Influence of Longitudinal Train Dynamic on the running safety of long freight trains

Faculty of Civil and Industrial Engineering
Department of Civil, Constructional and Environmental Engineering
Master Degree in Transport Systems Engineering

Candidate:
Orod Shamsafar
Student Number 1753744

Supervisor:
Prof. Riccardo Licciardello

A.Y. 2018-2019

Contents

Abstract

Rail transportation plays a Central role in freight transportation in the EU and therefore its efficiency is extremely important. The revenue of railway freight is directly linked to the train capacity. There are different methods for increasing capacity. Using longer trains has been the most common solution however restrictions derive from both infrastructure and vehicles. In particular for the latter, Longitudinal Train Dynamics (LTD) is a key restriction that is also related to running safety. LTD is a complex topic and it depends on many parameters of the vehicles, track geometry, traction or braking operations etc. thus, dealing with long trains requires further studies to ensure reliability and safety. This study is based on the use of simulation for LTD analyses. GENSYS is the multibody simulation software used to model the freight vehicles' running dynamic behaviour on a specific track that is used in tests for running safety ("S-curve"), where the wheel lift on the non-guiding wheels is the key assessment quantity. The work has consisted firstly in integrating the GENSYS environment with code for modularization, in order to make it easier to create trainsets with different types of wagons and providing the opportunity for other users to modify the model in a short time. The simulations were then performed and validated by comparing their outputs with S-curve test results from the International Union of Railways (UIC). In particular cases there are some differences between the simulation results and the test results which are probably due to the lack of input data information and to speed differences between tests and simulations. At the end of the study a sensitivity analysis for the buffer surface friction coefficient was performed. This coefficient is a key unknown quantity in the tests. The analysis showed that there is a buffer friction coefficient value at which the wheel uplift is highest.

Preface

This Master's Thesis is part of my Master of Science Transport system engineering at Sapienza University of Rome. I would like to thank my supervisor that he prepared situation for me than I could do one part of my thesis at KTH university of Stockholm, Also, I would like to thank Prof. Sebastian Stichel for the possibility to come to KTH Railway Group for this work I am grateful to Prof. Mats berg as my supervisor at KTH university. Special I thanks to Prof. Dr. Saeed Hossein-Nia who supported and helped me in all aspects while I had many questions about GENSYS, MATLAB or concept of dynamic studies. Also, Thanks to Visakh Krishna with weekly meeting always supported me at KTH university as my second supervisor there.

1. Introduction

1.1 Background

Rail transport is also known as train transport. It is a means of transport, on vehicles which run on tracks (rails or railroads). It is one of the most important, commonly used and very cost-effective modes of commuting and goods carriage over long, as well as, short distances. Since this system runs on metal (usually steel) rails and wheels, it has an inherent benefit of lesser frictional resistance which helps attach more load in terms of wagons or carriages. This system is known as a train. Usually, trains are powered by an engine locomotive running on electricity or on fuel. Complex signalling systems are utilised if there are multiple route networks.

Nowadays considering distances and the relevant cost of different transportation modes, usage of rail transport for both passenger and freight traffic is increasing. Promoting freight transport by rail to limit road congestion and reduce transport carbon emissions is preferred. A freight train or goods train is a group of freight cars or goods wagons hauled by one or more locomotives on a railway, transporting goods.

Rail transportation plays a central role in freight transportation in the EU then railway efficiency is an important topic. The revenue of railway freight is directly linked to the train capacity. The efficiency of the railway freight transportation sector is strictly related to the transportation capacity of the train. The possible solutions for increasing the efficiency are basically two: the use of longer trains or the use of faster also lighter wagons. The first solution has been widely used in North America and Australia, while the second has been studied in Europe, where the possibility to compose long trains is prevented by the network topology with too many stations and short lines between them. The possibility to use long trains in Europe is also limited by the adoption, in European cars, of the hook-buffers system for train coupling. This system allows lighter longitudinal loads than the automatic coupler used in other countries (e.g. North America), and despite the trial to introduce the coupler made by the European Community since the 1960, up to now, its use is sporadic in Europe. Comparing the two solutions, it must be observed that the use of faster trains also significantly increases the dynamic loads on the track, and this leads to lower axle loads permissible in Europe. For these reasons, the use of long trains appears to be more effective in the possible solutions to increase transport efficiency; therefore, nowadays, the researchers are directed to develop and improve this solution. Also, in Europe, where the network infrastructure and the vehicle specifications are not favourable.[1]

The length of a train is measured in number of wagons or in metres for general freight. Conventional freight trains in the US can average nearly 2,000 metres (6,600 ft). [2]

Companies have plenty of reasons to keep adding train cars. Long trains save on fuel and crews, reducing the cost of rail transportation. Longer trains also decrease the volume of trains through communities and improve productivity. And fewer trains on the network frees up track space for other traffic.

Freight trains with a total length of three or four times that average is possible with the advent of distributed power, or additional locomotive units between or behind long chains of freight cars. Locomotive units enable much longer, heavier loads without the increased risks of derailing that stem from the stress of pulling very long chains of train-cars around curves. So, increasing the train length by adding extra vehicle is one of the ways that the capacity could be increased.

1.2 Objective

For extensive rail freight transportation, one action to improve its capacity and efficiency is to run long trains. From a European perspective this typically means running freight trains longer than 800-900 m. However, there are technical challenges associated with long-train operation [3]. Beside all these advantages which are mentioned above there are some restriction for using of longer trains. They require studying longitudinal train dynamics (LTD) to determine the running safety.

[1] Zampieri, N. B. (2017). *Long train simulation using a multibody code. International Journal of Vehicle Mechanics and Mobility, 1.*

[2] Joiner, Stephen (11 February 2010). "*Is Bigger Better? 'Monster' Trains vs Freight Trains*". *Popular Mechanics*

[3] DYNAFREIGHT. (2017). *Retrieved from http://www.dynafreight-rail.eu/*

Longitudinal train dynamics is defined as the motions of rail vehicles in the direction along the track. It therefore includes the motion of the train as a whole and any relative motions between vehicles allowed due to the looseness and travel allowed by coupling and spring and damper connections between vehicles.

LTD is a complex topic and it depends on many parameters such as vehicles, track geometry, traction or braking operations etc. So, dealing with long trains requires further studies to ensure reliability and safety. Simulation is one of the useful methods for LTD study and is proposed solution for saving time and cost. Such accurate simulation allows rail operators to calculate the level of safety of a specific train in terms of longitudinal dynamics. GENSYS as Multi-Body Simulation (MBS) software is used in this study for simulation.

2. State of the art

2.1 Rail Vehicle applications

The railway system is complex. The dynamic response of a freight wagon strongly depends on the interaction between vehicle and track respectively vehicle and the transported goods. Main requirements for the technology used in freight transport systems are safety and cost efficiency.

Since the early 1970s applications have been developed for vehicle-track interaction studies. The development mainly started among some railway engineering companies. For instance, by creating special-purpose codes for two dimensional models of rail vehicles with two bogie each with two axles. Improve computer hardware and reduced computational cost, opened up for more general and commercially available applications. Today applications are often large programme systems within many possibilities. Some of the software originate from general multibody dynamics and have been extended by rail vehicle modules during the last decade. Among the railway engineering applications originating from early 1970s three applications, which are also used extensively today Should be mentioned: GENSYS, VAMPIRE and NUCARS. These Applications have been developed in Sweden, UK and USA respectively. [1] Two general multibody dynamics Software with railway modules are ADAMS and SIMPACK. They are mainly developed in USA and Germany respectively. The TrainDy project was launched to develop a system to calculate longitudinal dynamics in trains. This new tool is designed for widespread use and should be applicable worldwide.

2.1.1 GENSYS as a multi-body simulation (MBS) software

GENSYS is a software tool for modelling vehicles running on rails. In 1992 began the development of a three-dimensional general multi-body-dynamic program, and it was given the name GENSYS.

---

[1]Andersson, E., Berg, M., & Stichel, S. (2014). *Rail Vehicle Dynamics. Stockholm: KTH university.*

GENSYS is a general multi-purpose software package for modelling mechanical, electrical and/or mathematical problems.[1] Dynamic simulations in GENSYS are done by numerical integration in the time domain which solves the equation of motion with a fixed step integrator.

2.2 Modelling Vehicle-track dynamic interaction

Modelling issues will be divided in to three parts, i.e. Track models, Vehicle models and models for wheel rail contact. The different models require numerical data for their application.

2.2.1 Local coordinate systems

When creating models in GENSYS the user has access to three types of coordinate systems:
"fsys" =A fixed coordinate system located at origin
"esys" =A moving coordinate system which takes large angles into consideration
"lsys" =A moving coordinate system which only considers linear rotations
The coordinate systems are connected to each other according to figure 2-1
"bsys" is the body fixed coordinate system, which describes the position of the mass relative to its lsys.

Name	**Direction**	**Positive**
X	**Longitudinal**	**Forward**
Y	**Lateral**	**To the right**
Z	**Vertical**	**Downwards**
φ	**X-rot Roll**	**Right-hand rule (figure 2-2)**
χ	**Y-rot Pitch**	**Right-hand rule (figure 2-2)**
ψ	**Z-rot Yaw**	**Right-hand rule (figure 2-2)**

Table 2-1 Positive coordinate directions

[1] http://www.gensys.se

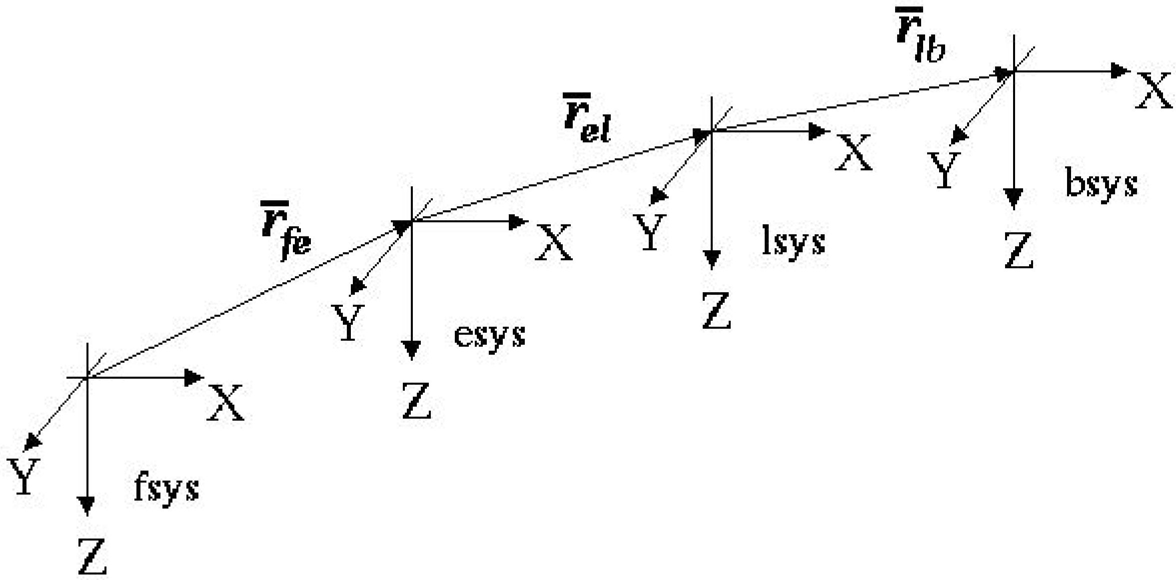

Figure 2-1 Local coordinate systems.

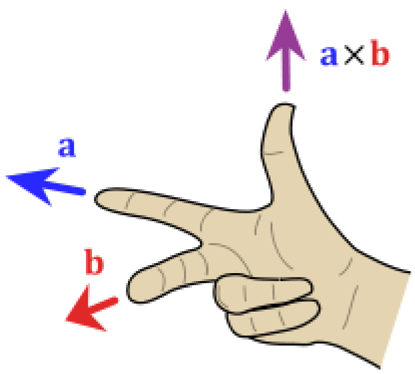

Figure 2-2 Right-hand rule

It is a good practice to have separate coordinate systems for all masses that have different longitudinal positions along the track, because then will all displacements be expressed relative to the track where the mass is located. The creation of unnecessarily many coordinate systems lengthens the execution time.

2.2.2 Track models

Track flexibility, nominal geometry (track alignment) as well as track irregularities must be modelled and described. Track flexibility influence track forces but under certain circumstance also lateral dynamic stability will be affected. The track alignment is described in two parts: Designed track geometry and Track irregularities. The designed track geometry describes the curve radiuses and cant (super elevation). Track irregularities are the deviations from the designed track geometry. Often the designed track geometry and Track irregularities are separated into two parts. The track consists of tangent track sections and circular curves, and in between these sections there are transition curves and how rails are coupled to track and how track is coupled to ground is modelled by vertical and lateral springs and dampers in Z and Y direction as shown in the figures below.

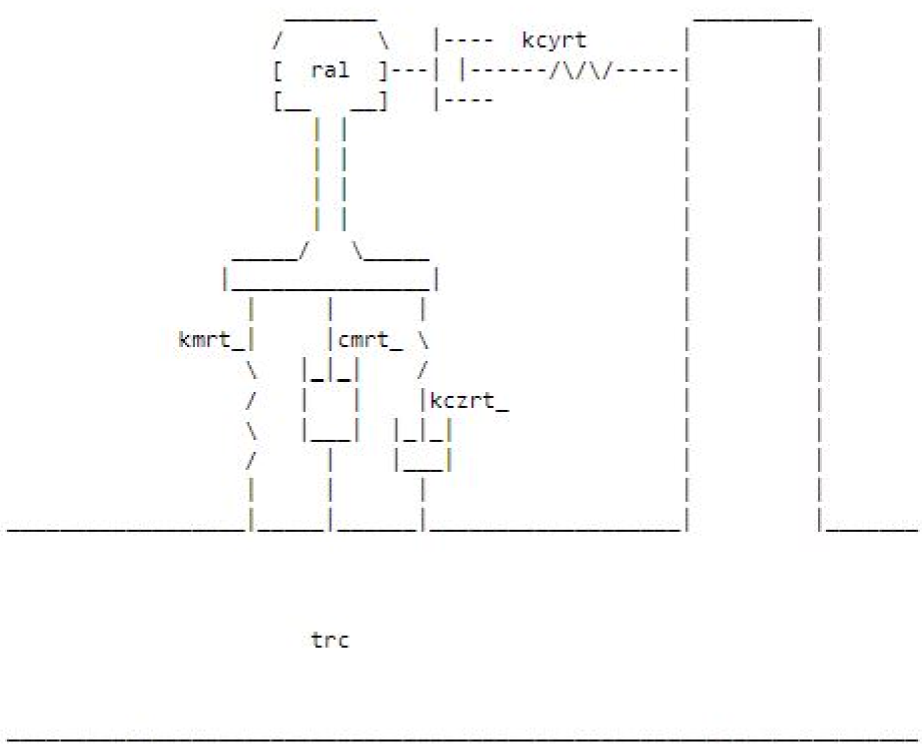

Figure 2-3 Couplings between rails and track

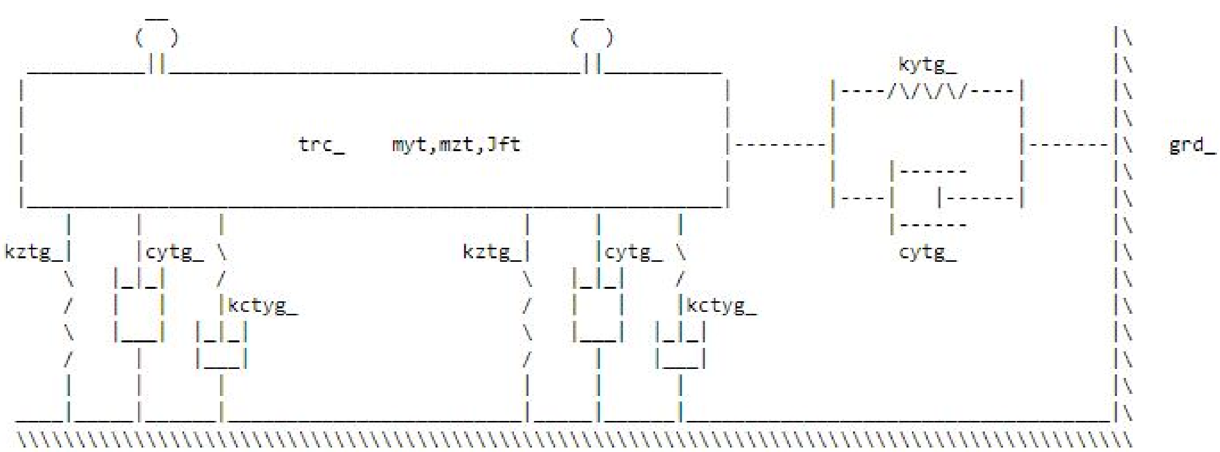

Figure 2-4 Couplings between track and ground

2.2.3 Vehicle models

The vehicle is modelled as several rigid or flexible bodies which are connected to each other by spring and dampers and links. In GENSYS environment there are several commands for coupling and regarding situation they can be used by modeller for modelling the Vehicle. Each vehicle can be divided to two main classes such as powered (tractive stock) and non-powered (rolling stock). Also, rail vehicle consists of two main part, Car-body and Running gear. The car-body is a part which is carries the payload. Running gear consist of wheel, axle and suspension as component which connect them together. Depending on the type of running gear there are two vehicle types:

a. Rigid frame vehicle. The running gear just composed of car-body and wheelset which are connected by suspension system.
b. Bogie vehicle. It is called as bogie, and bogie consist of one or more wheelset and frame and suspension system. This type of the vehicle has two level of suspension. Primary suspension between wheels and bogie frame and secondary suspension is located between bogie and car-body.so the suspension systems gives to bogie vehicle high performance specially when they are moving in the curve.

