



Optimizing Running Dynamics of the DLR Next Generation Train with Mechatronic Track Guidance



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In the research project "Next Generation Train", DLR is developing a concept for a double-decker high-speed train. The concept includes two-axle intermediate wagons, which have single-axle running gears with independently rotating wheels (IRW) and mechatronic track-guidance. This enables centering in the track and active radial steering for IRW pairs during curve passing. Thus, wheel wear and noise generation can be considerably reduced. SIMPACK multi-body simulations are used to verify and optimise the dynamic behaviour. The main tasks of the simulation are optimisation

of the mechatronic track guidance and optimisation of the suspension parameters for high ride comfort.

INTRODUCTION

The NGT (Fig. 1) is a double-decker high-speed train able to travel at 400 km/h while enabling continuous passage for passengers

on both levels. Within this concept, several rail specific research topics of the DLR are included [1]. For running dynamics, the two-axle intermediate wagons with a length of 20 meters are a special challenge. Conventional wheelsets cannot be used in the running gears due to limited space; so, all running gears receive IRW pairs. The



Fig. 2: Exterior view of NGT end and intermediate coach



Fig. 1: NGT design

end wagons are equipped with two-axle running gears (Fig. 2).

All wheels are individually driven in the NGT. Each of the intermediate wagon's wheels has its own 260 kW traction motor that provides the necessary torque without gearbox transmission. The traction motors also serve as actuators for active track

guidance and for radial steering. The use of IRW pairs makes it possible to overcome the usual goal conflicts between low-wear curve running and large stability reserves at high speeds. However, conventional wheelset's passive self-centering mechanisms must be abandoned for these benefits, and active track-guidance must assume this function in the NGT.

The main challenges do not come from desired compliance with the standards, e.g., for the acceptance of running characteristics (EN 14363 [2]), but in the additional project targets: The NGT should exhibit 20 % performance improvement regarding ride comfort and wheel lifetime. Parameter variations are used to tune the control parameters for a good

compromise between the conflictive aims of low actuator torques and low wheel wear. This is especially important on tracks with real irregularities.

The unusual car body geometry — tall and short — together with an axle base of 14 m, which is significantly shorter compared to the pivot distance of conventional bogie vehicles, results in modified dynamic properties. In addition, the bogies' effect of leveling track unevenness does not apply in single-axle running gears. Therefore, a special dynamic concept is developed.

NGT SIMULATION MODEL

For the simulations with SIMPACK, a shortened NGT unit comprised of four intermediate cars and two end cars is used (Fig. 3). Four intermediate wagons form a reasonable compromise: on the one hand, to enable investigation of the dynamic interactions between vehicles when inter-car dampers are used, and on the other hand, not to unnecessarily increase computational effort.

The aim of the running gear's design is to determine the suspension level's optimal

mechanical parameters. At first, only the mechanical degrees of freedom between the wheels, motors, car body, and running gear frame are defined in the MBS model without thereby taking into consideration their technical realization. All bodies are modeled to be rigid. The components' masses and inertias come from the initial design sketches. Apart from an active lateral centering device in the secondary suspension and the mechatronic track-guidance, all of the suspension's other elements are passive.

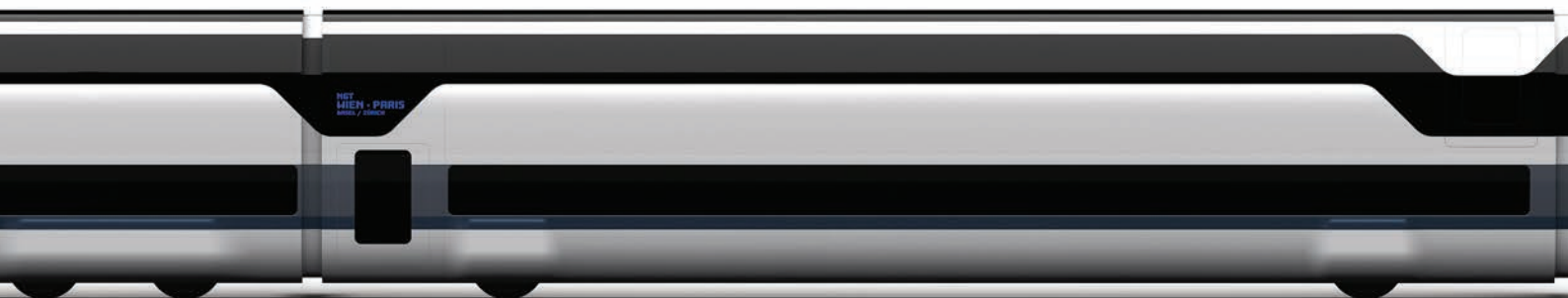
As a reference vehicle, a single-decker, four-axle single car with bogies and conventional wheelsets is also modeled. This vehicle reflects the approximate develop-

