

NowaitTransit[®] concept assessment. Modeling of trains on complex track geometry

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Abstract

This paper presents modeling and verification of Nowaittransit's concept of mass passenger transportation for big cities. Cars of the train, coupled in a closed loop, move continuously along the track but slow down in station areas due to the special scheme of car folding. Concept verification through modeling was requested by the investors.

Keywords: Mass city transportation; Train dynamics modeling; Vehicles in complex constraints; Investment in new technology

1 Introduction

1.1 Background

Nowaittransit AB has developed and patented new concept of mass passenger transportation for big cities. The closed loop of interconnected cars moves continuously along the track slowing down in station areas by the special scheme of folding cars.

The concept has advantages of high transport capacity of modern subway but at much lower costs for investment and exploitation providing that way attractive alternative to subway. The company has several Asian cities interested, but closing final contracts requires formal assessment proving that proposed functionality of the system can be achieved. The assessment is run presently in two stages; through computer modeling and through physical verification on the test track in Sweden. The computer modeling reported here was performed by Nowaittransit and Modelon and had two main objectives:

To prove that the concept has no "show stoppers" which may be hidden in dynamics of the long chain of the cars moving along the complex rail geometry. Requirements on the orderly start-up and braking shall be achieved and potential hazards identified.

To show that design team of the Nowaittransit has capacity and tools to handle complexity of mechanical and control systems of the train.

The interesting aspect of the project presented was that modeling was required by investors as a proof that a new concept is trustworthy enough to invest in the test track.

1.2 Short introduction of the NowaitTransit[®]

The underlying principle of the NowaitTransit[®] invention is a continuous train movement with a reduction of the traveling speed at the stations.



Figure 1: Nowaittransit mass transportation system

The length of the *NowaitTransit[®]* car is reduced through a 90-degree horizontal folding shown in Figure 1. The cars traveling out of the station areas have a normal transport speed, which during the folding is reduced by the factor 1:12 when the cars enter the station. The passengers can now board and disembark the train at the end of each slowly moving car. This speed at the station corresponds to the high end of normal walkway speeds. The passengers' entry and exit is further facilitated through use of moving walkways, making it acceptable for disabled persons.

Due to this continuous boarding/disembarking principle, station loads will be evenly distributed with no crowds of passengers waiting. Traditional systems have passengers gathering on the platforms and whole trainloads of people boarding and disembarking simultaneously. Accordingly NowaitTransit® stations can be smaller with capacities of stairs, elevators and stairways reduced. Small stations, light modular structures and simplicity allow reduction of investment costs to approximately 25 MEUR/km compared to 85-125 MEUR for conventional subway.

2 Objectives of the modeling and tests performed

2.1 Objectives

The main objective for modeling was proving that the concept can be realized. We concentrated accordingly on the following:

- Analysis of train structural singularity or system over-determination.
Mainly aspects of the train dynamics where movements of the interconnected cars are bound to 3D geometry of the rail
- Structural loads on the train components.
Load analysis was required to prove that the train can be accelerated and slowed down, and that the main train structures will hold intact through pre-identified hazard situations
- Identification and evaluation of factors of passenger comfort and train controllability

Assessment of the *NowaitTransit*® concept reported here should be seen as the final stage of the concept introduction to investors. The Modelica models will be further developed and verified to become eventually design tool of the full scale projects of the future.

2.2 Requirements on tests and introduction to main models developed

The objectives above were addressed by specifying simulation experiments required, which led to the final requirements on train models.

A couple of cars moving on rail of free definable geometry and coupled by a single distance beam was found the basic structure of the model. That structure was pretty straight forward to model, but it showed up quickly that the main problems came from the

long chains of cars acting on each. Long chains meant huge number of equations to solve and difficulties in defining initial conditions, which led to extremely long simulation times. We had to simplify the whole train model worked accordingly with two main types of models:

Centre Rail Model (CRM): where the cars, which travel on the central rail can turn round z-axis vertical to the rail line. The cars can now be forced into folding and un-folding according to angle α , pre-define function of car position (s) on the track. This scheme replaces here car-turning forced by changing of the rail gauge of the original concept.