Sometimes, typically in freight bogies, only a single-stage suspension is used.

For modelling of each level of suspension the properties of that element are important like the stiffness of the spring, or damper properties etc. Damping is usually provided in railway vehicle suspension using viscous or friction damping devices. There are many types of spring and damper such as coil spring, rubber spring, leaf spring, air spring, etc.

After modelling the vehicle or different type of the vehicle in GENSYS there is possibility to create a train-set by different number of vehicles, but it is necessary to define how we couple this vehicles to each other, So, the modelling of buffers and draw gear is important issue for creating the train-set. The brief view of commands which is relevant to Vehicle modelling is mentioned in appendix A. Generally, in the figure 2-5 Simple mechanical model of four-axle vehicle is shown. The car-body can be approximated in a model as a flexible or rigid car-body, Wagons are modelled torsionally flexible car-bodies to examine the effect of car-body torsional stiffness. For this, each car-body consist of two similar mass elements that joint at the center of mass by force element acting on all 6 DOF and the force element consists of a torsional stiffness.

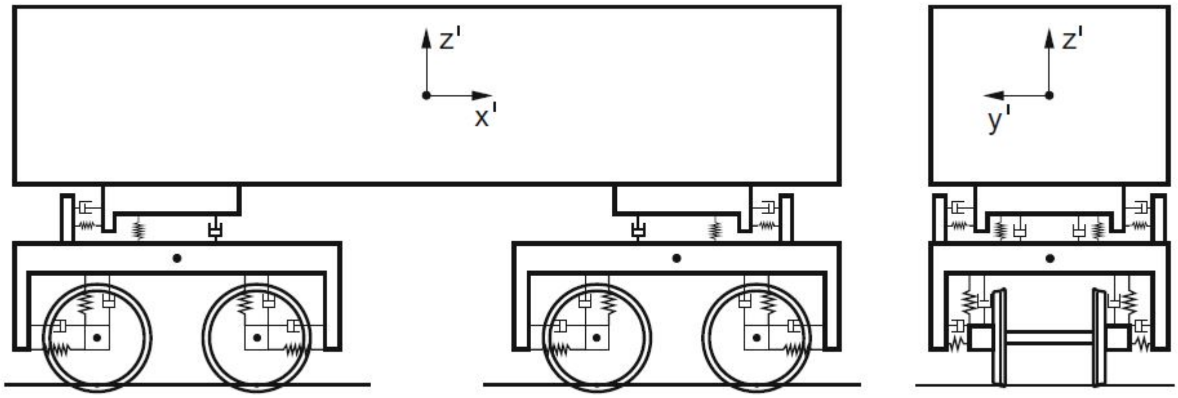

Figure 2-5 Simple mechanical model

2.2.4 Wheel-rail contact model

The guidance of railway vehicles is determined by a complex interaction between the wheels and rails, which requires a detailed characterization of the contact mechanism in order to permit a correct analysis of the dynamic behaviour. The kinematics of guidance of the wheelsets is based on the wheels and rails geometries. The movement of the wheelsets along the rails is characterized by a complex contact with relative motions on the longitudinal and lateral directions and relative rotations of the wheels with respect to the rails. The characteristic of the wheel-rail contact is important issue in rail vehicle dynamics, it is nonlinear and because of this characteristic always called as contact function[1]. In GENSYS contact function are usually calculated in separated program and the input parameter are the wheel and rail geometry, rail inclination, track gauge and wheelset inside gauge, and all this in put except track gauge are assumed to be considered variation along line.[2]

The wheel/rail-coupling is a very important coupling for a railroad vehicle, especially in lateral direction. Between the wheel-flanges and rails we have a clearance between 6-10 [mm], which is about the same as we have in secondary and primary suspension (at least

1 João Pombo, J. A. (2007). *A new wheel–rail contact model for railway dynamics.*

2 Andersson, E., Berg, M., & Stichel, S. (2014). *Rail Vehicle Dynamics. Stockholm: KTH university.*

on tangent track). Therefore, the wheel- and rail- profiles has a great influence on the lateral behaviour of the railway vehicle. In vertical direction however the contact point is very stiff, why the vertical comfort is not affected much, but it is important when calculating the vertical wheel rail forces.

Historically, Hertz contact solution is used since it is of closed-form. However, some of its underlying assumptions may be violated quite often in wheel-rail contact. The assumption of constant relative curvature which leads to an elliptic contact patch is of this kind.

According to Hertz, an elliptic contact area arises if two bodies are pressed together with the normal force N. Hertz theory has been the only realistic way of analysing the problem of normal contact in railway applications.

For wheel and rail interface, there are a number of dimensions that define the wheelset and track geometry. Following figure shows how they are defined:

Figure 2-6 wheelset and track geometry

Top of Rail is the line you get, when placing a ruler across the rails. N.B. In the figure above it looks like the origin of Rail and origin of Wheel are located at the same point. But in most cases, they are not. Only in very rare cases the contact point coincides with the two origins, and in those cases the two origins are located in the same point. Origin of Rail is defined to be on surface of the rail, located a lateral distance of “bo” from track center line. The Gauge Measuring Point is a point between Top of Rail and GAUGE_MEAS_INTERVAL beneath Top of Rail. The points on right and left side shall be chosen in a way that gives the shortest distance between the rails. Origin of Wheel is defined to be on the surface of the wheel, located at a lateral distance of “bo” from track centre line. Flange thickness is measured at height FLANGE_THICK_HEIGHT relative to origin of wheel.

Parameter	Definition
BO	Distance between the Nominal Running Circles
ORIGIN_TO_GAUGE	Distance from the Gauge Measuring Point to the Nominal Running Circle
GAUGE_MEAS_INTERVAL	Vertical interval for finding the Gauge Measuring Point
ORIGIN_TO_IWHEEL	Distance between inside wheel and Nominal Running Circle
WPROF_LAT_SHIFT	Possibility to laterally shift the wheels on the axle. E.g. simulating a thin or thick flange

Table 2-2 input data

For instance, Standard Gauge 1435 mm is also sometimes called Stephenson gauge. The distance between inside rail on tangent track is nominally 1435 mm (4' 8 1/2").
The following data are valid for standard gauge track:

BO	750 mm
ORIGIN_TO_GAUGE	32.5 mm
ORIGIN_TO_IWHEEL	70 mm

Table 2-3 Standard Gauge 1435 mm

2.3 Train-set

A train is a complicated dynamic system comprising multiple bodies with many degrees of freedom. Train are used for both passenger and freight transportation but here the main discussion is on the base of freight train which is composed of different type of vehicle in this project.

In this project train-set is composed by three vehicles and instead of other vehicle two longitudinal compressive force (LCF) are applied in each side of train set.

After inputting data and modelling the different element which are necessary such as track, Rails, vehicles as Substructures and define how to couple elements to each other, there are substructures for each type of vehicle. Inside these substructures also there are other level of substructure which are used for different part of vehicle such as bogies, wheelset, car-body, etc. also if move to inner layer of code there are many other substructures in lower level. For instance, Bogie substructure is created by calling different substructures such as wheelset, primary suspension, secondary suspension, etc.

For making train-set in GENSYS, regarding how many numbers of vehicle are needed for train-set should be called by vehicle substructure and in the order of train-set combination. In the figure 2-7 three substructures for vehicle is called to create the train set.

```
####################################################################################################
####                                                                                               #
#                                  Create the train-set                                            #
####                                                                                               #
####################################################################################################
####################################################################################################
#                                                                                                  #
#        $1= Current vehicle    $2= Vehicle ahead of current  $3= Load Weight                      #
#        $4=First Bogie type    $5=Second Bogie type          $6= Load Length                      #
#        $7=Load Width          $8=Load Height                $9= Car-body                         #
#        For  $4 and $5          Y25     Linksuspension   Y25_f         Linksuspension             #
#                                                                                                  #
####################################################################################################

  in_substruct vehicle_2ax_f  [ 1  0 ]   # 2axle
  in_substruct vehicle        [ 2  1   0e3    Y25_f   Y25_f   0.    0.   0.    flat   ]   # Sgns735 empty
  in_substruct vehicle        [ 3  2   62.4e3 Y25_f   Y25_f   19.9  2.76 1.300 flat3  ]   # Sgns735 empty
```

Figure 2-7 Create the train-set in GENSYS

Then it is necessary to couple these vehicles in their order together with coupling elements like buffer and draw gears. The three-dimensional wagon coupling model consists of a draw gear in the center as well as two side-buffers and bufferstops as shown in Figure 2-8. The vehicle connection modelling is based on the work of Cantone[1] in the development of the LTS TrainDy. The buffers and draw gears are modelled by their force-stroke characteristics,

[1] al, Q. W. (2018). *International benchmarking of longitudinal train dynamics.*

while considering a friction model for damping. Figure 2-9 is an example of Force characteristics for buffer loading and unloading.

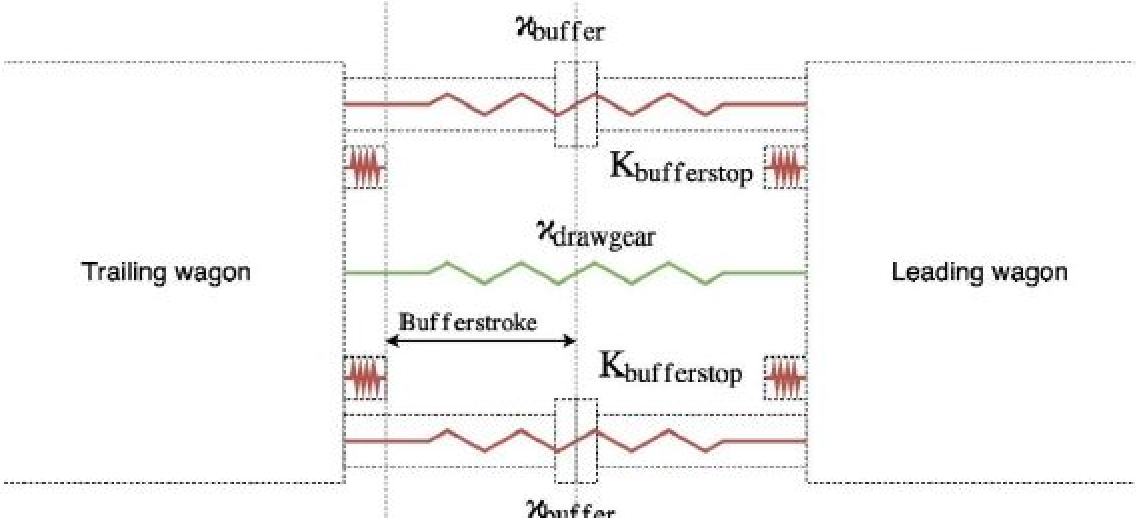

Figure 2-8 Modelling of longitudinal elements between two wagons: Top view

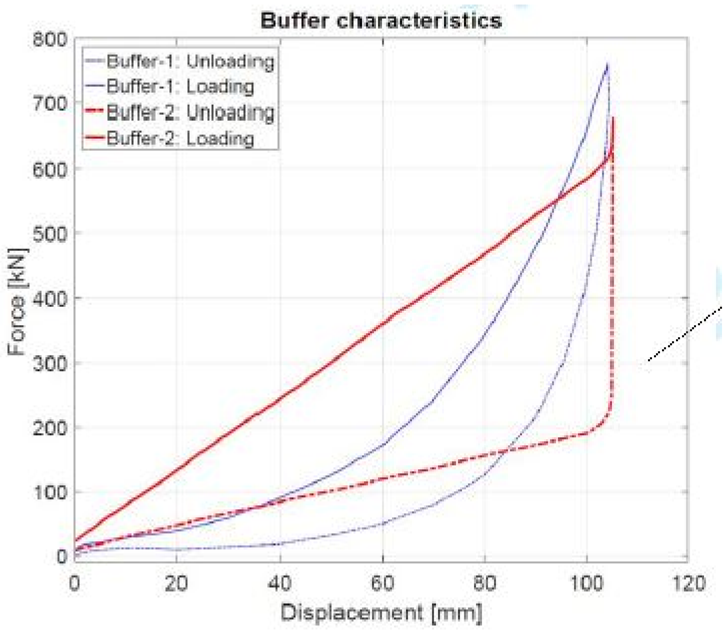

Figure 2-9 Force characteristics of buffer

In figure 2-10 and figure 2-11 the train-set model which is created with three vehicles in GENSYS is shown. The 1st vehicle is UIC single axle running gear and 2nd and 3rd vehicles are vehicle with Y25 Running gears. In next section the detail about this type of vehicle and running gear is described.

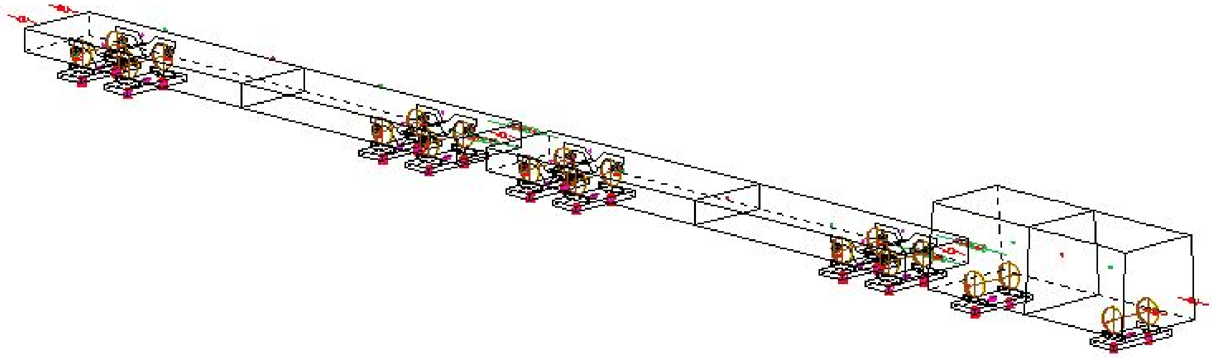

Figure 2-10 Train-set in GENSYS (3D view)

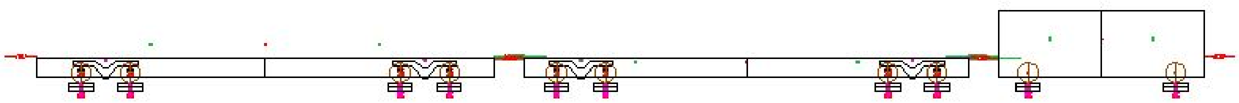

Figure 2-11 Train-set in GENSYS (side view)

2.3.1 UIC single axle running gear

Freight wagons with link suspension have existed for more than 100 years, as can be seen in Figure 2-12, and the link suspension is the most common suspension type for freight wagons in Europe today.

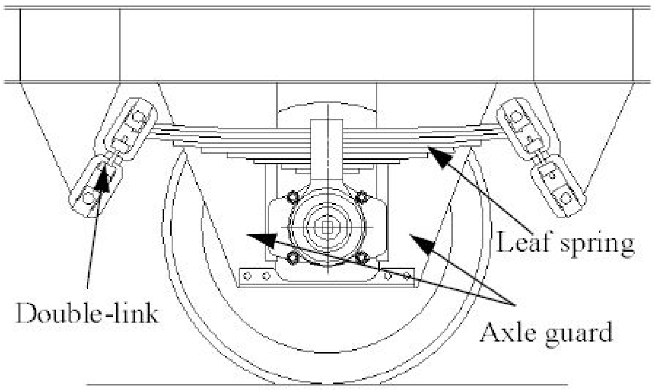

Figure 2-12 UIC double-link suspension

The UIC single axle running gear, which can be seen in Figure 2-12, consists of three main parts:

- Leaf spring
- Double-links
- Axle guard

The vehicle body is connected by double-links to the parabolic or trapezoidal leaf spring of the suspension, which rests on the axle box. This arrangement allows the axle box to move in both the longitudinal and lateral directions relative to the wagon body. The horizontal motion of the axle box is restricted by the axle guard. The principle of the suspension is that of a pendulum. In the longitudinal direction the suspension links are inclined, whereas in the lateral direction they are in a vertical plane when the vehicle body is in nominal position. The main advantage of this vehicle is the quasi static curving performance for a typical two-axle freight wagon with a wheelbase of about 9 m the relatively low longitudinal stiffness admits quite good steering performance down to 300-400 m curve radius on dry rails. On the other hand, according to hunting motion, the rung behavior of this vehicle is poor and the amount of damping in the horizontal plane provided by the links is often not sufficient and the properties of suspension change due to wear during the life cycle, these are disadvantage of this vehicle.[1]

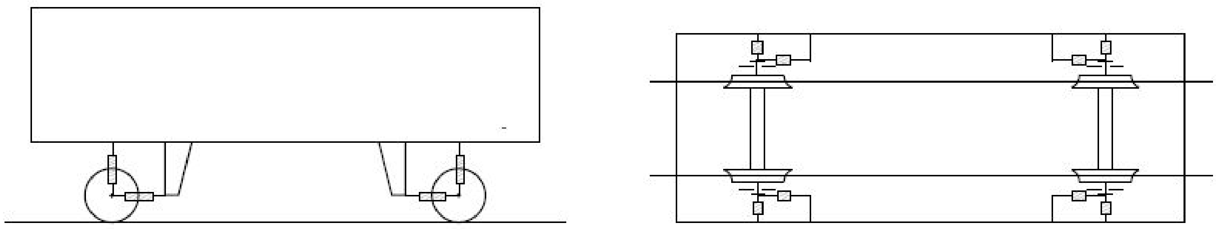

Figure 2-13 Two–axle freight wagon model

2.3.2 Y25 bogie

In 1960 SNCF started to develop a new type of freight wagon bogie. The bogie should be lighter and take less space than the standard bogie of those days. Due to the use of coil springs instead of leaf springs the bogie frame could be made shorter and lighter. The Y25 bogie shown in Figure 2-14 has an axle distance of 1800 mm and 920 mm wheel diameter.