ment status of a current, single-decker high-speed train. The vehicle's weight is defined to be 64 t corresponding to a wheelset load of 16 t for the NGT. The bogies have comparatively stiff wheelset guidance and a rather soft secondary suspension which essentially consists of an air suspension. All wheelsets are motorized in the model.

Three test tracks that approximately cover the spectrum of possible operational tracks are used for the simulation. Following an initial straight line, all three tracks contain an S-curve with intermediate straight sections and transitional curves. In addition, tracks 2 and 3 (Tab. 1) also contain a descending and ascending slope section. Generic track irregularities are generated which meet the demands regarding the tracks for acceptance test in EN 14363 App. C — with an extrapolation to 400 km/h.

The vehicle model's speed control guarantees nearly constant running speed during the simulation. The traction motors generate the necessary driving and or braking torques which create additional wear on the wheels from traction. The driving-resistance forces due to air resistance are neglected.

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	Test Track 1	Test Track 2	Test Track 3
Speed [km/h]	44	100	400
Curve radius [m]	150	600	8.500
Superelevation [mm]	0	120	170
Slope [%]	-	1	2
Track irregularities	ERRI high	ERRI high	Conform to EN 14363
Simulated time [s]	60	120	100
Percentage of total running distance [%]	3	7	90

Tab. 1: The three test track parameters

OPTIMISATION OF THE MECHATRONIC TRACK GUIDANCE

The control is based on the measurement $y(t)$ of the instantaneous distance between the center of the wheel pair and the virtual track centerline in the middle of the right and left rail. This distance is measured and fed back and compared to the

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set point w , which is defined to be zero. The actuation quantities of the control are the torques: the same absolute values are applied to the right and the left wheel but with alternating sign.

After excitation by a lateral track irregularity, the controlled wheel pair should perform a decaying oscillation between the two rails which is comparable to the hunting motion of a wheelset and is important for uniform wear distribution on the wheel profile.

Three types of disturbances act upon the running gear: the dynamic forces caused by the car body, the three-dimensional track geometry including curves, superelevations and slopes, and the track irregularities.

The controller (Fig. 4) only needs a P and a D part because optimization results did not expose relevant improvements using an integral term, so that the control structure was defined without an I part. In addition, an element is used which limits the actuating quantity in such a way that a certain maximum value is not exceeded. The controller is modeled using SIMPACK

Function Expressions. The motivation for the structure is to limit the number of torque peaks. It is expected that such events hardly influence the general wear evolution of the wheels if flange contacts are accepted instead of high torques.

Fig. 5 presents the maximum applied torques as a function of the total work done by friction, in relation to the frictional work of the reference vehicle. The simulation scenario was

defined according to test track 3 with a shorter simulation time. The optimization tool used to determine the control parameters is the MATLAB®-based DLR-in-house tool MOPS, which is an environment for the multi-objective-multi-parameter synthesis. MOPS and SIMPACK are invoked in loops by MATLAB as the framework master.

The initial control parameters,

which represent a wear reduction of 60 %, were used for the parameter variation with subsequently reduced limit values. The maximum applied torque was reduced from 1218 Nm down to 500 Nm (Fig. 6). The very important result is that such a reduction does not destabilize the control set-up. However, it is to be expected that such a reduction promotes flange contact events and causes significantly more wear. Even with 650 Nm maximum torque, the wear reduction is better than 50 % compared to the wear of the reference vehicle at track 3. This represents a good compromise between the actuation torques and the friction work.