CRM model will not allow studies of the rail boggy interaction but is a good approximation for studies of car propulsion and car interaction in open and closed loops of coupled cars covering at least one car transition zone (e.g. station of folding zone, station platform zone and un-folding zone).

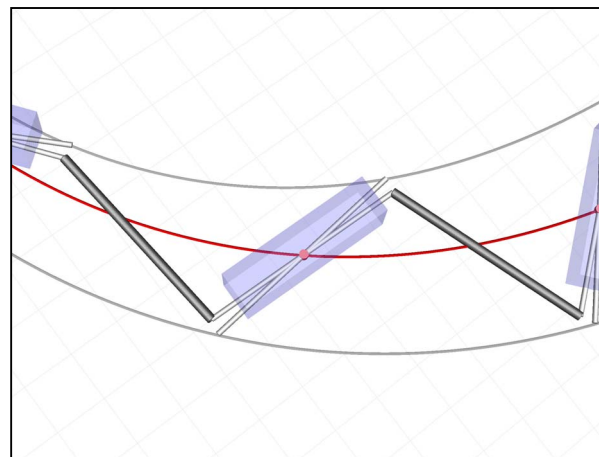


Figure 2: Cars and distance beams of the CRM model

Figure 2 shows part of the CRM animation, with middle (red) line representing centre rail, and two external lines showing trajectory of wheel-rail contact points.

Final Rail Model (FRM): where at least one basic car structure is run through various rail zones linked

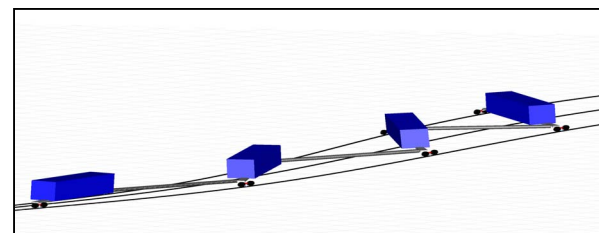


Figure 3: Two car couples ascending rail of FRM

with rest of the train represented by CRM. This model allows us study of car wheel interaction with

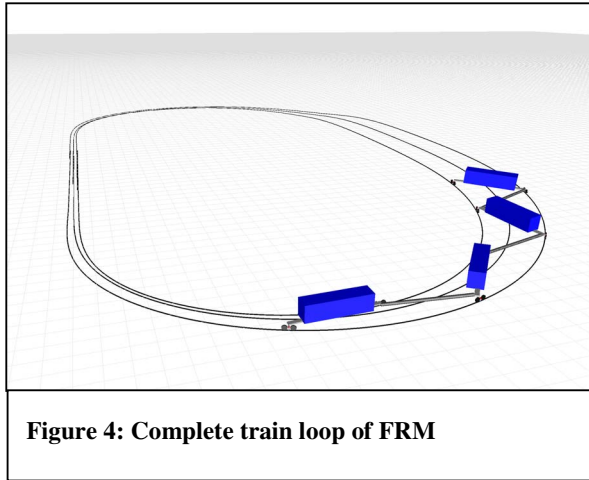


Figure 4: Complete train loop of FRM

the rail. Figure 3 shows FRM of the cars ascending rail, while Figure 4 shows complete rail loop of the same simulation.

3 Selected aspects of Nowait models

3.1 General

We present here the following aspects of Nowait-Transit® modeling:

- Tools for selection and testing of track geometry
- NowaitLib: Modelica library for simulation of train cars on the complex track geometry
- Car and rail components of the library

3.2 Generating track geometry

As it was already implied train of Nowait cars is basically over-determined. Due to the folding and unfolding schemes length of the closed loop of the train can vary. It becomes accordingly crucial to match dimensions of car components and car geometry to reduce those length variations until they could be absorbed by elasticity of train components and rail.

This complex process of selecting car geometry was facilitated by development of the package of Matlab functions, transforming input data (e.g. lengths of the zones) into output matrix 'trackTab' with description of rail geometry. The 'trackTab' is read as a table of Modelica models.

Two basic forms for track building are available:

- Polynomial, of continuous 1st, 2nd and 3rd derivatives

- Exponential, according to function $y = C \cdot \exp(-|s-s_0|^n \text{Exp})$

Exponential form allows symmetrical track geometry only, and has a convenient property of continuous derivatives. The track geometry may be varied in x-, y- and z-direction of the world.