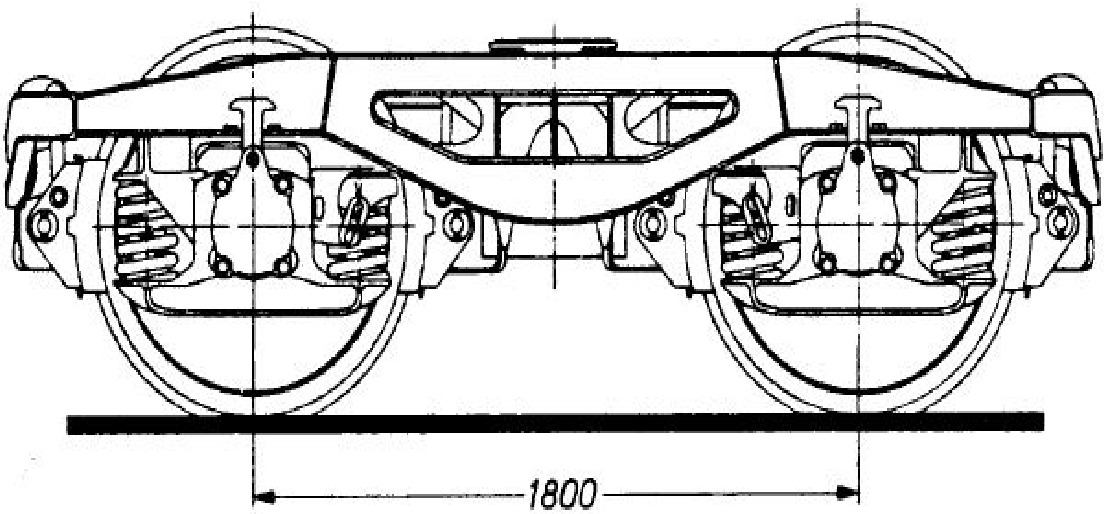

Figure 2-14 Y25 bogie

[1] *jonsson, p.-A. (2002). Freight Wagon running gear - a review* . Stockholm: Royal Institute of Technology.

The shorter bogie frame together with the use of coil springs instead of leaf springs makes the Y25 bogie slightly lighter and this is its advantage but on the contrary The performance of the Y25 bogie on curved track is quite poor and may produce high lateral forces and wear of wheel and rail and This is likely due to the stiff longitudinal primary suspension that does not allow for radial steering of the axles in narrow curves.[1]

2.3.3 Coupling and Buffers

The vehicle that make up the train are coupling together by coupling tools.

2.3.3.1 Coupling

The coupling connects two vehicles together allows for relative movement between vehicles and an example of coupler which is commonly used in Europe is Scharfenberg coupler.

2.3.3.2 Buffer

Many rail vehicles also have buffers, shock absorbing pads that limit the slack between the vehicles and decrease the effect of shock and avoid transferring the shock to car body.

2.4 Longitudinal Train Dynamics (LTD)

Longitudinal train dynamics is defined as the motions of rolling stock vehicles in the direction of the track (longitudinal). It therefore includes the motion of the train as a whole and any relative motions between vehicles. It is usually assumed that there is no lateral or vertical movement of the wagons (and locomotives). According the need to increase the capacity of train by increasing the length of the train, the running safety which is influenced by Longitudinal Train Dynamics play an important role. LTD is complex issue and can be affected by vehicle and operating condition such as infrastructure design, braking regimes, etc. With the increasing demands from the freight train operators with regard to payload scenarios, wagon types, braking scenarios and track routes, running safety of the freight trains could be critical especially at braking in infrastructure sections such as tight S-curves.

[1] jonsson, p.-A. (2002). *Freight Wagon running gear - a review . Stockholm: Royal Institute of Technology.*

2.4.1 Issues affecting Longitudinal Train Dynamics

Longitudinal Train Dynamics becomes a major issue concerning the running safety of long trains. Freight trains in Europe usually use pneumatic braking systems and the result of this is a delay in brake-force application along the train length. Longitudinal compressive forces (LCF) exchanged between two adjacent vehicles of a train have considerable impact on suitable length, applicable traction power, capacity, and permissible speed of freight trains. Wrong decisions concerning these parameters result in an increased risk of accidents due to derailments, and consequently damage to wagons, goods, and railway infrastructure. The difference in brake forces between different parts of the train could build up to high magnitudes with longer trains.[1] There are three categories which can affect LTD, and they are classified as, Vehicle based, track based, and operation based.

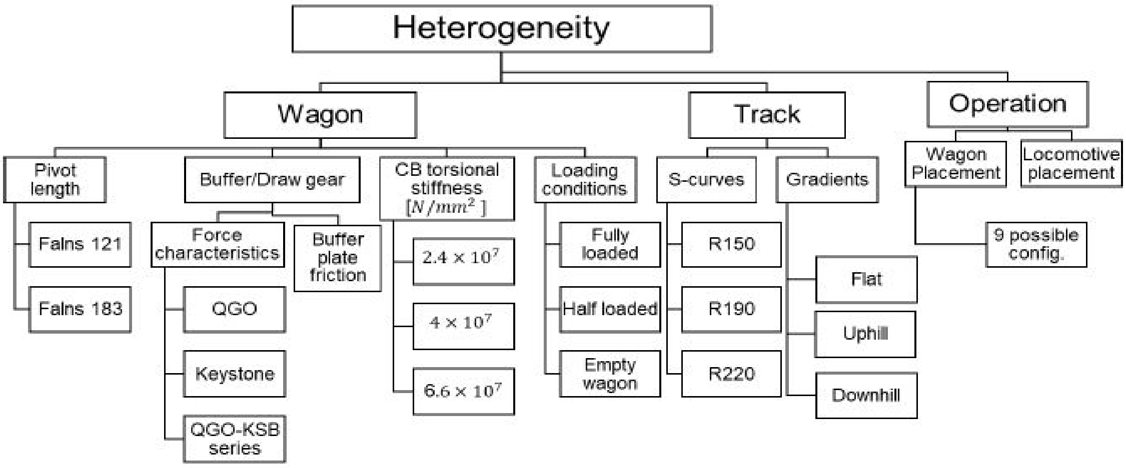

Figure 2-15general heterogeneities in the operation whose effect can be studied by simulation.

Different parameters' variety in combination of train-set could has effect on LTD, so they are called as Heterogeneity. Figure 2-15 lists some general heterogeneities in the operation whose effect can be studied by simulation.

1. Vehicle based includes:

[1] V krishna, V., Stichel, S., & Berg, M. (2017). *Longitudinal train dynamics for freight wagons passing through an S-curve. International Railway Symposium Aachen- IRSA. Aachen, Germany.*

a. Wagon body construction, which can be affected by type of car-body such as rigid car-body or flexible car-body with torsional stiffness, bogie pivot distance
b. Buffer and draw gear are nonlinear force elements that connected the wagons or locomotives. They are characterizing by loading and unloading curves and between these two curves there is an area which represent the energy absorbed.
c. Running gears influence the LCF due to suspension system.
d. Payload is the other vehicle-based issue which is so critical with respect to running safety since it effects the LCF. Regarding effect of adjacent wagon which is relevant this issue also can be considered as operation-based class. Because the position of the wagons regarding, they payload are in order in Train-set are important. For instance, in our main simulation a train-set with 3 vehicles, the critical situation happens when an empty wagon is surrounded by to full loaded wagons on a tight S-curve.

2. Track based issues such as curve radius, curve shape and cant can affect the force on vehicles.
3. Operation based depends on the train operator or sometimes loco driver's choice of operation and as mentioned previously wagon arrangement and locomotive arrangement can influence the LTD.[1]

The effect of all issues which are mentioned above can be study as the Sensitivity analysis. After creating train-set model all the parameters should be kept constant and just the parameter which should be studied in each simulation take the different value or if it refers to arrangement of wagon different arrangement can be analysis for studying of Sensitivity analysis.

[1] V krishna, V., Stichel, S., & Berg, M. (2019). *Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.*

3. Methodology

International Union of Railways (UIC530-2) tests needs more time and cost sources. Regarding the test requirements, simulation is proposed solution for saving time and cost. Simulation of long train behaviour in each situation is one of important issues of studying LTD. There are different tools for 3-dimensional multi-body simulation (MBS). GENSYS as MBS software is selected for this research which is to be used in 3D simulations of rail vehicles dynamics. This study is carried out for mostly common types of freight running gears. UIC single axle running gear, and Y25 bogie. Also, different types and sizes of car-bodies as rigid and flexible Car-bodies are modelled. Flexible car-bodies are modelled based on two separated similar mass elements that jointed together at the centre of mass by a force element which acting on all 6-degree of freedom. The force element consists of a torsional stiffness.

3.1 Modularization

GENSYS is multibody simulation (MBS) software which is used for 3D simulations of rail vehicles. It is Based on bottom up approach, A bottom-up approach is the piecing together of systems to give rise to more complex systems, thus making the original systems sub-systems of the emergent system. In a bottom-up approach the individual base element of the system is first specified in great detail. These elements are then linked together to form larger subsystems, which then in turn are linked, sometimes in many levels, until a complete top-level system is formed. This strategy often resembles a “seed”model, by which the beginnings are small but eventually grow in complexity and completeness.

Its bottom-up approach gives opportunity to have different types of components but on the other hand it has a massive file structure, for instance, in one main file for a one rail vehicle with a car-body and two bogies, it has more than 1000 command lines which makes the modification a bit harder. Each user can create models with different methods. However, other users who want to modify or use this model must spend more time to read and understand. Inside this main file also there are substructures which are used to avoid duplicating codes for similar elements.

A common model in GENSYS is to be coded in one main file and all elements which is necessary for modelling are to be defined in this file.

The program CALC is the central calculation program in GENSYS. The program can be started with four different scripts depending on which type of analysis is required. The different scripts are:

- QUASI, which calculates the quasistatical state of the input data model, i.e. seeks the position where all the speed derivatives are equal to zero.
- MODAL, which performs eigenfrequency calculations of the input data model.
- FRESP, which performs frequency-response analysis of the input data model.
- TSIM, which performs numerical integration in the time domain.

The program is a general variable processing program. All the major functions in the program are labelled variables. The variables are dependent on each other according to a specific system described in the input data. The input data model can be built-up of local coordinate systems, bodies, couplings, and mathematical functions. The mathematical functions are defined by the main command "func" and are very powerful. In addition to creating new variables in the memory, user can also transfer output data in existing variables.

The main file includes these main parts:

- Headlines

  The text is read from the lines first non-blank character until the end of the line. If the user wishes to begin the header line with a blank, this must be marked by the header being inserted within acute accents "Headtext". If a word in the headline is preceded by the $-sign, the CALC program will try to find a variable with the same name and replace the variable name including the $-sign with the variables value at time=0. If there is no variable name in the program's memory, this will not affect the content of the head text.
- Calculation type

  To select type of calculation should be used which are mentioned above.
- Track

  Modelling the track and define the irregularities and other things which are relevant to track.
- Vehicle Frame

To define the car-body also coordinate system with respect to Car-body center of gravity.

- Bogie

  In this section all necessary parts of bogie are modelled such as bogie frame, primary and secondary suspension elements and how they are coupled to each other also coordinate system with respect to bogie.

- wheelset

  define the wheels and axle

- Creep

  All Creep forces tangential to the contact surface, etc.

- Etc.

GENSYS include Substructure, If the same input data shall be repeated several times with only minor differences in the actual data, the input data can easily be formulated in a substructure with arguments. When the substructure is later called, the different values can be entered into the substructure's argument. Every substructure is given a name "struct_name", and the content of the substructure is defined within brackets [ ]. This substructure is now stored in a temporary file for later use in the directive in_substruct.

Beside what is mentioned above also for Modularization and use the advantage of it, Standardizing nomenclature of vehicle building is necessary to give this advantage that for modifying the code or model not necessary to read whole the code to find that what is the name of each element of vehicle and how user has defined it.

For this the standard nomenclature are divided to three main part:

- Substructures file names
- Vehicle component names (Car-bodies, Bogies, Axles and etc,)
- Vehicle and track details names (Dimensions, Masses and Etc,.)

In the figure 3-1 below, it is shown as an example how to use standard names, for instance,

1. “carbody_box_f “as substructure file name for calling the car-body which is defined in a substructure under the name of carbody_box_f which shows that it is box type car-body and the letter “f “at the end refers to the flexible car-body .
2. “car_$1f” as vehicle component name refers to the element of car-body body and the letter “f” at the end refers to front box. Because for modelling the flexible car-

body, each car-body consist of two similar mass elements that joint at the center of mass by force element acting on all 6 degree of freedom. The force element consists of a torsional stiffness. F and B as suffix for flexible car body to show front and behind

3. "mc_$1/2" for mass of car body as Vehicle and track details names.

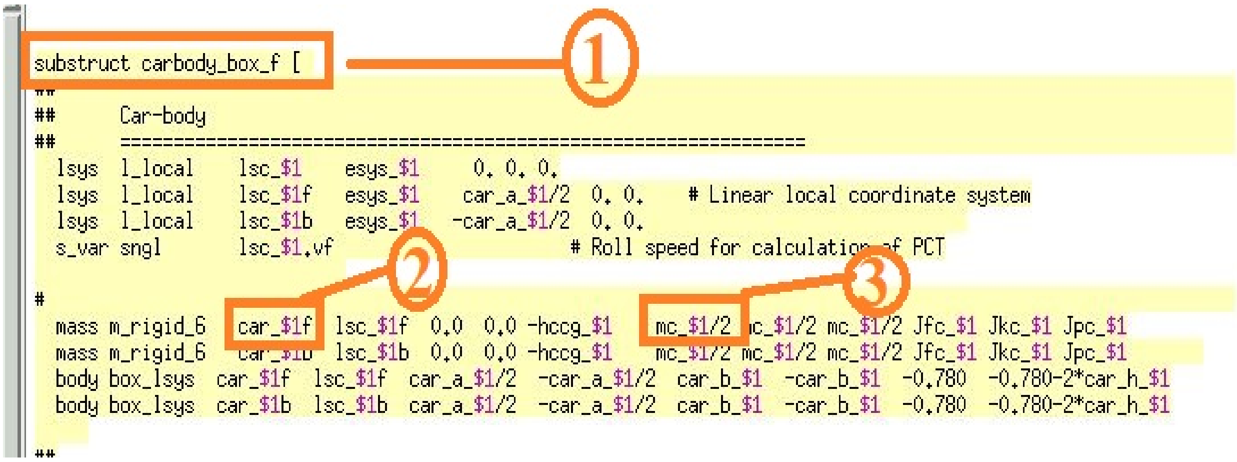

Figure 3-1 example of standard nomenclature using

The proposed solution for modularization is based on dividing whole the codes in two groups:

1. Main file:

   For calling the substructure files and it includes commands for example, calculation types, calling vehicle for train-set, etc.

2. Substructure files:

   Are classified in multiple levels and to be called by Main file

In the figure 3-2 it is shown how different part of code divided into different levels. And the library for using in GENSYS Main file are created.

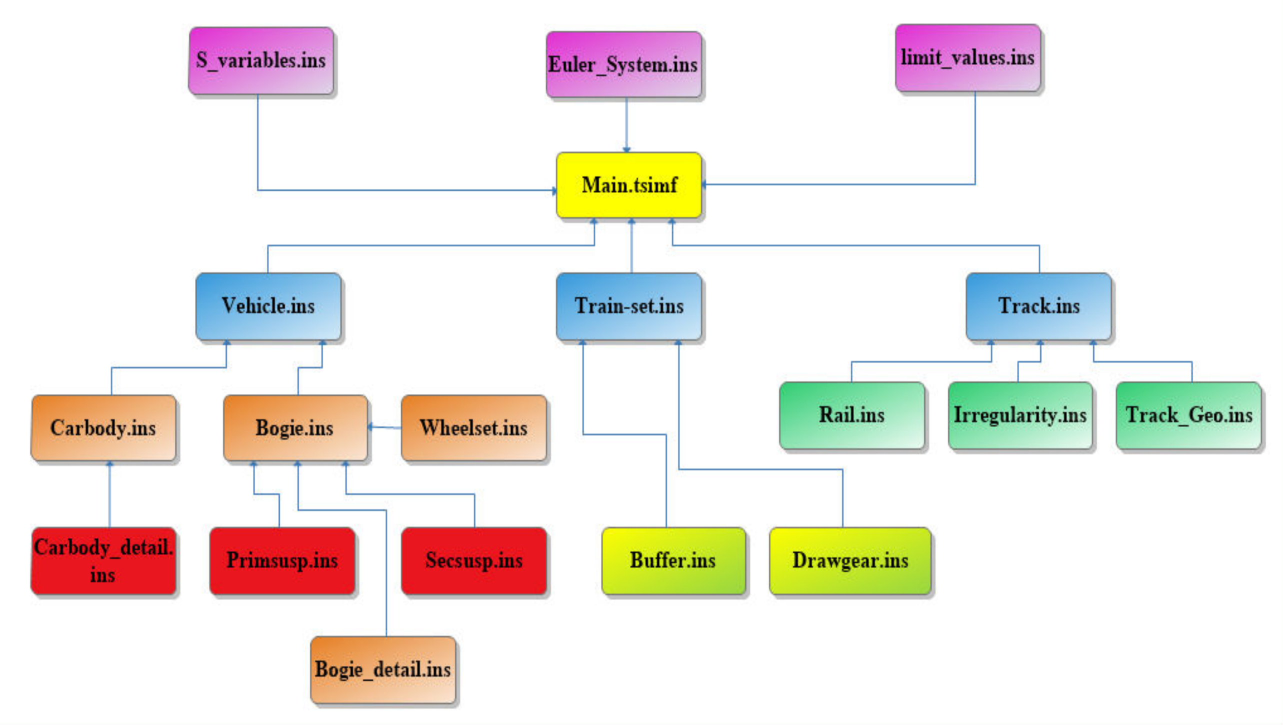

Figure 3-2 Structure of GENSYS with using Library

One main file for managing the model and calling substructure file in different levels then Vehicle file as substructure and as it is mentioned before, substructures are created in multiple levels. Vehicle as the highest level of substructures works a main substructure for gathering vehicle data from lower levels. And in lower levels for instance we have car-body and car body details or bogie and bogie detail substructure. Car body and bogie are as main substructure of lower level and just calls details from lower level and modification are done on the detail's substructure, not in mains substructures.