The area in which the wear occurs, and the volume proportional to the frictional energy dissipated on each wheel, is calculated in a post-processing routine from the simulation results and averaged over all wheels. The wear parameters used have been validated in a previous investigation. The results from the three test tracks are then weighted by the percentage of total running distance (Tab. 1) and extrapolated to a 10.000 km running distance. Besides the absolute amount of material loss, the place on the wheel where the wear occurs is especially relevant. Fig. 7 shows the profile geometry in the upper portion and the wheel profile's calculated wear depth below. The NGT running gear's active track-guidance in narrow curves leads to a much better wheel position in the track and thus to a considerable wear reduction, primarily in the flange area, where wear is particularly critical to the wheel's service life. Overall, material abrasion on the NGT intermediate wagon's wheel declines by 43 % compared to the

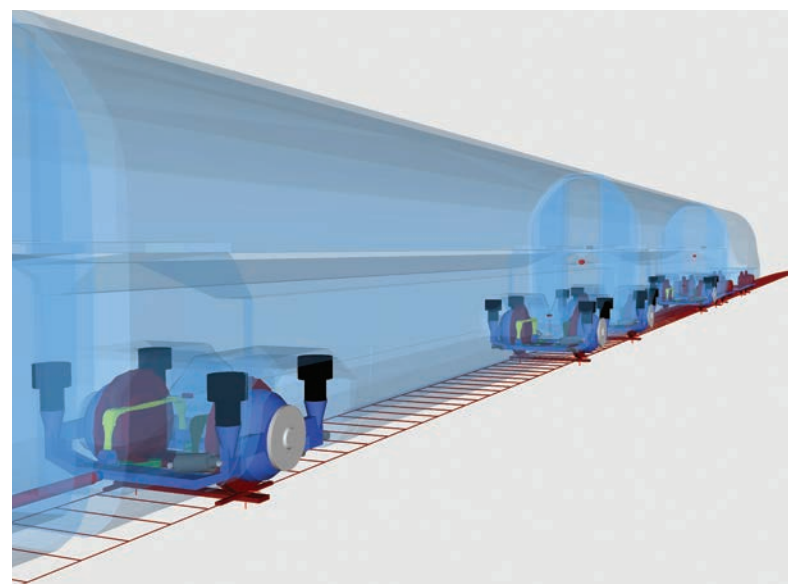


Fig. 3: SIMPACK model of the NGT

reference vehicle, which is significantly better than the required 20 %.

RIDE COMFORT IMPROVEMENTS

According to established expectations, the two-axle intermediate cars with the initially selected spring stiffness and damping parameters exhibit unsatisfactory comfort behavior compared to the reference vehicle since shorter car bodies are generally more vibration-prone.

However, a global train dynamics concept is being pursued to achieve better comfort than in the reference vehicle. This increases the individual car bodies' inertia through suitable coupling of the cars to reduce the effect of a single excitation. The running gear's suspension continues to support the car body's mass and must ensure that the entire train follows the stretch as a unit and does not tip over. On the other hand, the suspension should transfer as little as possible of the higher-frequency excitation from track irregularities to the vehicle. Therefore, a large part of the damping from the secondary suspension is relocated to dampers between the individual cars. Moreover, significant progress is being achieved via inter-car anti-roll elements.

The criterion for average comfort (NMV value) according to EN 12299:2009 [3] is used to assess ride comfort. To this aim, the acceleration signals are initially evaluated with comfort filters and then analyzed statistically. Measurement points in the individual NGT cars are placed in the same way on each floor as in the reference vehicle.