Changes in z-direction (altitude) are required mainly for slowing down / acceleration of the folding / unfolding cars by transfers between kinetic and potential car energy. This z-compensation can be complete (100% kinetic energy at normal train velocity transferred to the potential energy) or partial only. Examples of the polynomial and exponential geometry are shown in Figures 5 and 6, presenting car folding angle, velocity and elevation of both cases.

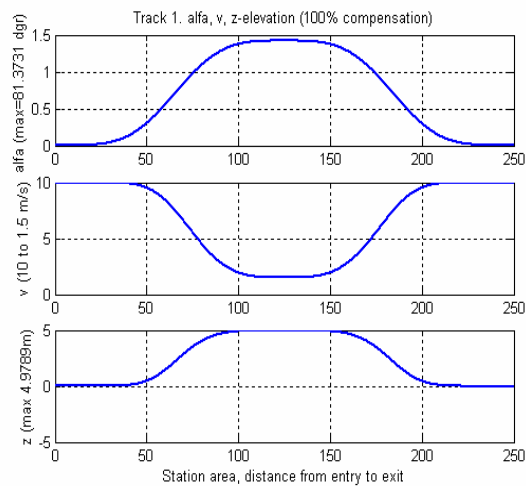


Figure 5: Profiles of car folding angle, velocity and z-elevation for exponential track geometry

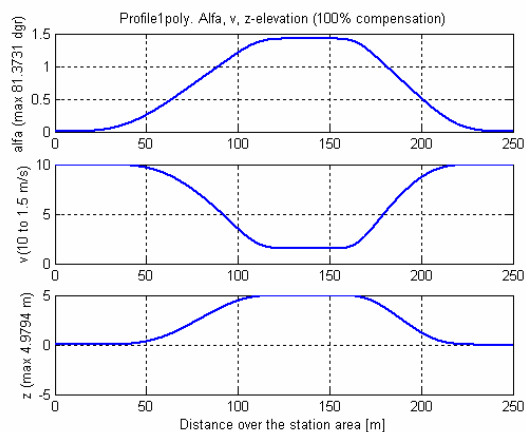


Figure 6: Profiles as car angle, v and z, for polynomial track geometry

Matrix 'trackTab' is used for centre and final rail models. It can be noted from Figure 2, that required geometry of each rail (upper and lower lines) can be

unequivocally decided from centre line geometry, dimensions of car components and angles of the car in relation to car centre. All this information is available in matrix 'trackTab'.

3.3 Testing of track geometry

Matlab-generated track geometry must be tested. Initial testing is done using special Matlab functions, the final testing through Modelica models. There are three criteria which can be evaluated in Matlab: 1) length of the train between any two cars holding the same angle shall be constant, 2) number of cars between any two points of the track shall be constant, and 3) velocity of moving cars shall comply with constant car passing frequency (number of cars / sec).

Results from testing track geometry of Figure 6 are shown in Figure 7.

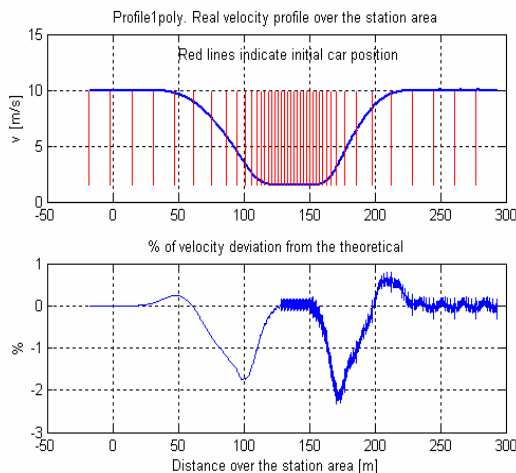


Figure 7: Testing results of polynomial geometry of Figure 6

The testing showed positive results concerning third criteria; final velocity variation was contained in approximately +/- 0.1 %. The vertical lines on the upper plot of Figure 7, indicate initial position of cars in the transition zone. Vector of initial positions is used for initialization of Modelica simulations.