3.2 UIC 530-2 method

Leaflet UIC 530-2 describes the tests to be performed to assess the running safety if wagons on so-called s-curves. The test is carried out to demonstrate the permissible LCF through propelling tests. UIC Leaflet 530-2 defines conditions that must be complied with by wagons from a running safety point of view, irrespective of their type of coupling. Running safety is taken to mean negotiating twisted track and the longitudinal compressive forces generated during braking or propelling movements.

An important aspect of interest as far as Longitudinal Train Dynamics (LTD) is concerned is the push test, which is explained in detail in the document. The test is conducted to demonstrate the permissible Longitudinal Compressive Force (LCF) through propelling tests. These tests are carried out on a flat S-curve with a radius of 150 m and 6 m of straight track section between the circular sections as described in Figure 3-3. The standard procedure consists of the wagon being tested kept empty, surrounded by two 'barrier' wagons. The specification of the leading and the trailing barrier wagons are described as well. The barrier wagons are then surrounded by intermediate wagons on each side with a locomotive on one end and a measurement car on the other. The test train configuration can be seen in Figure 3-4.

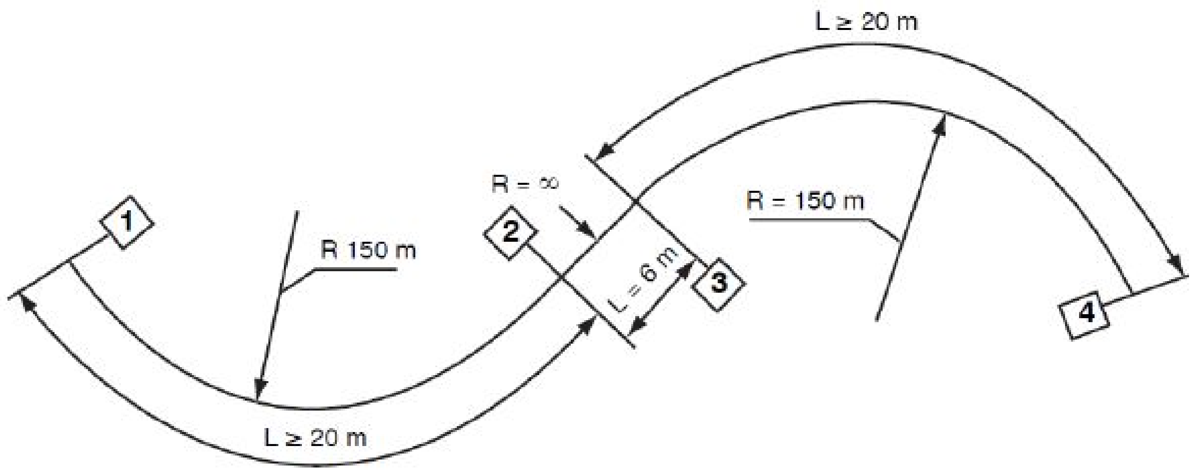

Figure 3-3 UIC 530-2 Track layout

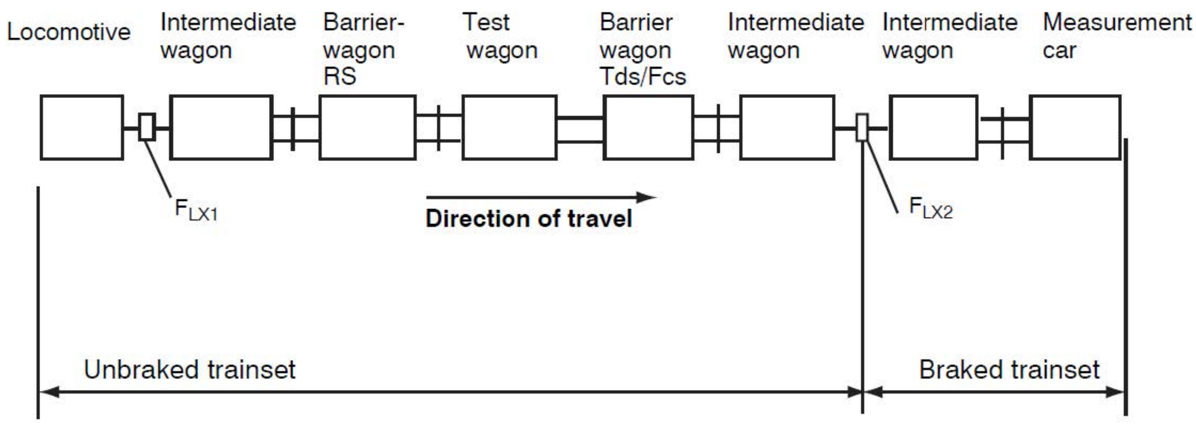

Figure 3-4 UIC-530-2 Train configurations

The buffer head height difference is to be kept approximately 80 mm between the test wagon (higher) and the barrier wagons (lower) and the surfaces slightly lubricated. The test train hence constructed is then propelled into the S-curve at a speed of 4 to 8 km/h with a constant (static) LCF. The LCF is generated by the propelling locomotive on one end and braking wagons on the other. The torsional stiffness ($Ct*$) is measured prior to the test. It is the torsional stiffness of the wagon body which for an angular rotation ϕ that corresponds to the torsional moment ($F \times 2b*$). The relationship is given by equation

$$C_t^* = \frac{2a^* \times 2b^* \times F}{\phi}$$

where $2b^*$ is the lateral distance between the buffers, F is the vertical force and $2a^*$ is the bogie pivot distance. The following parameters are measured during the tests:

- Longitudinal Compressive Force
- Wheel-uplift on all wheels
- Lateral forces on the axle boxes exerted on all the axles
- Deformation of axle guards on all wheels
- Lateral movements of the buffers between the barrier and the test wagons
- Track markers in Figure 3-3
- Distance covered.[1]

So, the assessment criteria to decide derailment are:

- Uplift of a non-guided wheel of more than 50 mm over a distance of 2 m.
- Climbing of guided wheels by more than 5 mm.
- Stabilized track stress (lateral forces)

  $H_{\lim(2m)} \geq 25 + 0.6 \times 2Q_0 \; [KN]$

Where, Q_0 is the mean vertical force of the wheel on the rail.

Instantaneous wheel-lift value of 10 mm for all wheels which can be seen as a compromise between the 50 mm limit for non-guided wheels over a distance of 2 m and 5 mm for the guided wheels in the UIC standard, is considered as derailment criterion.

[1] DYNAFREIGHT. (2017). *Retrieved from http://www.dynafreight-rail.eu/*

3.2.1 UIC 530-2 Test Configuration

UIC track base test are carried out on a flat S-curve with a radius of 150 m and 5.35 m of straight track section between the circular sections as described in Figure 3-5.

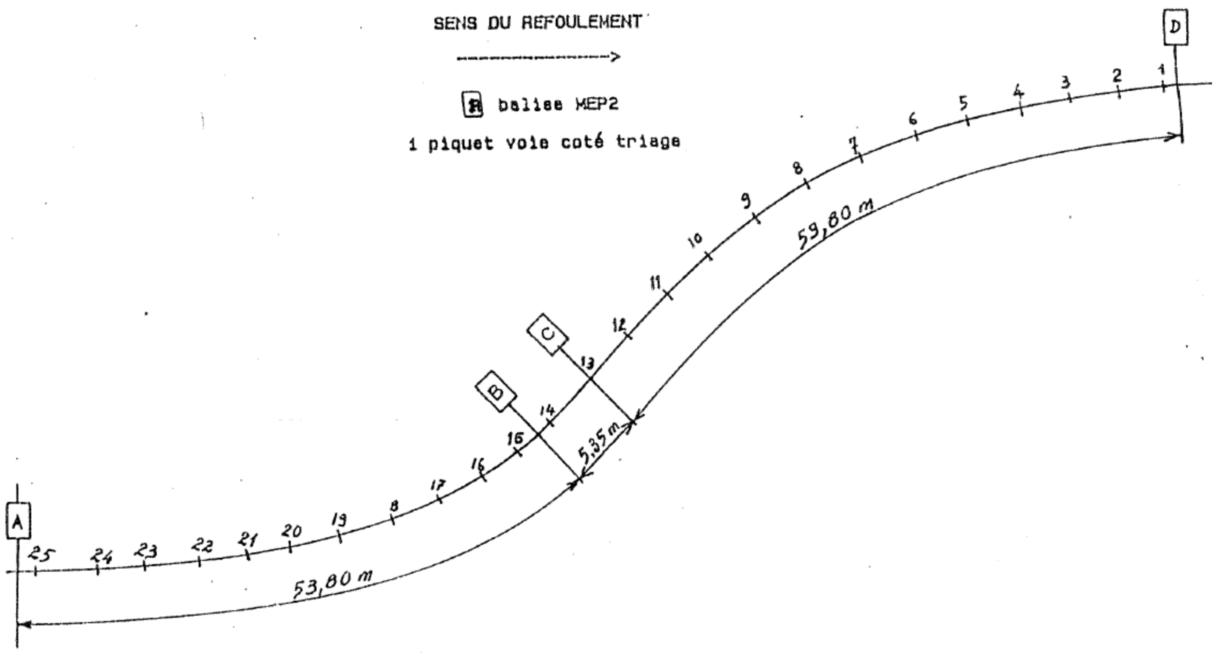

Figure 3-5 Track geometry

It can be seen the standard procedure consists of the wagon being tested kept empty, surrounded by two 'barrier' wagons. The specification of the leading and the trailing barrier wagons are described as well. The barrier wagons are then surrounded by intermediate wagons on each side with a locomotive on one end and a measurement car on the other

The following parameters are measured during the tests:

- Longitudinal Compressive Force
- Wheel-uplift on all wheels
- Lateral forces on the axle boxes exerted on all the axles

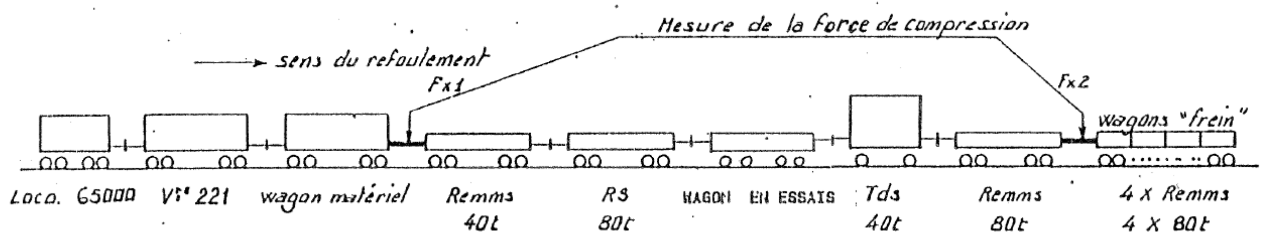

Figure 3-6 Train Composition and place of measurement

- Rs and Tds wagon are loaded with 20 tons per axle.
- Tds wagon: length over buffer 9,6 m, wheelset distance 6 m.
- Rs wagon: length over buffer 19,9 m, pivot distance 13 m.
- Buffer height difference 80 mm between frame wagons and test wagon.
- Greased buffer surface.
- No pretension of buffers.

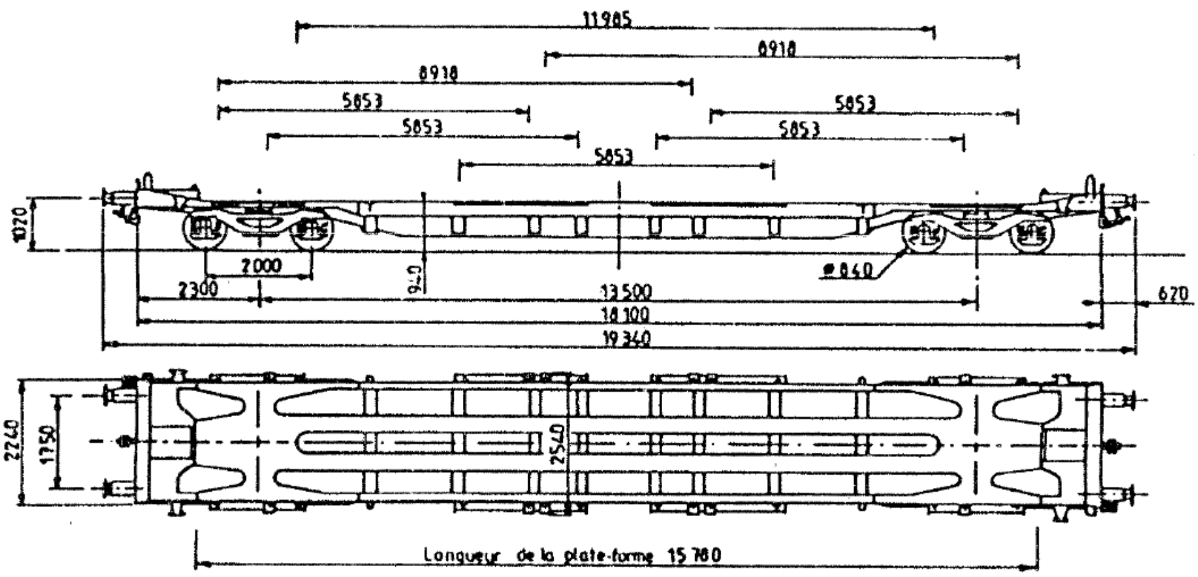

Figure 3-7 Test wagon data

- Wagon S70 type Sgmss
- Bogie type Y33A.
- Bogie flexibility 3mm/t for mass up to 12 t. For higher masses 1 mm/t
- Buffers length 620 mm, spring compression max. 105 mm, width 450 mm
- Wheel diameter 840 mm
- Tare weight 18 tons
- Torsional stiffness for similar wagon (multifret 160) is 4.1 x 1010 kNmm²/rad.
-

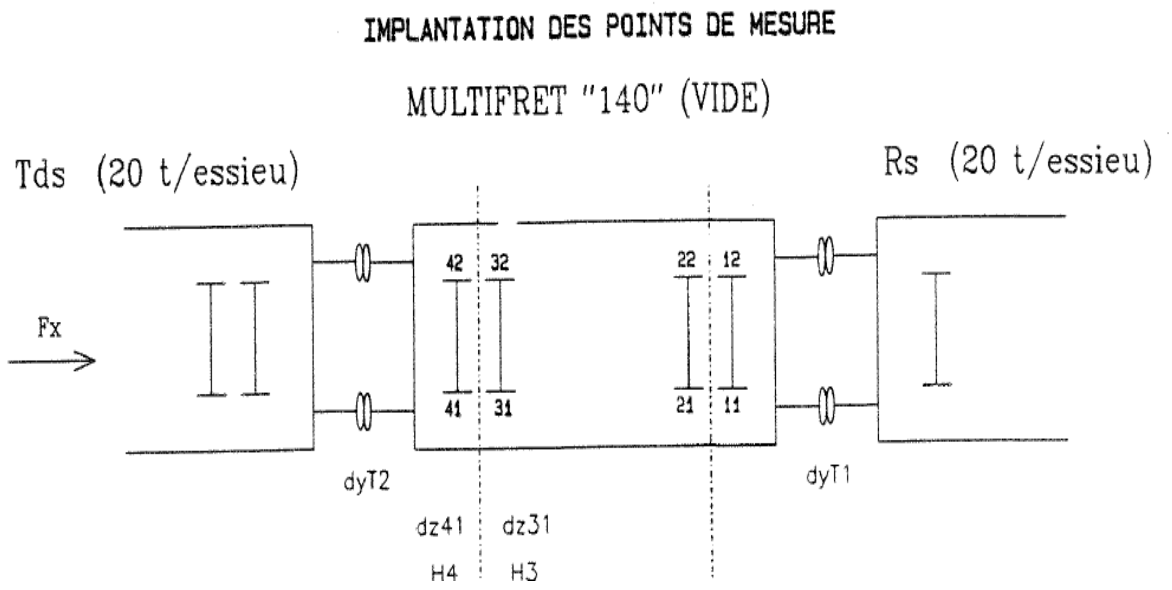

Figure 3-8 Measuring devices

The out put data provided by Deutsche Bahn Germany (DB) was prepared for three diferent longitudinal compresive forces 200 KN, 210 KN and 270 KN. The train speed was approximatly constant around $4\,{}^{Km}\!/_{h}$. During the test when the uplifte increase and when it reaches to specific level according to safety test stopped.