NMV values calculated for intermediate wagon 2 at 400 km/h on test track 3 are all considerably below 1.5 (Fig. 8). According to the standard, the vehicle should be

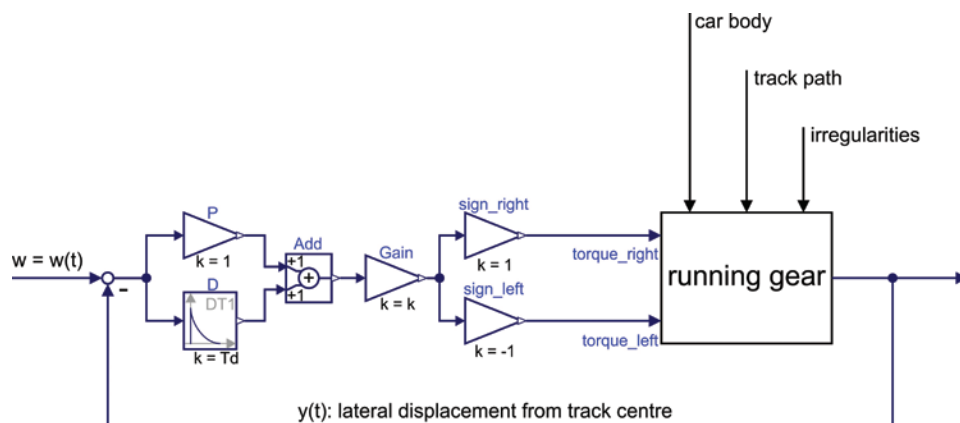


Fig. 4: Control structure of the mechatronic track guidance

described as "very comfortable." The relative values in comparison to the reference vehicle (each in the same measurement position) are more interesting. Due to the car body's pitching and yawing motions, ride comfort is fundamentally worse in the area over the running gear than in the middle of the car body. However, since comfort values between the individual

measurement positions in the NGT scatter significantly less than in the reference vehicle, the NGT provides, a consistently better ride for all seating positions. On average, the required 20 % comfort improvement in the intermediate wagons was exceeded by five percentage points.

SUMMARY AND OUTLOOK

The simulation demonstrates the general feasibility of the mechatronic track guidance system. However, there are some

challenges. In the past, the realization failed because of a lack of practicable sensors, an adequate control algorithm and the costs for the high number of converters and motors. The development of a control system, including the sensors and the optimization

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of the suspension, is the main focus of the described research activities. One challenge is the development of an onboard sensor system that is able to identify the position of the wheels relative to the rail. The construction of the sensors must be robust enough for railway operation.

Finally, the innovative running gear concept contributes to the integrated and environmentally friendly train concept of the NGT. Since the NGT has a realization horizon of approximately 20 years, a commercial application seems to be possible assuming decreasing costs of electronic components

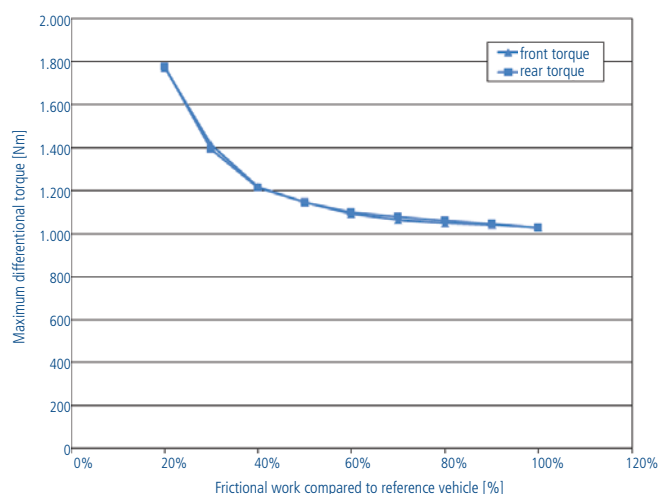


Fig. 5: Pareto front of the conflicting optimization goals: actuation torques versus friction work

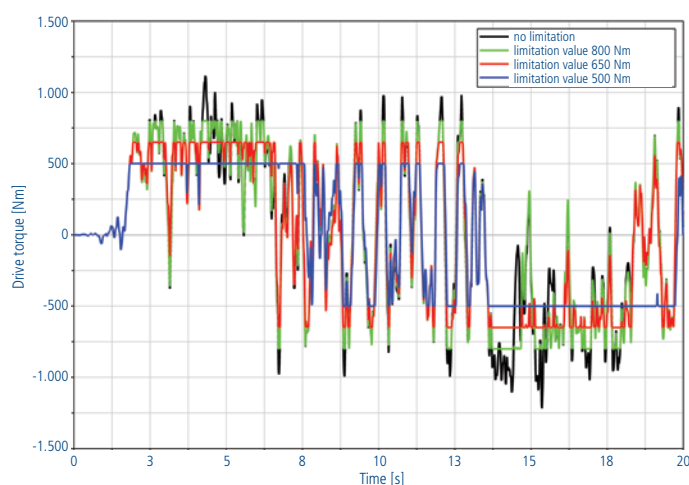


Fig. 6: Drive torques on the right hand side of the first wheel pair with subsequently reduced limitation values