3.4 NowaitLib Library

All modeling *NowaitTransit*[®] trains follow formal Modelica instructions, considering initial development of the system library including formal verification of library modules. The name of the library is NowaitLib and library structure is shown in Figure 8.

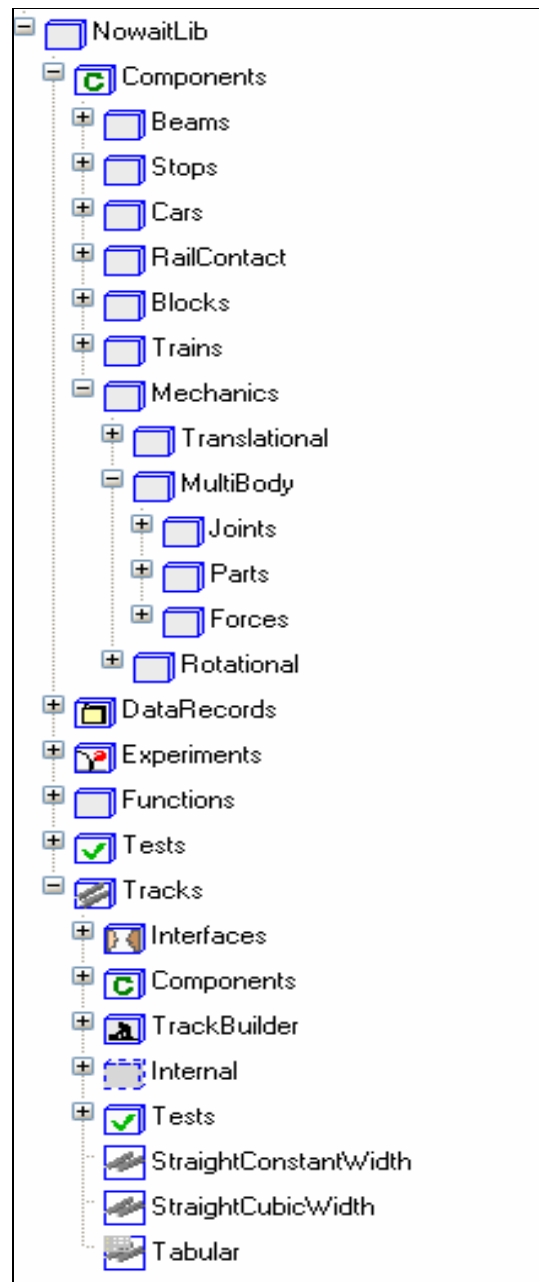


Figure 8: Structure of the NowaitLib library

The components of the library are universal in a sense they can be applied to various kind of bodies moving in boundaries of any track geometry defined in pre-defined table (here 'trackTab')

3.5 Main models of the NowaitLib

Main train components modeled are cars, distance beams for car coupling and finally track/rail elements. Models of the cars and beams built on the standard Modelica Mechanics of MultiBody Library.

One of the main problems encountered was placing free body of the car in constraints of the track.

generalizing modification of the MultiBody.Joints.Internal.Pismatic joint where $r_b = n*s + r_a$. The following modifications are