UIC based on track test has drawbacks. It requires time and recourse and just can run for a limit number of scenarios. All the measurements are done base on the test wagon and in this case, it is hard to consider the different influencing factors which are affected the test wagon. The other influencing factor can be such as the effect of other adjacent wagon, different buffers type, buffer friction, etc. on the other hand if it is necessary to have a sensitivity analysis based on one element, a lot of number of run require and as it is mentioned it takes time and resource. The other and most important drawback refer to that UIC based on track test is conservative. It can be seen from the test conditions that the estimation of permissible LCF is quite conservative in the procedure and may not necessarily reflect the normal operation of freight wagons. Also, according to heterogeneity different composition of train is difficult specially it is not possible to run the test in different track geometry. According the different combination of train or track geometry different LCF limits can be calculated. So, for overcoming to this drawbacks, simulation is proposed.

3.3 Simulation

A simulation is an approximate imitation of the operation of a process or system;[1] the act of simulating first requires a model is developed. This model is a well-defined description of the simulated subject, and represents its key characteristics, such as its behavior, functions and abstract or physical properties. The model represents the system itself, whereas the simulation represents its operation over time. The one-dimensional approach in the Longitudinal Train Simulators (LTS) calculate the force along the train and there is no possibility to analysis the derailment risk for example in sharp curve due to lateral forces. Because this method just focuses on along train. So, three-dimensional (3D) simulation can evaluate train forces along train and other forces such as lateral forces. Performing 3D simulation for long train is computationally expensive and impossible for high numbers of combinations.[1]

[1] V krishna, V., Stichel, S., & Berg, M. (2019). *Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.*

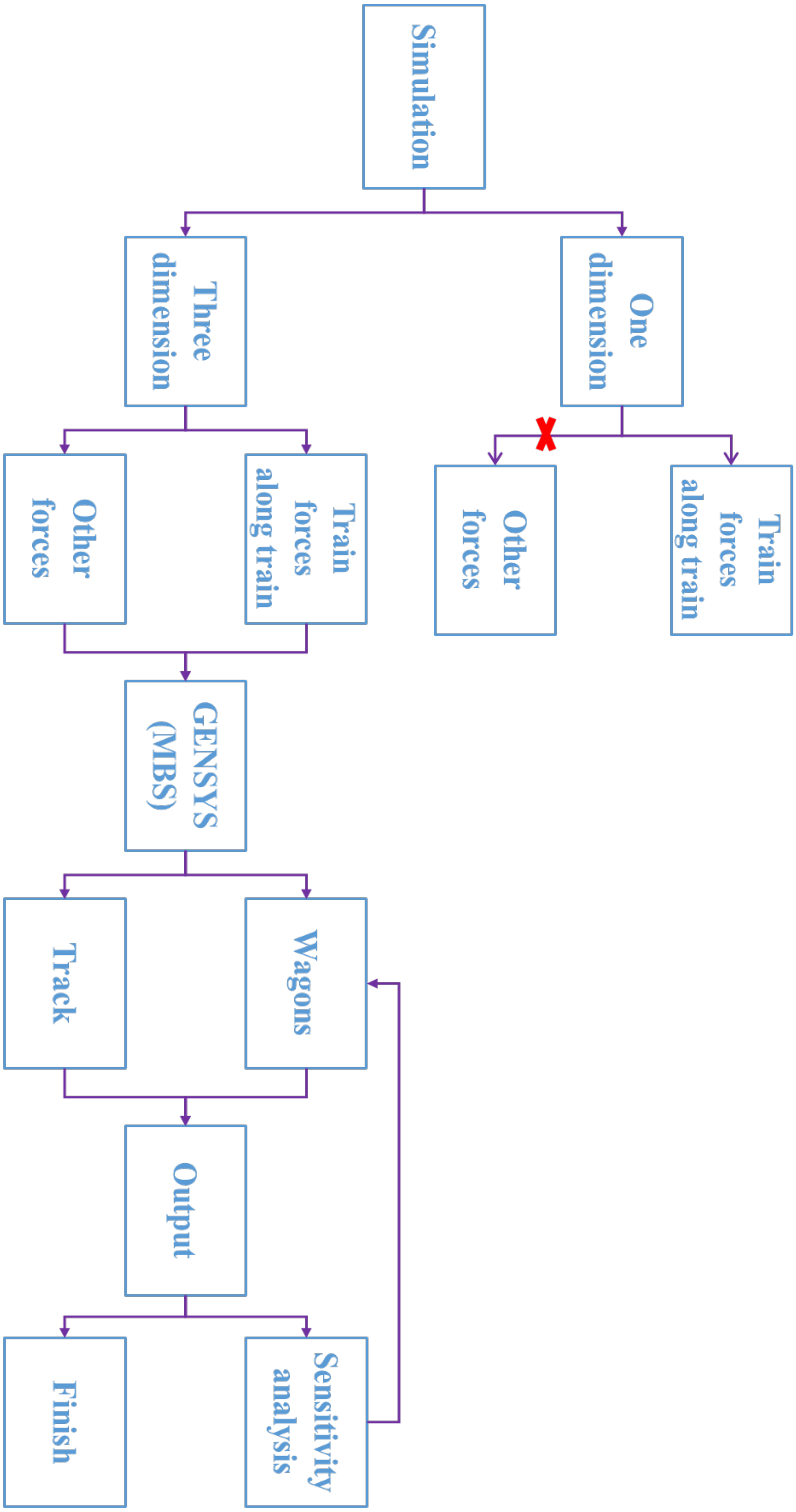

Figure 3-9 Simulation methodology

The simulation methodology and the difference between one- and three-dimensional simulation in the figure 3-12 it is shown. So, in one dimensional simulation just the forces along train can be calculated and the other forces cannot be analyzed however in the three dimensional all forces can be calculated. First the Track and Train-set should be modelled then by running the model the output is accessible. In both case there is opportunity to run different scenarios. Also, sensitivity analysis for each parameter by keeping other parameter constant and just changing the input for that parameter can be done in simulation. In this project the sensitivity analysis was done for buffer friction and in the following sections it is described.

The simulation methodology developed from UIC standards and give this opportunity to overcome UIC based on track test drawbacks. Simulation is proposed solution for saving time and cost. In the simulation approach which includes the detailed and simplified vehicles and its elements to allow the simulation of the longitudinal dynamic of the entire train, and calculation of the wheel-rail forces for the detailed sub-models. It makes an availability to analysis the effect of the longitudinal efforts on the wheel-rail forces and accordingly on the vehicle safety.

GENSYS as MBS software are selected to do these three-dimensional simulations and in GENSYS both wagon and track are modelled and for this the modularization, which is described previously, are used. By running simulations, results can be gotten to do post-processing steps. If we need more run for analyzing the effect of parameters which are mentioned as heterogeneities again, we must back and change the specific parameter which we want to study the effect of that and keep all other Parameter and situation constant and run the model again for several times in simulations.

The simulation in this project was done with 3 vehicles, the test vehicle which is surrounded by two other vehicles. For this simulation each run takes 1 hour but the speed which is considered for each simulation is $8\,{}^{Km}\!/_{h}$. But for running the simulation under the speed of $4\,{}^{Km}\!/_{h}$ which was done in this project for 3-4 cases, it takes between 4-5 hours. Most of these simulation records is based on test wagon. This mean that Simulation model take in to account middle wagon parameters which are affected by the adjacent wagons. The present simulations are performed on flat S-curve and in detail they are described in this section.

A five-wagon train simulation was also carried out in other project by Visakh Krishna[1] to check the influence of the number of wagons on various indices of the middle wagon.it is mentioned on this article by him, "the maximum deviations observed in the wheel-lift and lateral wheel-rail forces in comparison to the three-wagon train were 2% and 0.3% respectively. Moreover, the simulation took about three hours to complete, therefore found not viable for iterative simulation studies". One of the most important modelling tasks, that of the wagon connection, consisting of energy absorption devices such as draw gears and buffers.

3.3.1 Simulation framework

The train is composed of three wagons as shown in figures 3-13, middle wagon is called test wagon which is surrounded by two wagons and those are called barrier wagon. Two longitudinal compressive force are applied to each end of the train for the effect of other wagons. The test wagon is considered empty and two barrier wagons are fully loaded. It would represent the critical case of an empty wagon surrounded by two loaded wagons in the freight train.

Simulation is carried out for 2 most common types of running gear:

- UIC single axle running gear
- Y25 bogie

The first vehicle is UIC single axle running gear with flexible box car-body and the following vehicles are Y25 Bogie with flat and flexible car-bodies.

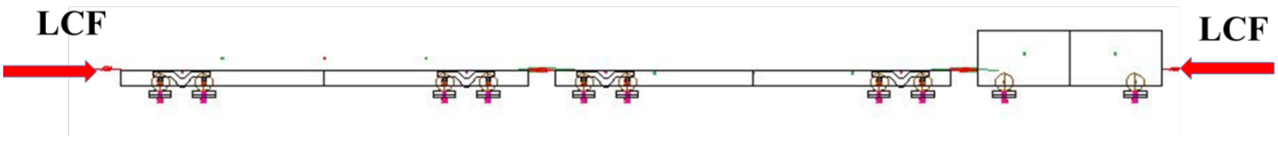

Figure 3-10 Train-set with 3 wagons and longitudinal compressive force at each end

The three wagons are modelled as shown in Figure with 6 DOF in these directions:

- X, Y, Z As translational degrees of freedom.
- φ, χ, ψ As rotational degrees of freedom about X, Y and Z axis respectively.

[1] V krishna, V., Stichel, S., & Berg, M. (2019). *Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.*

Wagons are modelled torsionally flexible car-bodies to examine the effect of car-body torsional stiffness. For this, each car-body consist of two similar mass elements that joint at the centre of mass by force element acting on all 6 DOF .The force element consists of a torsional stiffness ($C_{t\varphi}$) calculated according to Equation below in the φ direction. The relation between $C_{t\varphi}$ and C_{T^*} (the torsional elastic stiffness of the wagon body) is derived from and given by: [1]

$$C_{T\varphi} = \frac{C_{T^*}}{2a^*}$$

$2a^*$ is the bogie pivot distance.

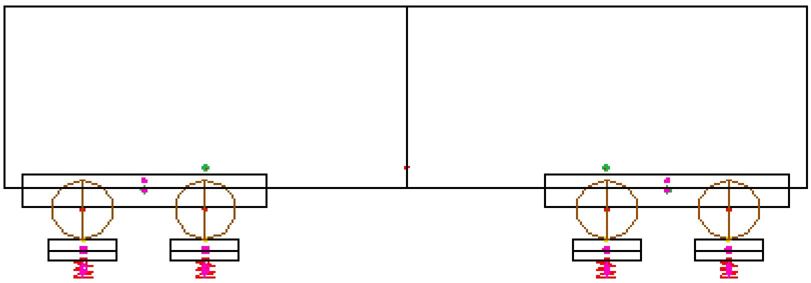

Figure 3-10Torsionally flexible car-body in GENSYS

Flat S-shaped curves with short transition lengths similar to the one defined in the UIC 530-2 norms and based on track sections in parts of Germany are focused in the present study. The track design geometry consists of S-curves with two circular sections of constant curvature separated by an intermediate straight section. While the S-curve has a sudden transition from the straight section, due to numerical issues encountered during the simulations, a minimum value of 2 m is assigned.[2]

Test condition:

- Barrier wagons are taken as loaded.
- Test wagon is taken as empty.
- Running speed is kept at 8 km/h
- Curve radius=150m

[1] DYNAFREIGHT. (2017). *Retrieved from http://www.dynafreight-rail.eu/*

[2] V krishna, V., Stichel, S., & Berg, M. (2019). *Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.*

Derailment criterion is the same as UIC 530-2:

- Uplift of a non-guided wheel of more than 50 mm over a distance of 2 m.
- Climbing of guided wheels by more than 5 mm.
- Stabilized track stress (lateral forces)

$$H_{\lim(2m)} \geq 25 + 0.6 \times 2Q_0 \ \left[KN\right]$$

Where, Q_0 is the mean vertical force of the wheel on the rail.

Instantaneous wheel-lift value of 10 mm for all wheels which can be seen as a compromise between the 50 mm limit for non-guided wheels over a distance of 2 m and 5 mm for the guided wheels in the UIC standard, is considerd as derailment criterion.

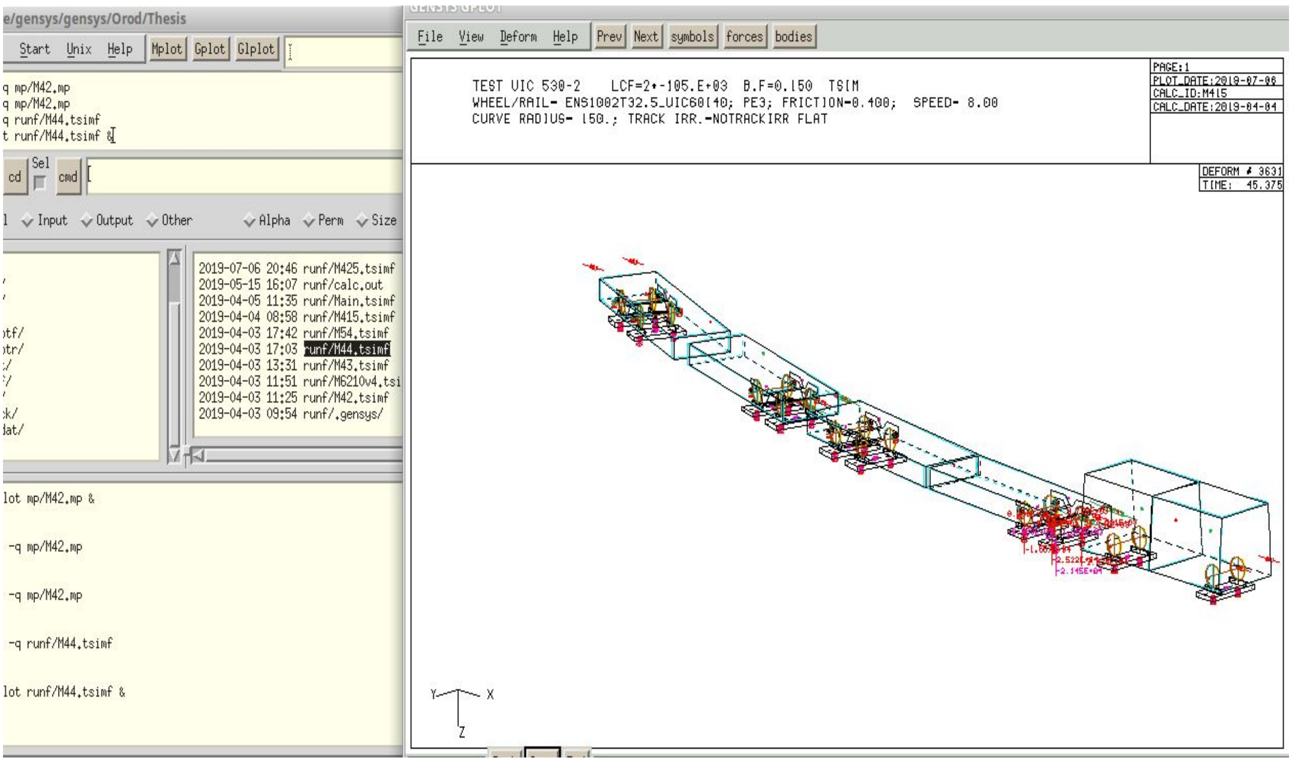

Figure 3-11 GENSYS environment (forces and deformation on train during moving on tight S-curve)

3.4 Validation

One of the real problems that the simulation analyst faces is to validate the model. The simulation model is valid only if the model is an accurate representation of the actual system, else it is invalid. Validation and verification are the two steps in any simulation project to validate a model.

- Validation is the process of comparing two results. In this process, we need to compare the representation of a simulation model to the real system. If the comparison is true, then it is valid, else invalid.
- Verification is the process of comparing two or more results to ensure its accuracy.

For wagons- Running safety- propelling tests according International Union of Railways (UIC530-2) were carried out. For saving time and resource simulation is suggested.

- Are the simulation results reasonable?
- Is simulation modelled properly?

So, simulation results should be validated before using the model or post processing steps. There are test results based on the UIC 530-2 standards and test data which are provided by Deutsche Bahn (DB). Simulation is performed with the test data and then the results of simulation and test results are compared for validation of model.

