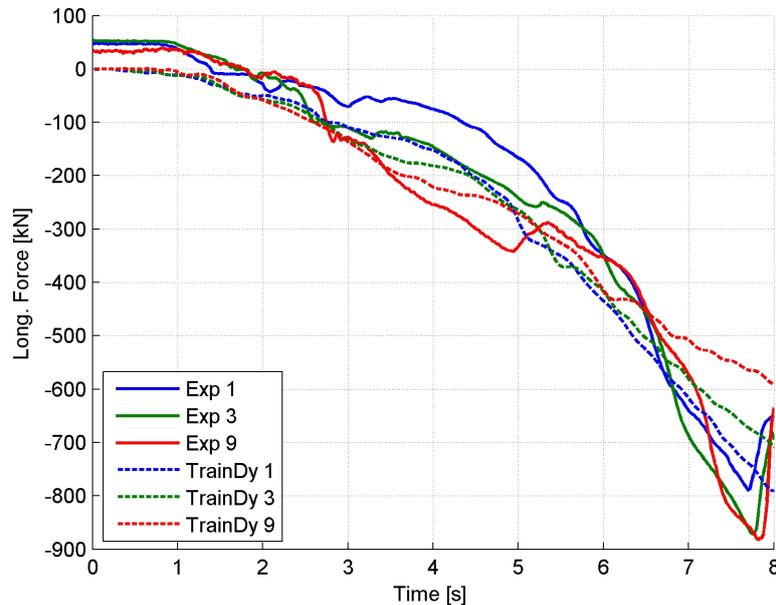


Fig. 8 Longitudinal force

Fig. 7 refers to a DB train, whose length is 1200 m with a distributed braking: in this case there are two locomotives, one at the head and the other at the middle of the train. Fig. 7 shows the time evolution of the pressure in brake pipe for the second half of the train only, in order to increase the readability. The agreement among experimental measurements and the simulated counterpart is satisfactory: the biggest differences are at the very beginning of the simulation and they regard the vehicle 47 which is very close to the second locomotive.

5 Potential of the System

The new system TrainDy simulates all longitudinal forces related parameters with a high accuracy. Complex buffer interaction (regarding modelling) like “miner” and other equipment can be mapped. A complete manoeuvre of the train can easily be modelled by selecting locomotives and wagons from a database, defining track sections and movement conditions based on distance, speed or time. After the definition of all boundary and initial conditions and the calculation accuracy the system will simulate the resulting forces. TrainDy allows the user to define the degrees of freedom of the vehicle components for the calculation (like longitudinal forces, vertical forces, roll and pitch).

This accurate simulation offers the railway operators the opportunity to calculate the level of safety regarding the longitudinal forces for one specific train or even a specific type of transport. Agreeing one defined safety level for railway operation, the European rail sector will increase, because of international harmonized rail transport and more liberated markets. The aim is to define an international accepted risk level and methodology to assure, the actual level of safety stays constant. This definition will be undertaken using the new TrainDy software and by negotiating a procedure to calculate the safety level.

The harmonization of international freight train operation is an important task to increase the amount of tons transported by the railways within Europe. Different operational rules are complicating the transport and are slowing down the velocity, especially at or nearby national borders. UIC has the aim to support processes for establishing standards and specifications to increase the transport volume.

Standardisation was undertaken e.g. in UIC-Leaflet 421 which contains regulations for the consist and braking of international freight trains. Leaflet 421 defines limits for international freight transport regarding brake regime, velocity, mass and length of these trains. The basis and the reason for this limiting value were due to longitudinal dynamics and international negotiation.

One basic field to provide seamless freight transportation is the use of int. accepted standardized brake regimes, the occurring longitudinal dynamic forces and the international use and acceptance of computations to negotiate these tasks. The new UIC Software TrainDy offers these possibilities.

To expedite the process the UIC will additionally establish an expert group, to expand the limiting values of leaflet 421. This expert group defines the Role of the new software within this leaflet and will additionally define an international agreed level of safety and a procedure to define this level. To fulfil the requirement of international acceptance, national safety agencies, railway operators and infrastructure owners must agree to define calculation conditions. Additionally railway suppliers will have to map their equipment in a data base to be used by all Railway Operators. This offers the Industry the opportunity to use international verified simulation techniques and to offer optimized components and assemblies to the railway operators.

Regarding these boundary conditions the TrainDy system will break conventional borders of railway operation without restricting the access of non TrainDy using operators. Focussing the future, the approach of defining margins for longitudinal forces or other related values will have a direct impact on international specifications like the TSI Operation.

Due to the new open source like approach the System will not only be bound to European requirements. The system can be extended with new modules taking into account features of other countries/continents and is no longer restricted to the area of operation. Calculations regarding the pantograph, the wheel / rail interface or even more detailed investigations with the focus on derailments and accidents will be a result. But also the interests of the industry will be covered. The open interfaces will allow the users to produce modules to model a three dimensional train, to simulate the behaviour between bogies and wagons, to develop new buffers, draw gears, brake systems and brake concepts like distributed brake control etc..

Due to the new consortium UIC expects not only UIC members but also research institutions and Industry to bring in their ideas and engagement for new approaches. The Programming language MATLAB[®] – which is a standard for simulation and modelling of mechanical systems – helps in keeping the complexity of the source code small and enables each stakeholder to develop modules on their own or to find external software developers producing their new modules.

The UIC guarantees for quality and reliability of the whole system. New modules can be evaluated and in case of validation by UIC, being implemented into the latest official version certified by UIC.

6 Impact on Railway business

Railways in Europe are using longitudinal simulation for different tasks. Of course railways in other parts of the world like China, United States, Australia and Africa share the basic physics, but with slightly different equipment regarding brakes, couplers, etc.. Additionally different operational modes lead to a situation where each railway institution produced their own system, which reflected exactly the hardware and operational behaviour of the railway companies. Up to now merging different systems would have been very expensive and of course not in the interest of the development teams.

Consortium

The possibilities and constraints of railway operations are evolving in the light of ongoing advances in technology and growing traffic volumes, and the same is true for the TrainDy system, which must respond appropriately to these new contexts. In order to ensure this and to maintain the technical expertise concerning the programme, a UIC "consortium" is due to be set up, which will be open both to UIC members and manufacturers, institutes and universities.

In this summer 2008 the development of the UIC "TrainDy" project is complete and a UIC version verified by UIC experts will be available, which will be incorporated into the consortium.

Each member joining the consortium will pay a signing-up fee. In return for this, members will be able to access the source code (open code). Any member can introduce additional desired modifications or modules, which are to be paid for separately. The Consortium Steering Committee will emphasize on international approval for additional modifications or modules. This guarantees that an internationally-agreed and verified version is always available as the official UIC version.

In order to prevent use of the source code becoming impossible to monitor, the consortium management team should exercise close supervision. In addition, as well as the task of executing contracts concerning distribution and support, the consortium also ensures that the source code is not distributed without authorisation.

The legal requirements for setting up an open consortium are currently being investigated by UIC.

For actual information about the project and the software, please refer to: <http://traindy.uic.asso.fr>

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