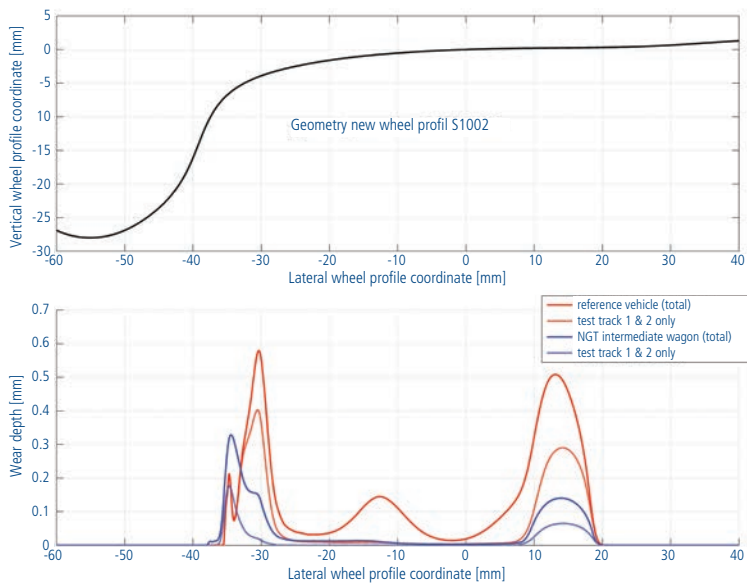


Fig. 7: Forecast of the wheel wear for 10.000 km

within this time. The mechatronic track guidance solves all problems related to curving of rail vehicles, by minimizing the creep. The mechatronic track guidance offers advantages not only for high-speed applications. Especially for trams, the guidance system can reduce the creep in curving which causes many other problems, for example, friction induced vibrations [4].

Simultaneous to the running gear, the lightweight car body structure is being developed at the DLR Institute of Vehicle Concepts and the Institute of Composite

Structures and Adaptive Systems. Fig. 9 shows a first conceptual design of the running gear integrated into the car body. The next step is dedicated to the specific design of suspension elements that meet the mechanical properties identified by the presented study. The flexibility of the car body structure will also be considered during ride comfort investigations.

REFERENCES

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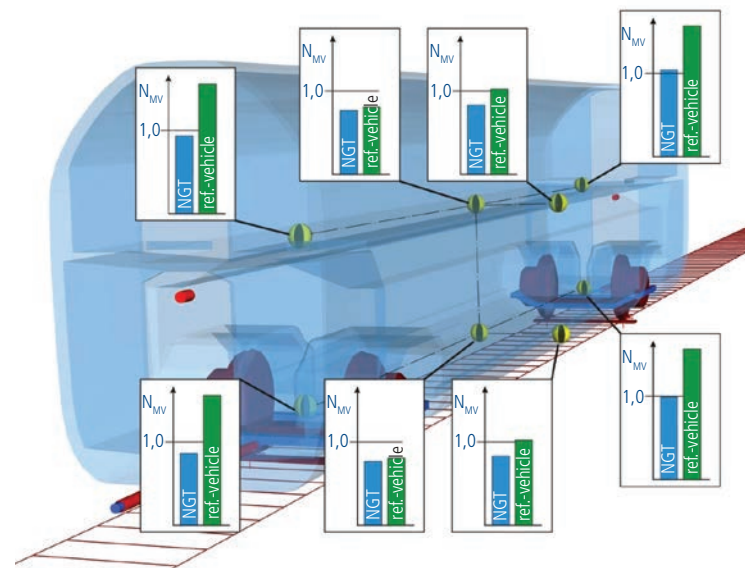