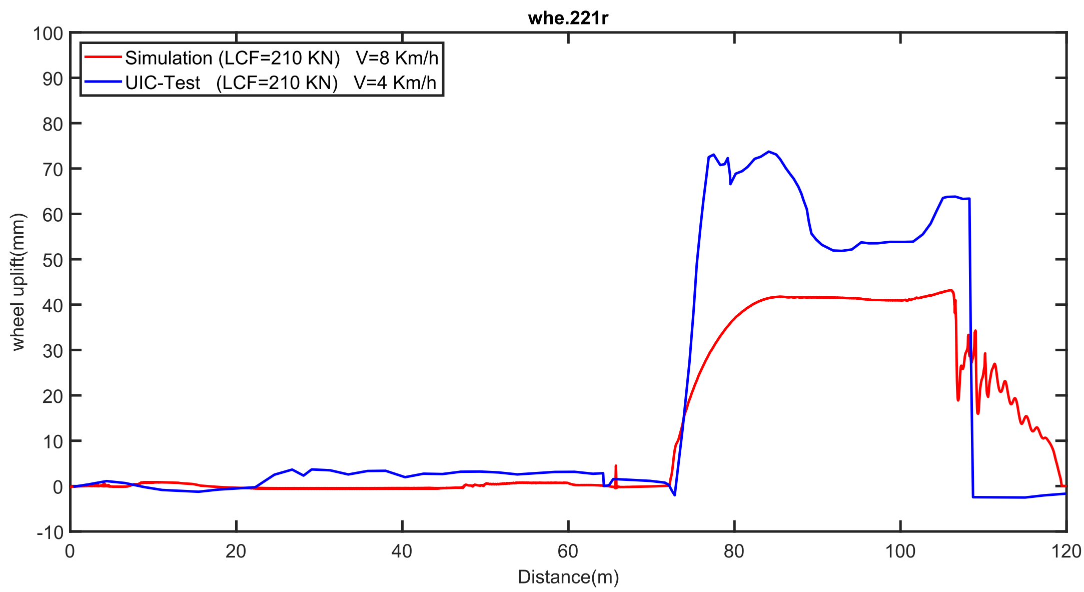

Figure 3-12 wheel uplift result (Test wagon second bogie first axle non-guided wheel)

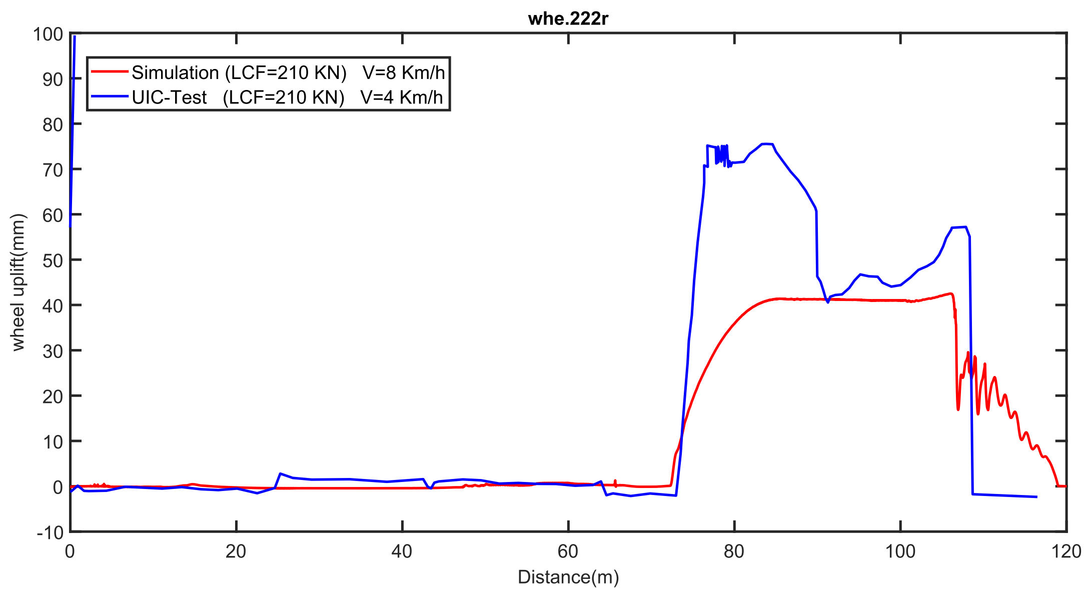

Figure 3-13 wheel uplift result (Test wagon second bogie second axle non-guided wheel)

In the figures above it can be seen the results for wheel uplift. The blue line shows the UIC and red line shows the simulation. It is approximately the same but for example at the end of the UIC test it is clear that sudden dropping happened, and it referes to this fact that the test stopped when wheel uplift reach to specific value but in simulation was done till end of it.

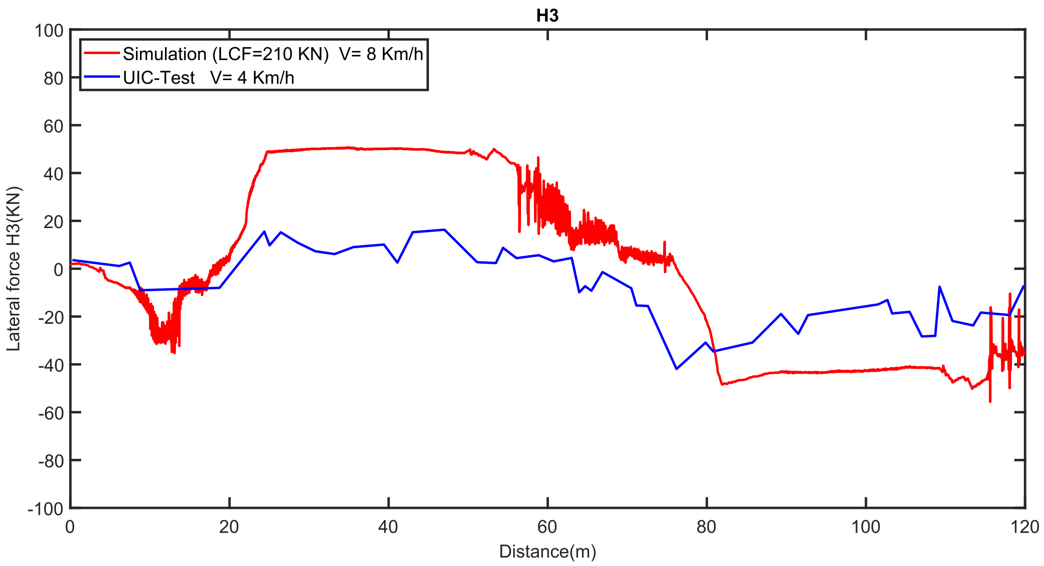

Figure 3-14 lateral force first Axle of second bogie

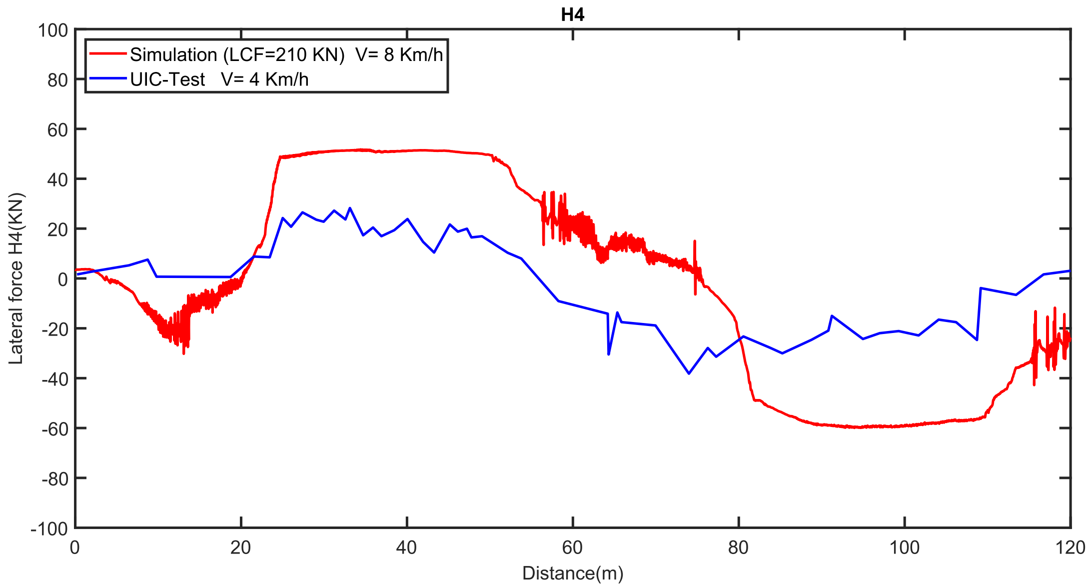

Figure 3-16 lateral force second Axle of second bogie

Here it can be seen the lateral force difference, which are affected to the first and second axle of second bogie of test wagon. Again, the blue line shows the UIC and red line shows the simulation. However, the behaviour is the same but There is a difference in value, and it could be referring to two most important issue:

- It refers to speed differences.
- And second one refers to uncertainties which were mentioned in previous slides.

This two issue just are the ideas based on the lateral force concept but in further studied it can be considered by running the simulation at the same speed of the UIC track based test and fining more detail about input, however it is hard to cover the second issue, but by fixing the speed as the UIC track base speed the value of lateral forces for real test and simulation should be closer to each other.

3.4.1 Uncertainties

Even if the comparison between the simulation's results and test's results explain the validation of model, some uncertainties remain, due to:

- Different input data between test and simulation such buffer friction, rail wheel friction ,for running a simulation it is necessary that all in input data be accessible however according to UIC test which there were not information about some details such as rail wheel friction or buffer surface friction and other details which were necessary for simulation so some input were used as common value for that parameters.

- Speed differences.

  On the other hand, because of time limitation different speed was used for simulation than the speed was used in UIC test. It was mentioned $8\,Km/h$ were selected as constant speed for simulation, but the test is based on $4\,Km/h$ and in some cases it is not constant.
- Test condition is also conservative and stopping test on large wheel uplifts, but the simulation was done till end.

4. Results

After validation now the result of simulation can be used in our post process. Also, because the UIC based on track testis conservative and in many cases the test was stopped and not be done till end, in simulation we can see the system behaviour till end of the simulation.
This Model is created by using the library which is created based on modularization of GENSYS environment and by getting the validation and also comparing the result of model when modularization was used and when not , we can reach to same results, so it can be confirmation the methodology of modularization.
In this section the output of simulation for different parameters such as LCF, wheel uplift, and Lateral forces during the passing of train-set through the S-curve are shown by figures and the derailment criterion for wheel uplift is discussed.
The result is based on three different longitudinal compressive forces 200, 210 and 270 KN

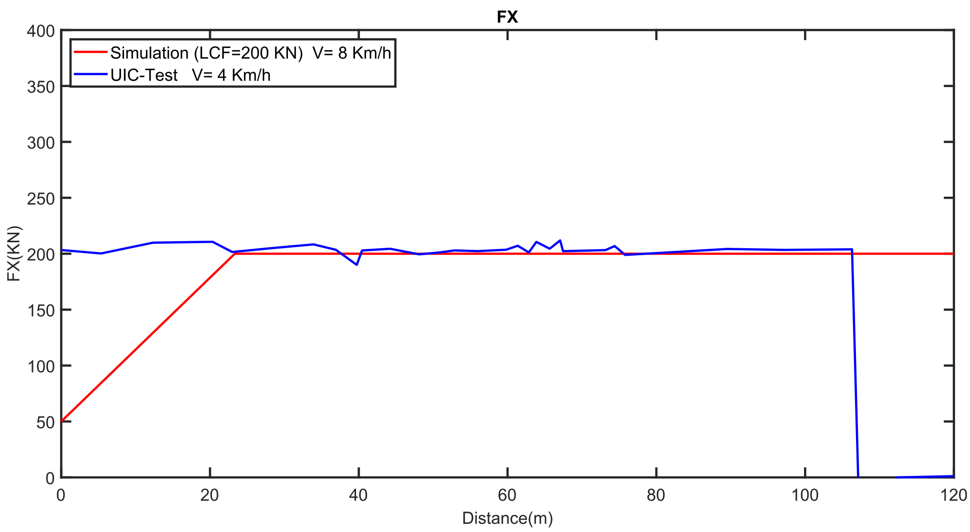

Figure 4-1 LCF=200KN during Test

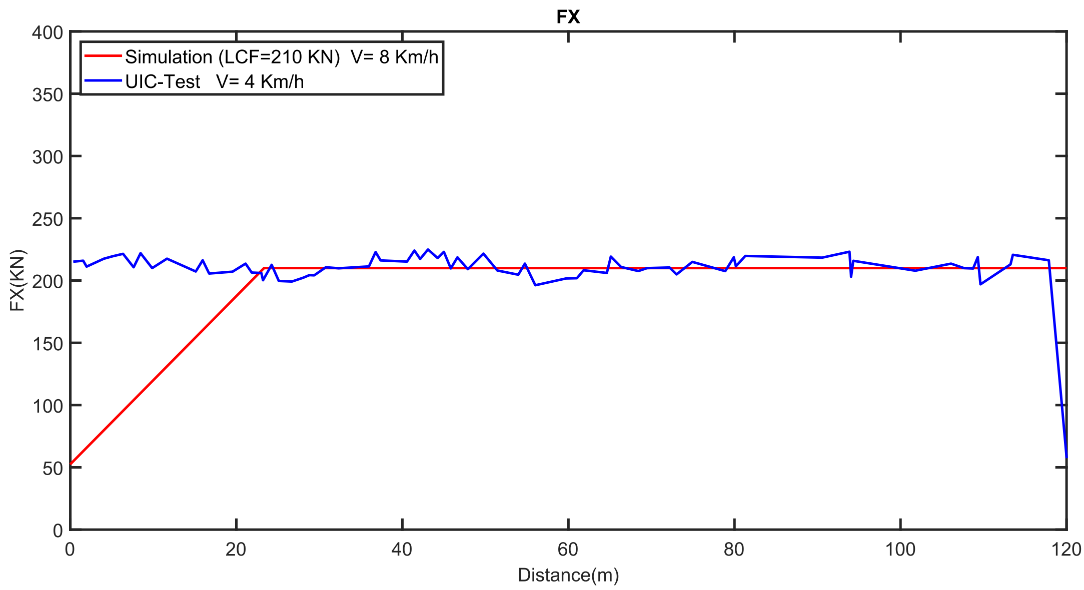

Figure 4-2 LCF=210KN during Test

The blue lines are refereeing to UIC-Test and the red lines are referring to Simulations

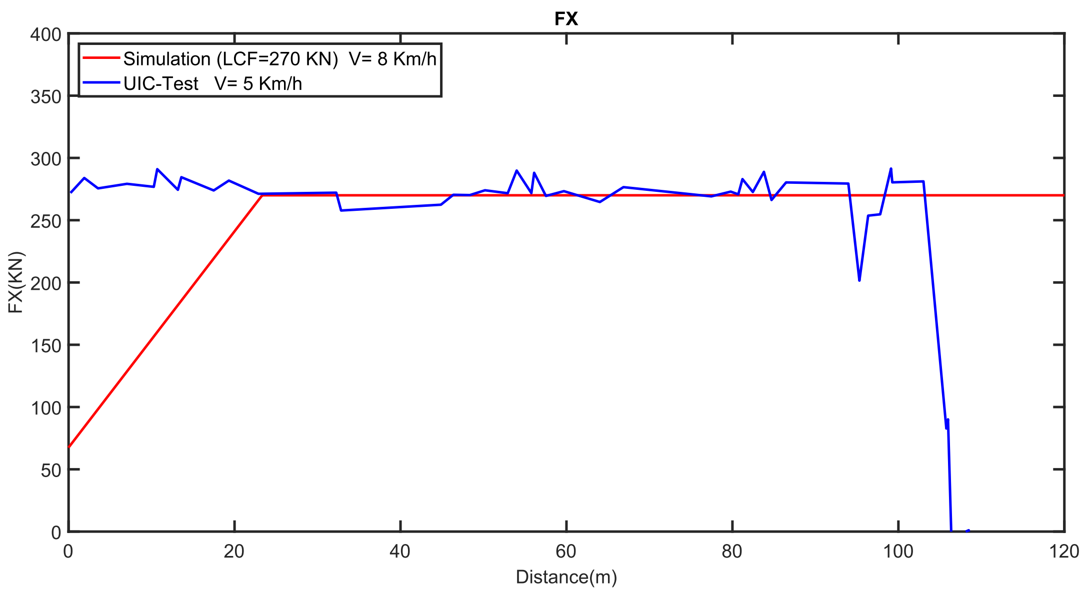

Figure 4-3 LCF=270KN during Test

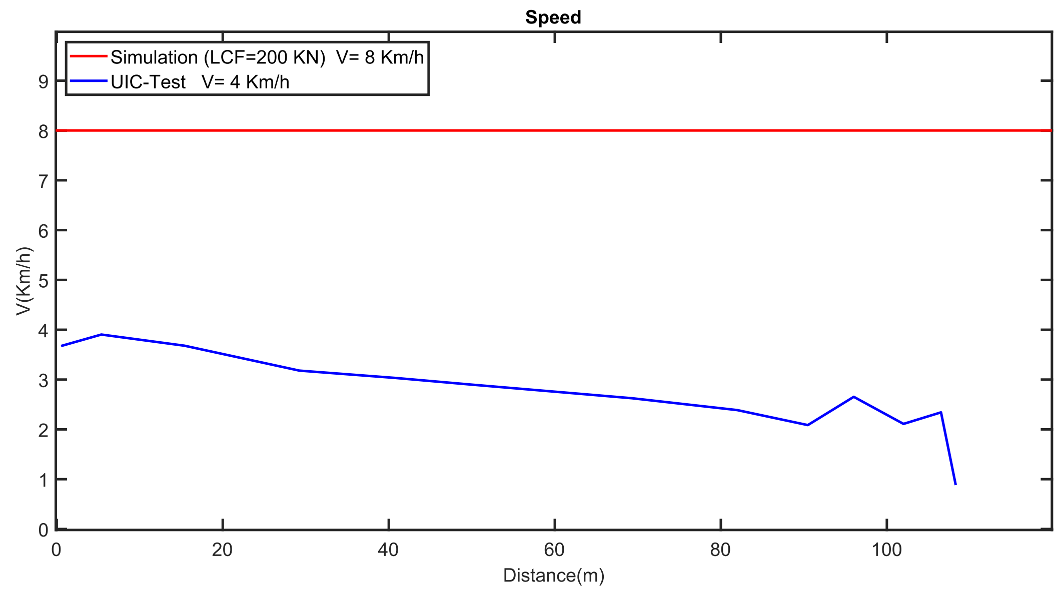

Figure 4-4 Speed during test (LCF=200 KN)