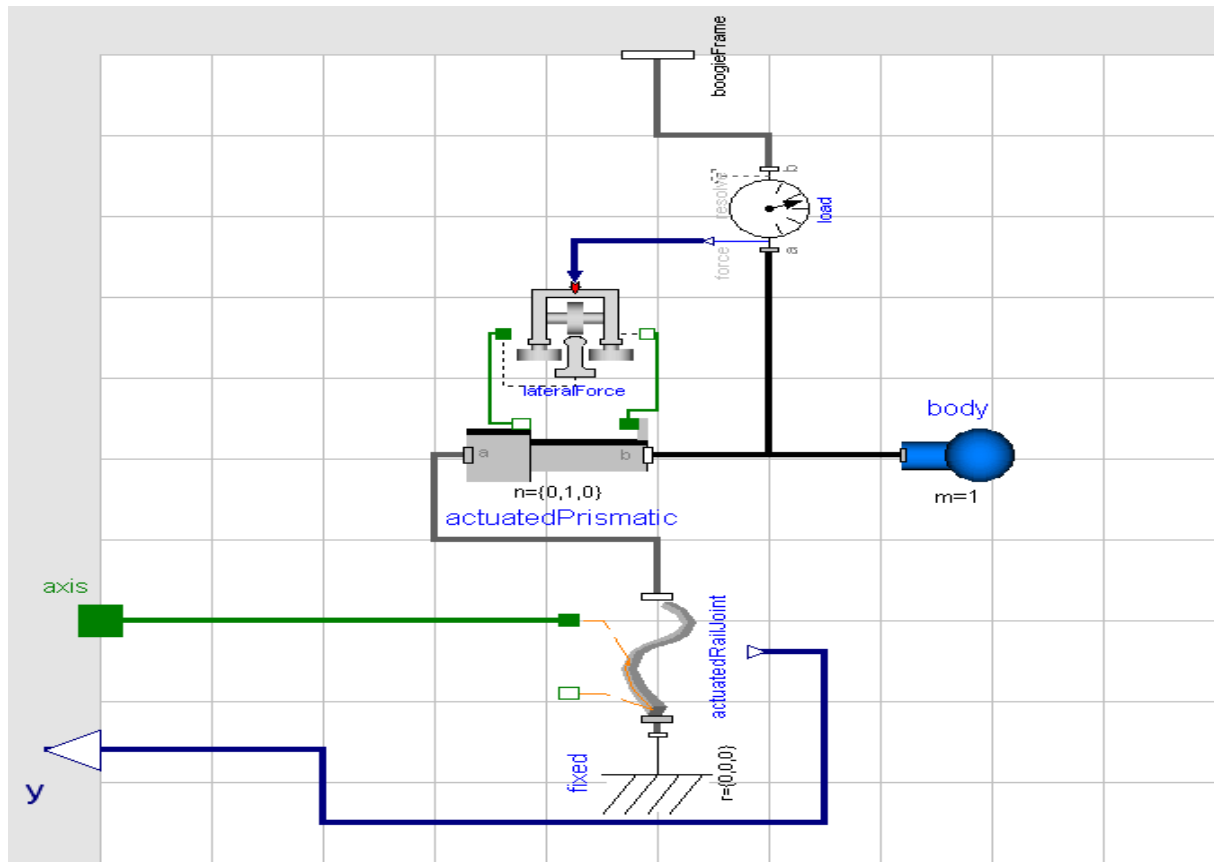


Figure 9: Main components of the track - car interconnection

Figure 9 shows main components of the Contact-Point model used in FRM for interconnection of the wheel contact point (CP) and rail, where:

- CP of the wheel is connected through MultiBody frame 'bogieFrame'
- ActuatedPrismatic component models lateral (y-direction) movements of the rail
- LateralForce component calculates forces acting on the CP (and car bogie), there mainly centering force of wheel crowning, and friction
- Track geometry is enforced through 'actuated-RailJoint' getting 'trackTab' data through 'axis' connector.

'RailJoint' model describes the (translational) motion along a track defined in space by vectors of frames 'a' and 'b' (Figure 10), as $r_b = r(s) + r_a$. It can essentially be considered as a

essential for train modeling:

- The track is able to follow any (two times differentiable) trajectory in space given via the outer function 'track.position'. This means that also the orientation of 'frame_b' relative 'frame_a' must be given (for the prismatic it is assumed that there is no relative rotation), here via the outer function 'track.orientation'.

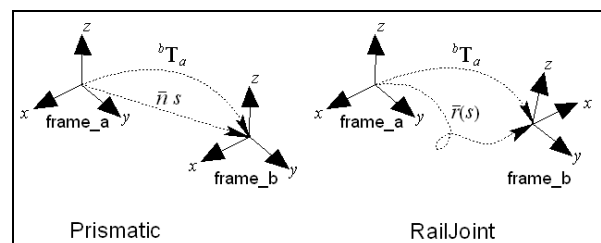


Figure 10: RailJoint as extension of Prismatic joint

- To allow efficient symbolic manipulation of the functions ‘track.position’ and ‘track.orientation’, the differentiations are provided through ‘track-Tab’ table. Note especially that for this application, it is assumed that dr_{rel}/ds points in the x-direction of frame_b. The differentiation has to be possible at least three times to resolve the motion equations on acceleration level of both rotational and translational loops.