Fig. 8: Comparison of the comfort numbers for the first NGT intermediate wagon and the reference vehicle at different seating positions

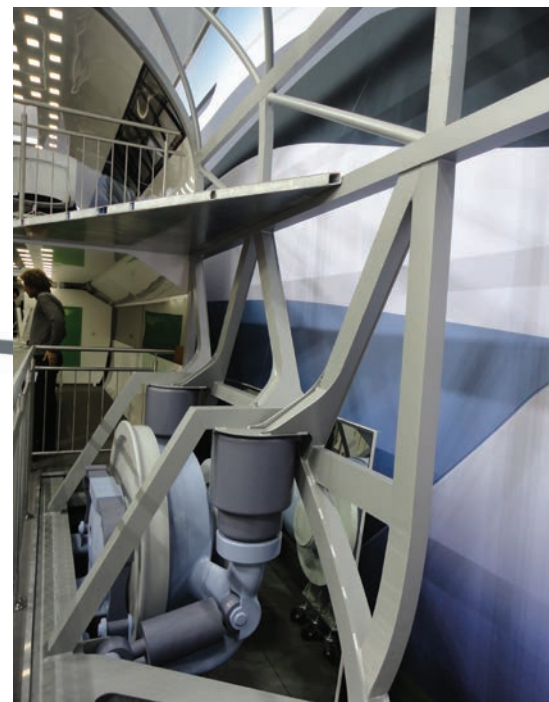
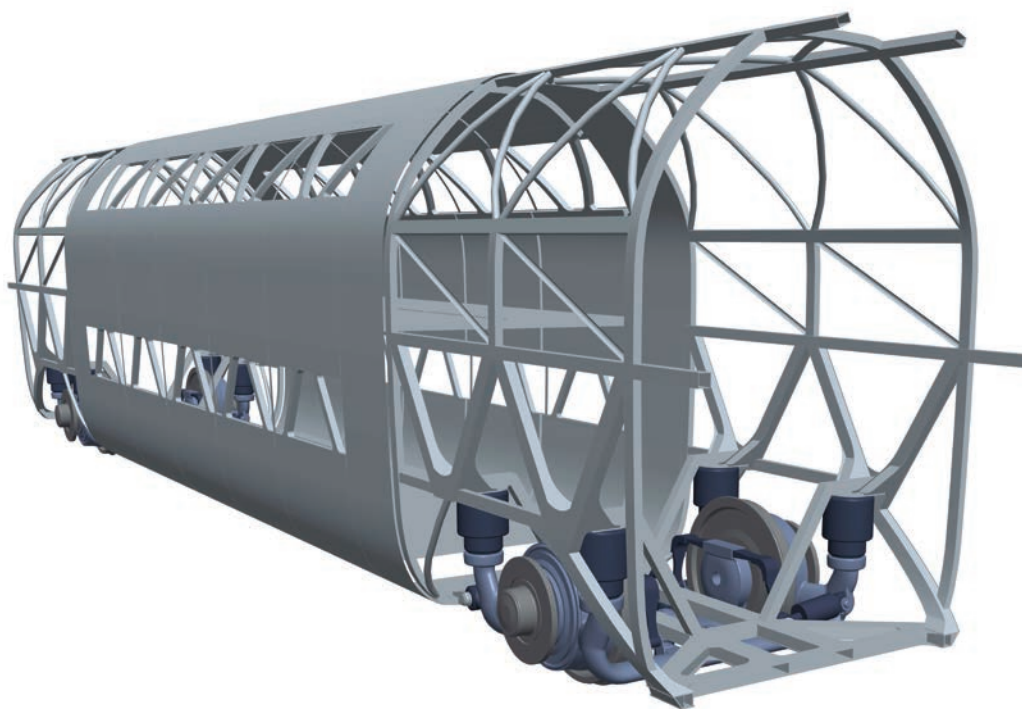


Fig. 9: Running gear integrated into the lightweight car body structure (left: CAD Model, right: parts in 1:1 scale as mock-up, shown at the Inntrans 2012 trade fair in Berlin)