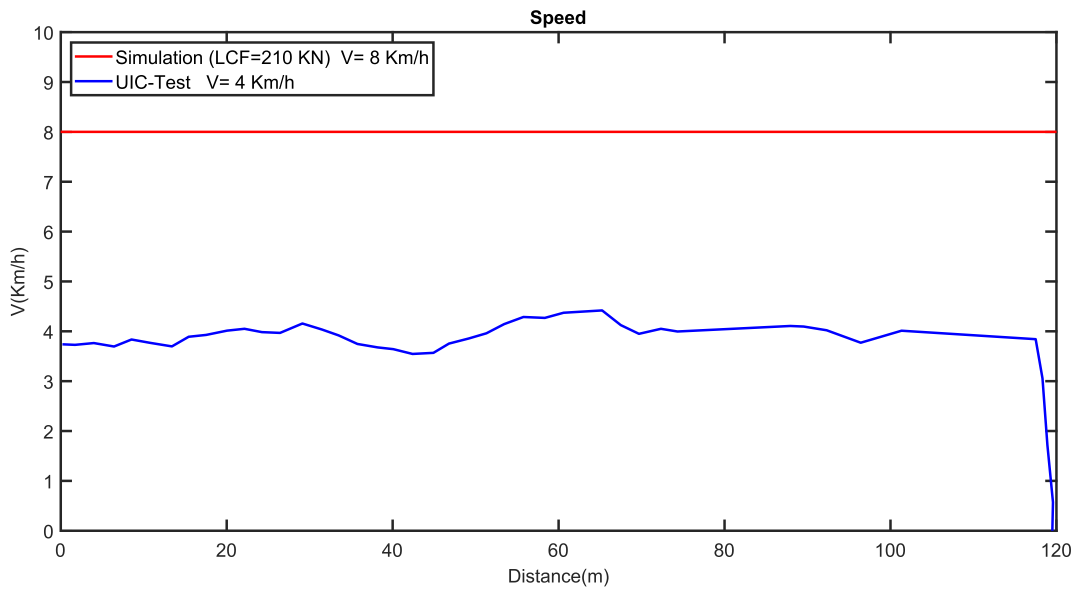

Figure 4-5 Speed during test (LCF=210 KN)

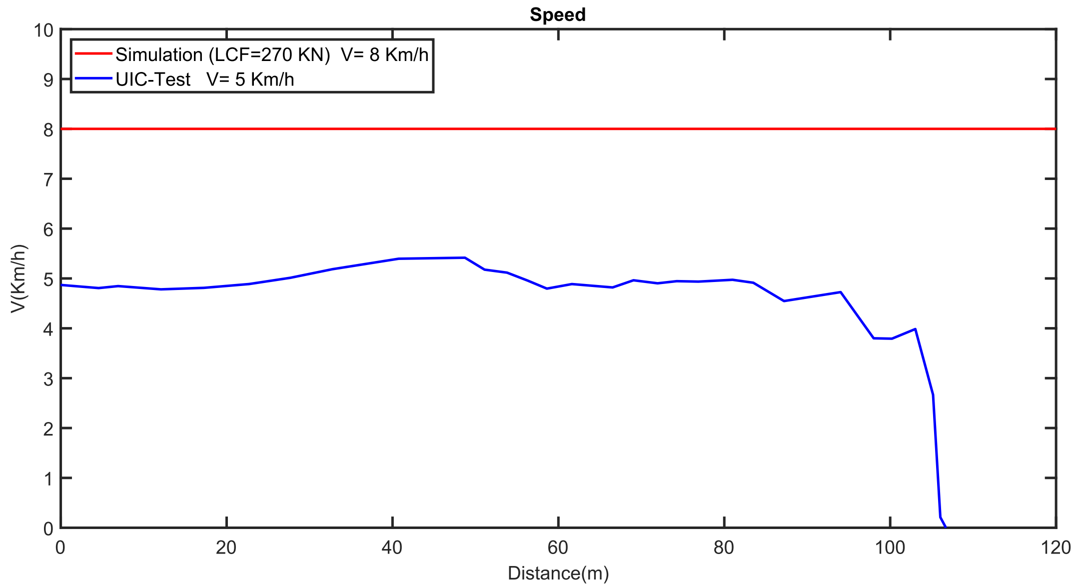

Figure 4-6 Speed during test (LCF=270 KN)

And about wheel uplift for LCF 200 and 270 KN the results are shown in the figures below. For LCF=210 KN the result is shown on validation section.

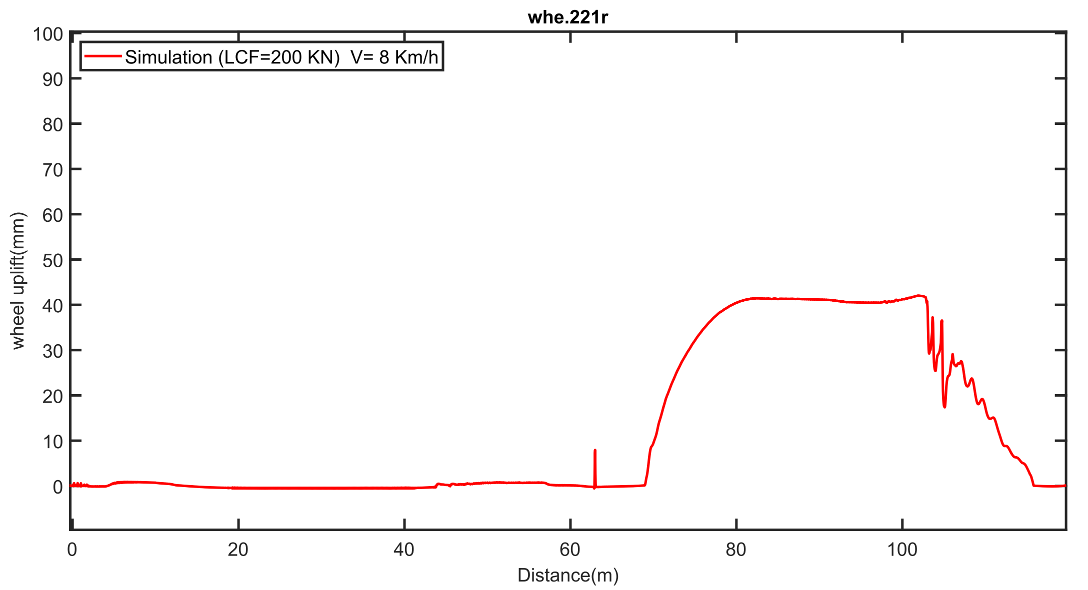

Figure 4-7 Wheel uplift result (second bogie first axle non-guided wheel LCF=200KN)

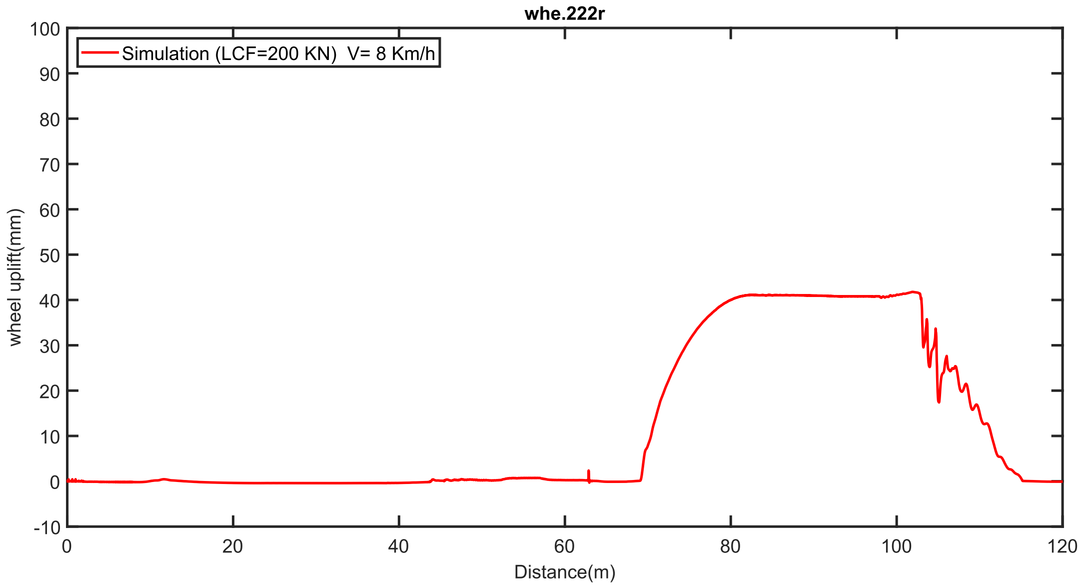

Figure 4-8 Wheel uplift result (second bogie second axle non-guided wheel LCF=200KN)

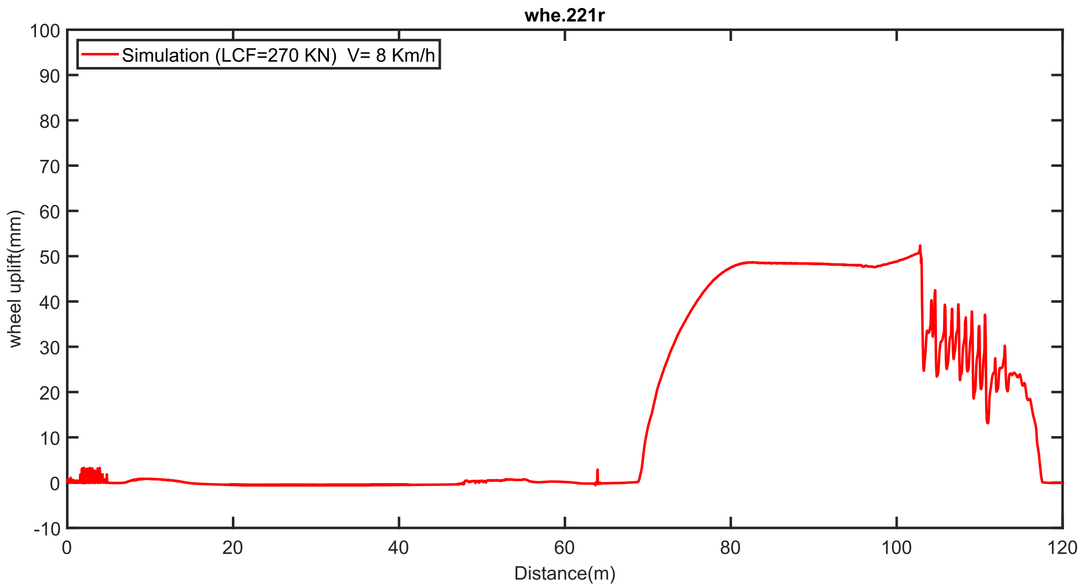

Figure 4-9 Wheel uplift result (second bogie first axle non-guided wheel LCF=270KN)

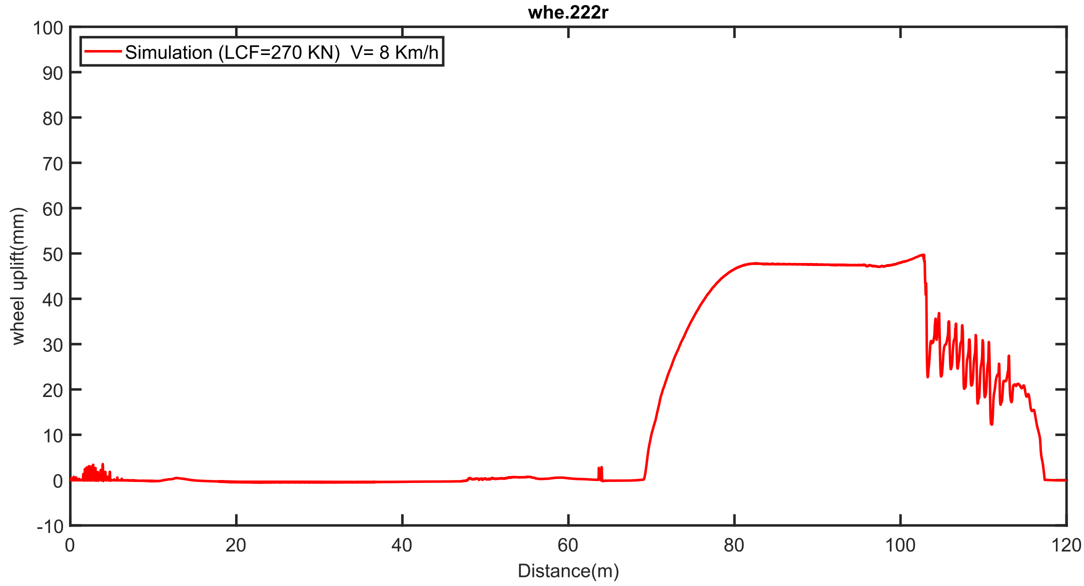

Figure 4-10 Wheel uplift result (second bogie second axle non-guided wheel LCF=270KN)

According to the figure 4-10 it is obvious that wheel uplift passed the value of 50 mm in the simulation and according derailment criterion it considered as derailment of train-set. By analyzing the results of UIC based on track, it can be seen in the LCF=270 KN there is sudden fall for wheel uplift at the end part of track. It happened between the 100m and 120 m on the S-curve and by looking at the LCF and speed figures at same point it can be seen the speed and LCF become zero. So, it shows test is stopped suddenly because of safety and conservative issues.

In real test wheel uplift passed the maximum allowed value for uplift and the test was stopped but simulation is done till end and the result confirm the derailment with respect to derailment criterion.

In further study it can be evaluate the position of train-set when the derailment. To find that each vehicle is in each point of track to analysis the effect of adjacent wagon on test wagon based on their position which can be affected be changing the buffer angle difference.

The buffer angle combined with the longitudinal buffer forces and the friction on the buffer-head surface influence the magnitude of the resulting lateral forces.[1]

[1] V krishna, V., Stichel, S., & Berg, M. (2019). *Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.*

4.1.1 Sensitivity analysis

The buffer surface friction is a parameter which is consider for the case of sensitivity analysis.

After validation according to sensitivity analysis methodology which was mentioned in follow simulation chart the model were run in same condition for different buffer surface friction it can be seen here all the detail are constant and just buffer surface friction changed from 0.1 to 0.3 for 7 different value and also the rail wheel friction kept constant as 0.3 the thing that is seen there is strong dependency between the wheel uplift and buffer surface friction. By increasing the buffer surface friction wheel uplift has specific increment. but the interesting point is that this increment is happen till a specific value of buffer surface friction after that, by increasing the buffer surface friction the wheel uplift value decreased and then again by increasing buffer surface friction derailment happens.

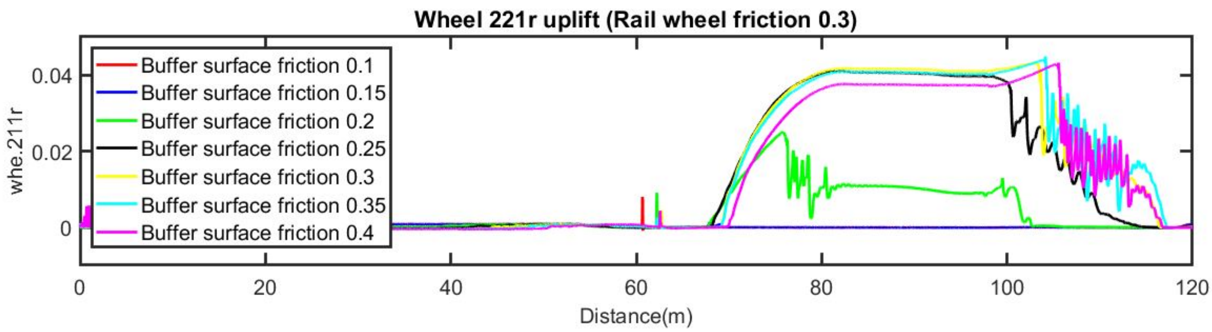

Figure 4-11 Wheel uplift for different buffer frictions (rail wheel friction =0.3) for non-guided wheel

Again the same analysis for another rail wheel friction 0.4 and used variable buffer surface friction, wheel uplift increase by increasing the buffer surface friction and same behaviour is seen with previous model with rail wheel friction =0.3 , It seems that by increasing the buffer surface friction the displacement in Z direction for wheel increases and close to derailment area the displacement in Z direction decrees and by compromising the displacement in Y direction increases and derailment happens.

Finding the maximum uplift and according to that finding the relevant buffer surface friction is require more simulation with small intervals of buffer surface friction also this value can be different for different rail wheel friction value or maybe other parameters too.

And it needs more times for studying and finding the value or relation between them. And it can be done in future studies.