As a result, the relative velocity and d’Alembert’s principle are always in the heading direction dr/ds which is the x-axis of frame_b. This model is extended as MultiBody.Joints.Internal.Prismatic to allow addition of Translational flanges.

4 Summary of experiments run on the models

The experiments run on the models covered three main groups:

- Tests/generation of the track geometry and dimensioning of cars and car coupling elements
- Tests of the longitudinal forces acting between cars in dynamic situations of train runs, start-ups, and different cases of braking down
- Tests of complete train sets including bogie and wheels moving along the complex rail geometry.

The first group was run through package Matlab functions as reported already above. The Matlab results were confirmed by Modelica/Dymola experiments.

Tests of the longitudinal forces required models of the long chain of cars and were run accordingly on the centre rail models.

Tests of complete train sets required simulations on the final rail models.

All tests were run on the ‘representative track geometry’, covering mainly two basic profiles; one of complete station zone, and second of 90° curve with cars folding and un-folding in order to manage curves of relatively small radii required for adoption of the train track to existing city environment.

4.1 Experiments run on the centre rail model

Experiments of this group concentrate on demonstration of forces between cars, and forces required to drive/brake cars through raising and falling parts of

the track ($\delta z/\delta s$), and cars on the curves in x-y plane. The following groups of experiments were run:

- Cars run in constant base velocity,
- Cars of the starting train; accelerated from $v=0$ to base v ,
- Cars of the braking train; slow down from base v to 0.
- Cars in “let free” situation, cars are left over without any external forces testing car behaviour on the raising and falling part of the track
- Train emergency brake down (according to international standards)
- Train in accidental brake down (i.e. hazard)

In addition to the above tests concerning mainly identification of the dynamic behaviour of the NowaitTransit train, the following tests were added:

- Test of passenger comfort. Comfort factors were selected measuring forces acting on passengers.
- Test of car controllability (only initial evaluations)

4.2 List of experiments run on the final rail model

Experiments run on the final rail model were essentially the same as for CRM. The focus of testing was moved here on the following:

- Verification of compatibility between CRM and FRM (does CRM reflect real behavior of cars on the variable gauge track?)
- Verification of the wheel movement on the rail. E.g. prove that wheel friction across the rail will limit lateral sliding of the wheel
- Verification of train controllability during selected phases of the train operation. This to estimate complexity of the train control system (Note: here identify potential problems only)

5 Examples of experiments run on the centre rail track

Experiments listed above are exemplified here on three case only:

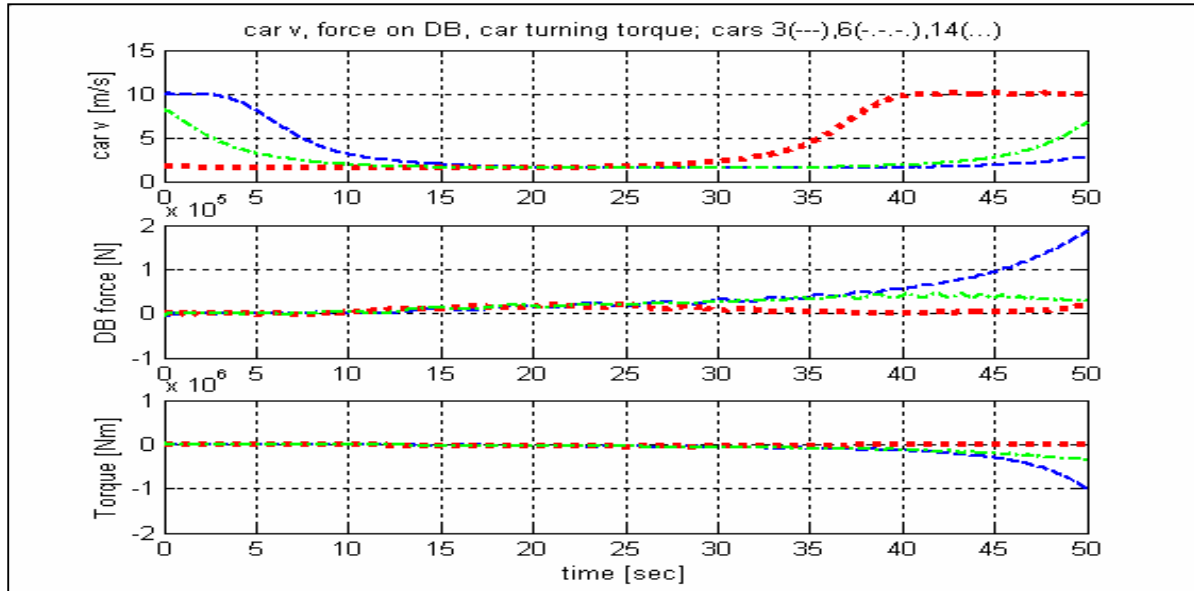


Figure 11: Cars of the CRM in normal operation passing station area

Case 1 (Figure 11): shows, velocities of cars, forces on distance beams and car turning torques during a normal car passage of the station area. Note that the case reflects the special situation when cars in transition are not propelled but only pushed through by the cars still on straight part of the track

Case 2 (Figure 12): shows the same car configuration as for case 1. Here cars are slowed down from 5 to 0 m/sec. This case is special as well as cars in transition are braked but slowing down of the cars on straight part of the track. Note pulsing character of forces and torques implying that control is required.