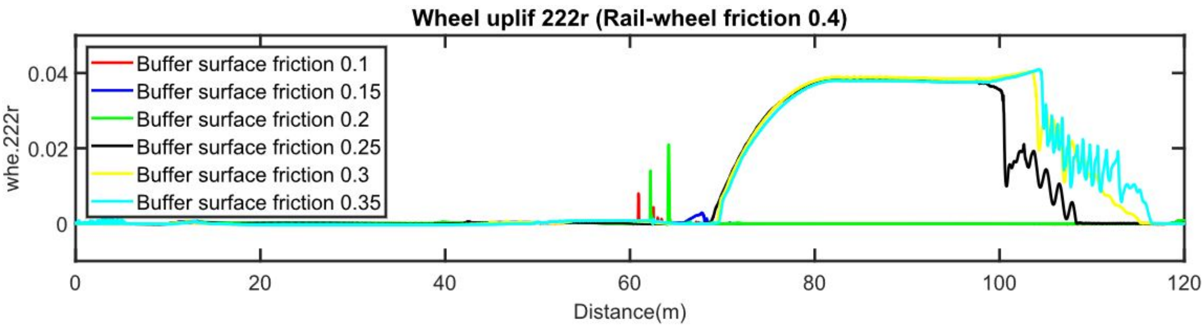

Figure 4-12 Wheel uplift for different buffer frictions (rail wheel friction =0.4) non-guided wheel

5. Discussion

Generally, it can be said that the rail mode is safe in particular when compared with road transport. Safety has improved dramatically over the last 50 years, a result of a number of measures in traffic management as well as stricter rules for rail operations (improved vehicles standards inspection, management practices).

Increasing the rail transportation capacity, especially freight transport is one of the main important topics to increase the rail efficiency. According this there are two possibility to increase the capacity, high speed train and longer train and with respect to network topology and short distance between station there are some restrictions. The development of long trains is related to specific technical issues that are object of further studies to ensure reliability and safety.

The work has analysed a long train using the multibody code GENSYS. The benefit of the proposed approach consists in the possibility to realise mixed models of the train. For this issue modularization and creating library is suggested that make it easy to make train with different combination. Modularization gives opportunity to easily modifying the model and reduce the risk of making mistakes while modification happens. Also, there is possibility to create the train-set with different combination in short time by using library.

Simulation can save time, cost and resources. On the Contrary the experimental setup in UIC 530-2 methodology, the simulation doesn't limit train heterogeneities while testing.

The work has analysed a train-set using the multibody code GENSYS. The benefit of this approach is analysing different composition of train-set and studying the sensitivity analysis to different component changes. In addition to determining the sensitive parameters, it is also necessary to evaluate the likelihood of different combinations of the heterogeneities. For example, the probability of having a sharp S-curve of radius 150 m along with steep gradients is unlikely. Accounting the same for the tolerable LCF calculation could result in conservative values, hence restricting the number of wagons.

According the simulation results It could be seen that there is strong dependency between the wheel uplift and buffer surface friction. By increasing the buffer surface friction wheel uplift has specific increment. It happens till a specific value of buffer surface friction then by increasing the buffer surface friction the wheel uplift value decreased and then derailment happens. By running more simulation there is possibility to find the value for buffer surface friction where after that by increasing the buffer friction wheel uplift decreases and then derailment happens.

Also, in future studies there is possibility by using simulation to analysis the sensitivity of other parameters and the effect of them on train steering and wagon running safety. With simulation it can be analysis the effect of adjunct wagon on test wagon based on the buffer angles differences. So, simulation gives the possibility of running different scenarios and save time and resources.

6. References

al, Q. W. (2018). International benchmarking of longitudinal train dynamics.

Andersson, E., Berg, M., & Stichel, S. (2014). Rail Vehicle Dynamics. Stockholm: KTH university.

DYNAFREIGHT. (2017). Retrieved from http://www.dynafreight-rail.eu/

João Pombo, J. A. (2007). A new wheel–rail contact model for railway dynamics.

jonsson, p.-A. (2002). Freight Wagon running gear - a review. Stockholm: Royal Institute of Technology.

L. Cantone. (n.d.). TrainDy: The new Union Internationale des Chemins de Fer software for freight train interoperability. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit, vol. 225, no. 1, pp. 57–70, 2011.

L. Yang, Y. K. (2015). Assessment of the curving performance of heavy haul trains under braking conditions.

M. Spiryagin, Q. W. (2017). nternational benchmarking of longitudinal train dynamics simulators: benchmarking questions.

UIC. (2008). UIC Code 530-2: Wagons-Running Safety.

V krishna, V., Stichel, S., & Berg, M. (2017). Longitudinal train dynamics for freight wagons passing through an S-curve. International Railway Symposium Aachen- IRSA. Aachen, Germany.

V krishna, V., Stichel, S., & Berg, M. (2019). Tolerable longitudinal forces for freight trains in tight Scurves using three-dimensional multi-body simulations. Rail and Rapid Transit.

Zampieri, N. B. (2017). Long train simulation using a multibody code. International Journal of Vehicle Mechanics and Mobility, 1.

7. Appendix A

Here just a small part of GENSYS command which are used to define a vehicle with Y25 bogies and rigid car-body is mentioned. Also inside this code there is just some substructure which are called and the information of them don't exist in the appendix, because there are huge number of line for command exist, (more than 2500 lines) just here for an brief introduction of commands in GENSYS environment this part are added to the report, for more information there is possibility to follow it on GENSYS website.

7.1 Vehicle Modelling in GENSYS (Y25)[1]

```
###
###    Vehicle properties
#[-]{  ===========================================================

 substruct vehProperties [       # $1 car_#
##
##  Basic vehicle geometry
##  ----------------------
  func const acb_$1=    6.5      # bogie pivot semi-distance (longitudinal)
  func const aba_$1=    1.5      # wheelset semi-distance within a bogie (long.)

##
##  Vehicle bodies
##  --------------
## Car-body (c)
  func const actaracg_$1=  0.0        # centre of gravity position, longitudinal
  func const hctaracg_$1=  2.0        # centre of gravity position, vertical
  func const mctara_$1=  52000                              # mass
  func const Jfctara_$1= mctara_$1*(1.50^2+1.538^2)/3                # moment of inertia, roll
  func const Jkctara_$1= mctara_$1*(1.50^2+(acb_$1+aba_$1+.58)^2)/3     # moment of inertia,
pitch
  func const Jpctara_$1= Jkctara_$1                              # moment of inertia, yaw
  func const hfloor_$1= 1.3       # floor level
##
```

[1] *GENSYS homepage. (n.d.). Retrieved from GENSYS official website : http://www.gensys.se*

```
## Bogie frames (b)
 func const hbcg_$1=   0.7        # centre of gravity position, vertical
 func const mb_$1 =  10000        # mass
 func const Jfb_$1=   3000        # moment of inertia, roll
 func const Jkb_$1=  10000        # moment of inertia, pitch
 func const Jpb_$1=  15000        # moment of inertia, yaw
##
## Axles (a)
 func const ro_$1 =   0.50        # centre of gravity pos., vert. (wheel radius)
 func const ma_$1 =   2000        # mass
 func const Jfa_$1=   1200        # moment of inertia, roll
 func const Jka_$1=    250        # moment of inertia, pitch
 func const Jpa_$1=   1200        # moment of inertia, yaw
##
## Track pieces (t)
 func const myt_$1= 2e3*2.5*2.5*1.36    # Density 2e3 kg/m^2
 func const mzt_$1= myt_$1
 func const Jft_$1= mzt_$1*(2.5^2+2.5^2)/12

####
####   Secondary suspension:
##[-]{ -------------------------------------------------------------
##
## Secondary suspension: Coil springs between car and bogie
## -------------------------------------------------------------
 func  const  kzcb.B_$1=  1.0              # lateral semi distance [m]
 func  const  kzcb.H_$1=  1.0              # top of spring [m]
 func  const  kzcb.hs_$1= 0.32             # height of spring [m]
 coupl p_lin  kxcb_$1=    0.0    600e3        # stiffness, longitudinal shear [N/m]
 coupl p_lin  kycb_$1=    0.0    600e3        # stiffness, lateral shear [N/m]
 func  const  kzcbF0_$1= -mctara_$1*9.81/4    # preload force
 coupl p_lin  kzcb_$1  = kzcbF0_$1  900e3     # stiffness, vertical compression [N/m]

##
## Secondary suspension: Anti-roll bars
## -------------------------------------------------------
 func const  kfcb.H_$1= 1.0       # Height above top of rail [m]
 coupl p_lin kfcb_$1  = 0. 2.5e6  # Roll stiffness [Nm/rad]

##
## Secondary suspension: Traction rods
```

```
## ---------------------------------------------------
 func  const ktr.Ac_$1= 7.5      # rod position in car-body, longitudinal
 func  const ktr.Ab_$1= -.2      # rod position in bogie,   longitudinal
 func  const ktr.Bc_$1= 0.0      # rod position in car-body, lateral
 func  const ktr.Bb_$1= 0.0      # rod position in bogie,   lateral
 func  const ktr.Hc_$1= 0.4      # rod position in car-body, vertical
 func  const ktr.Hb_$1= 0.3      # rod position in bogie,   vertical
 coupl p_lin ktr_$1=    0.  25e6  # stiffness
 coupl p_lin ctr_$1=    0. 100e3  # parallel viscous damping

##
## Secondary suspension: Lateral bumpstops
## ---------------------------------------------------
 func  const    kycbs.H_$1=   1.0            # Height above top of rail [m]
 coupl p_nlin_s kycbs_$1=  0. 0.030,  0.0      # Break-point #1 [m],[N]
                     0.040, 15e3      # Break-point #2 [m],[N]
                     0.090,  2e6      # Break-point #3 [m],[N]

##
## Secondary suspension: Vertical bumpstops
## ---------------------------------------------------
 func  const    kzcbs.A_$1=   0.0            # Longitudinal distance    [m]
 func  const    kzcbs.B_$1=   1.0            # Lateral semi-distance    [m]
 func  const    kzcbs.H_$1=   1.0            # Height above top of rail [m]
 coupl p_nlin_s kzcbs_$1=  0. 0.025,  0.0      # Break-point #1 [m],[N]
                     0.030, 15e3      # Break-point #2 [m],[N]
                     0.080,  2e6      # Break-point #3 [m],[N]

##
## Secondary suspension: Lateral viscous dampers
## ------------------------------------------------------
 func const    cycb.A_$1 = 0.34         # damper position, longitudinal
 func const    cycb.Bc_$1= 0.9          # position in car-body, lateral
 func const    cycb.Bb_$1= 0.4          # position in bogie,   lateral
 func const    cycb.Hc_$1= 0.7          # position in car-body, vertical
 func const    cycb.Hb_$1= 0.6          # position in bogie,   vertical
 coupl p_lin   cycb_$1=    0.0  40e3     # damping coefficient

##
## Secondary suspension: Vertical viscous dampers
## ------------------------------------------------------
```

```
 func const   czcb.A_$1 = 0.34        # damper position, longitudinal
 func const   czcb.B_$1 = 1.25        # damper position, lateral
 func const   czcb.Hc_$1= 1.0         # position in car-body, vertical
 func const   czcb.Hb_$1= 0.5         # position in bogie,   vertical
 coupl p_lin  czcb_$1=   0.0  40e3    # damping coefficient

##
## Secondary suspension: Yaw viscous dampers
## --------------------------------------------------------
 func const   cccb.Ac_$1=  7.3            # position in car-body, longitudinal
 func const   cccb.Ab_$1= -0.4            # position in bogie,   longitudinal
 func const   cccb.Bc_$1=  1.3            # position in car-body, lateral
 func const   cccb.Bb_$1=  1.3            # position in bogie,   lateral
 func const   cccb.Hc_$1=  0.7            # position in car-body, vertical
 func const   cccb.Hb_$1=  0.6            # position in bogie,   vertical
 coupl p_lin  kccb_$1= 0. 25e6            # series stiffness
 coupl p_nlin cccb_$1= 0. -1.032 -26e3       # Blow-off compression
                   -0.032 -16e3       # Damping coeff. compression
                    0.     0.
                    0.032  16e3       # Damping coeff. expansion
                    1.032  26e3       # Blow-off expansion
##[-]} - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

####
####   Primary suspension:
##[-]{ ------------------------------------------------------------------------

##
## Primary suspension: springs
## ------------------------------------------------------------------------
 func const kmba.B_$1=   1.0   # spring position, lateral
#
 func const kmbaF0_$1= (2*kzcbF0_$1-mb_$1*9.81)/4
 coupl p_lin36 kmba_$1=    0.    0. kmbaF0_$1  0.    0.    0.
                  20e6   0.    0.    0.    0.    0.
                   0.   20e6   0.    0.    0.    0.
                   0.    0. 1200e3   0.    0.    0.
                   0.    0.    0.    0.    0.    0.
                   0.    0.    0.    0.    0.    0.
                   0.    0.    0.    0.    0.    0.
#
```

```
coupl p_lin36 cmba_$1=   0.   0.   0.   0.   0.   0.
              20e3  0.   0.   0.   0.   0.
               0.  20e3  0.   0.   0.   0.
               0.   0.  5e3   0.   0.   0.
               0.   0.   0.   0.   0.   0.
               0.   0.   0.   0.   0.   0.
               0.   0.   0.   0.   0.   0.

##
## Primary suspension: Lateral bumpstops
## -------------------------------------------------------------------------
 func const   kybas.H_$1= 0.4        # Height above top of rail [m]
 coupl p_nlin_s kybas_$1=  0.         # symmetric non-linear stiffness
                0.025  0.0   # break-point #1
                0.050  1e6   # break-point #2

##
## Primary suspension: Vertical bumpstops
## -------------------------------------------------------------------------
 func const   kzbas.A_$1= 0.0        # Longitudinal distance   [m]
 func const   kzbas.B_$1= 1.1        # Lateral semi-distance   [m]
 func const   kzbas.H_$1= 0.4        # Height above top of rail [m]
 coupl p_nlin_s kzbas_$1=  0.         # symmetric non-linear stiffness
                0.025  0.0   # break-point #1
                0.050  1e6   # break-point #2

##
## Primary suspension: Vertical viscous damper
## -------------------------------------------------------------------------
 func const  czba.A_$1 = 0.0        # damper position, longitudinal
 func const  czba.Bb_$1= 1.1        # damper position, lateral in bogie
 func const  czba.Ba_$1= 1.1        # damper position, lateral in axle
 func const  czba.Hb_$1= 1.0        # damper position, vertical in bogie
 func const  czba.Ha_$1= ro_$1      # damper position, vertical in axle
 coupl p_lin czba_$1=   0.  60e3     # viscous damping

##
##     Coupling track - ground
##     ==========================================================
 coupl p_lin kytg_$1 =  0.  40e6
 coupl p_lin cytg_$1 =  0.  2*.55*sqrt(kytg_$1.v1*myt_$1)
```

```
 coupl p_lin kcytg_$1=  0.  2*pi*072.*cytg_$1.v1

 coupl p_lin kztg_$1 = kmbaF0_$1-(ma_$1+mzt_$1)/2*9.81  220e6        # Stiffness under ballast
 coupl p_lin cztg_$1 = 0.  2*0.36*sqrt(kztg_$1.v1*mzt_$1/2)          # Damping in ballast
 coupl p_lin kcztg_$1= 0.  2*pi*91*cztg_$1.v1

##[-]}  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
]
#[-]}  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 in_substruct vehProperties [ " " ]      # $1 car_#




##
## Local linear coordinate systems
## ================================
##
## lsys l_local  l_name   esys      a        b     h
## ---------------------------------------------------
 lsys  l_local  lsc_$1    esys_$1   0.0      0.0   0.0
 lsys  l_local  lsb_$11   lsc_$1    acb_$1    0.0   0.0
 lsys  l_local  lsb_$12   lsc_$1   -acb_$1    0.0   0.0
 lsys  l_local  lsa_$111  lsb_$11   aba_$11   0.0   0.0
 lsys  l_local  lsa_$112  lsb_$11  -aba_$11   0.0   0.0
 lsys  l_local  lsa_$121  lsb_$12   aba_$12   0.0   0.0
 lsys  l_local  lsa_$122  lsb_$12  -aba_$12   0.0   0.0
#
 s_var sngl  lsc_$1.vf  # Roll speed for calculation of PCT


####
####     Vehicle and track masses
##[-]{   ==================================================================
##
## mass m_rigid_6  m_name   lsys    acg    bcg  hcg      m     m     m     Jf    Jk    Jp
## ------------------------------------------------------------------------------------------
 mass m_rigid_6   car_$1    lsc_$1  accg_$1 0.0 -hccg_$1    mc_$1   mc_$1   mc_$1   Jfc_$1  Jkc_$1
Jpc_$1      # car-body
 mass m_rigid_6   bog_$11   lsb_$11  0.0    0.0 -hbcg_$11   mb_$11  mb_$11  mb_$11  Jfb_$11
Jkb_$11 Jpb_$11     # bogies
```

```
 mass m_rigid_6  bog_$12  lsb_$12  0.0   0.0 -hbcg_$12  mb_$12  mb_$12  mb_$12  Jfb_$12
Jkb_$12 Jpb_$12

##
## Create wheelsets
## ==================================================================
 in_substruct create_axl [ $111 ]
 in_substruct create_axl [ $112 ]
 in_substruct create_axl [ $121 ]
 in_substruct create_axl [ $122 ]

##
## Create track-pieces
## ==================================================================
 in_substruct create_trc [ $111 ]
 in_substruct create_trc [ $112 ]
 in_substruct create_trc [ $121 ]
 in_substruct create_trc [ $122 ]
#
 mass fixpoint_6  grd_$1   lsc_$1    0.0  0.0  0.0      # ground points
 mass fixpoint_6  grd_$111 lsa_$111  0.0  0.0  0.0
 mass fixpoint_6  grd_$112 lsa_$112  0.0  0.0  0.0
 mass fixpoint_6  grd_$121 lsa_$121  0.0  0.0  0.0
 mass fixpoint_6  grd_$122 lsa_$122  0.0  0.0  0.0
##[-]} - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```