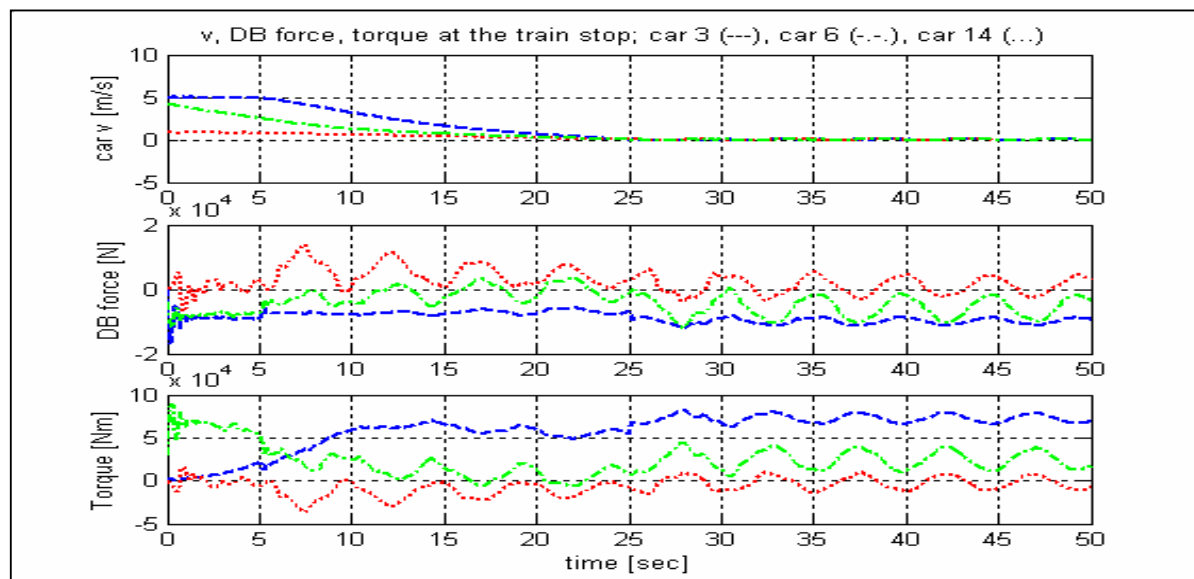


Figure 12: Cars in CRM during train stop from 5 to 0 m/sec

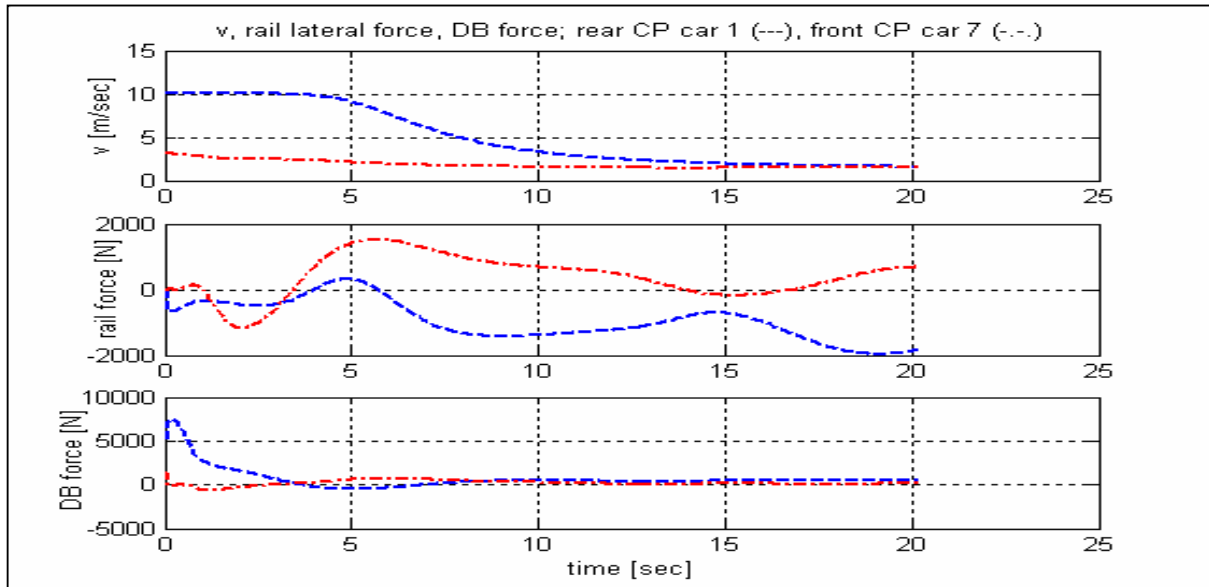


Figure 13: Cars of FRM during normal operation in station area

Case 1 (Figure 13): shows, velocities of cars, lateral forces on the rail and forces in distance beam acting on the selected cars of the train during normal passage of the station area.

6 Summary of results and conclusions

The study presented here had the main purpose to show for investors deep knowledge of the proposed NowaitTransit® concept. The study resulted accordingly in the models which allow ‘driving’ Nowait train along various track geometry. The study had the ambition to identify the process of driving long trains along complex track geometry, which implies that the modeling effort shall be continued. We can tell today that no distinct ‘show stoppers’ were identified, but at the same time we see difficulties to be met. There are clear tendencies to longitudinal car oscillations. Main effort of the studies was to generate track geometry reducing those oscillations to the minimum, which showed up feasible. The coming modeling stages should concentrate on design and verification of the train propulsion system, on finding optimal algorithms for train control (done partially in ref [1]) and on verification of the auxiliary systems for train start-up and brake-down. We are pretty advanced in further model development allowing study of the complete loops of the interconnected cars (Figure 14). Modelica models and package of Matlab functions are already powerful tools but must be developed further to ensure that train design and design verification will be effective and trustworthy.

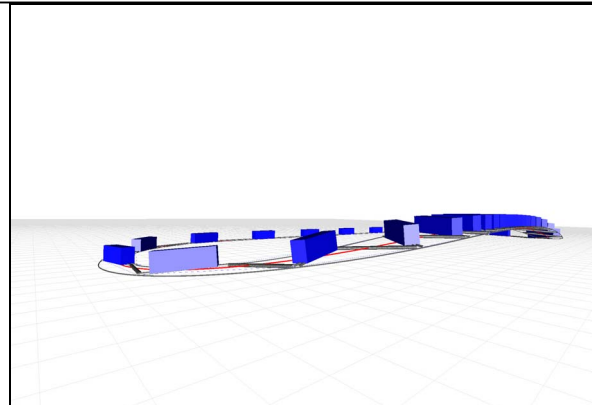


Figure 14: Animation of the complete closed loop of Nowait train model

7 References

- [1] Dynamic Simulation of the Train Concept Nowait Transit. Master Thesis, Daria Madjidian, Arash Majedi. 2005. Department of Automatic Control. LTH