Simulation of Rope-Propelled Automated People Mover Systems in SIMPACK

In recent years, the use of Rope-Propelled Automated People Movers (RAPM) for public transport in airports and city centres has increased steadily. These transport systems consist of guided vehicles which are propelled by a wire rope and operate automatically on a separate guideway. With RAPM, the rope's elasticity has a crucial influence on the system dynamics. Consequently, an elastic rope model has been implemented in SIMPACK, which can be combined with state-of-the-art elements to enable the modeling of the complete RAPM system. This enables the prediction of system dynamics, in emergency stop scenarios and standard operation, which is an important input for system design.

Fig. 1: Rope-propelled Automated People Mover in Las Vegas, Nevada

INTRODUCTION

Automated People Mover (APM) systems are used to execute high-capacity passenger transportation over short distances. This task can be accomplished using either conventional on-board drive components or a rope drive which transmits the propulsion forces to the vehicles. In the latter case, the system is called an RAPM.

RAPM vehicles normally contain no on-board drive or braking systems which leads to low acoustic emissions and light vehicle and guideway structures. Thus, the guideway structures used are cost-effective and desirable from an architectural viewpoint (Fig. 1).

> *"...the current project has developed and implemented an elastic rope model designed for RAPM in SIMPACK."*

Fig. 2 shows one possible technical configuration of an RAPM drivetrain. The electric motors and brakes are connected to the drive bull wheel which transmits both the drive and braking forces to a closed wire rope loop. The rope is guided by bull wheels in the stations and by sheaves along the guideway. Finally, the traction forces are transferred to the vehicle bogies by means of grips.

Since the system lengths of modern RAPM can reach up to 3 km, rope elasticity has a critcal influence on the overall system dynamics.

In railway and automotive engineering, system dynamics prediction using multi-body systems (MBS) represents the state of the art. For RAPM, this approach can also be applied for vehicle modeling. However, in order to ensure correct drivetrain behavior in the simulation, it is necessary to consider the rope's mass and elasticity. There is currently no rope element available in state-of-the-art MBS software that fulfills these requirements, and the application of a significant number of standard MBS elements (e.g., spring-mass chain) to model the complete rope loop is inefficient. Consequently, the current project has developed and implemented an elastic rope model designed for RAPM in SIMPACK.

ONE-DIMENSIONAL ROPE MODEL

The model development was based on a comprehensive determination of the decisive physical phenomena. The determination revealed that sag oscillations of the

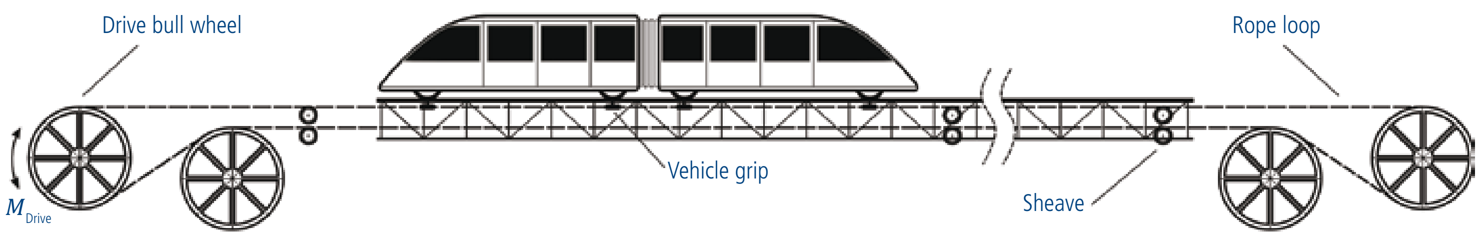

Fig. 2: Possible technical configuration of an RAPM drivetrain [1]

rope can be omitted due to the small sags, which result from the high pretension, and the short rope spans. Furthermore, the centripetal acceleration at the bull wheels and sheaves is negligible due to the low axial rope velocities.

In the substituted mechanical system, the rope is cut at the vehicle grips, and only displacements in the longitudinal direction are taken into account (Fig. 3).

Consequently, a simple, one-dimensional Lagrangian approach is applied. This leads to a modified one-dimensional wave equation, which describes the rope motion as a function of time and length:

$$\frac{\partial^2 u}{\partial t^2} = \frac{1}{\lambda}\left(EA\frac{\partial^2 u}{\partial s^2} + q\right) - a_S$$

In this Partial Differential Equation (PDE), the longitudinal rope displacements and the acceleration of the reference body are denoted by $u(s, t)$ and $a_s(s, t)$, respectively. λ is the mass per unit length, and EA represents the axial stiffness of the rope. The interaction between the rope and the bull wheels is modeled by longitudinal forces $q(s, t)$.

This PDE can be transformed into a set of Ordinary Differential Equations (ODEs) using Galerkin's Method and a Finite Element approach:

$$\underline{M}\,\underline{\ddot{u}} + \underline{C}\,\underline{u} = \underline{f}$$

This equation contains the rope's mass matrix $\underline{M}$ and the stiffness matrix $\underline{C}$. The vector $\underline{f}$ includes the external loads on the rope, the boundary conditions at the grip points and the acceleration of the reference body.

IMPLEMENTATION

With SIMPACK, subsystems with internal dynamics can be included by applying user-defined Force Elements. Hence, the coupled ODEs which describe the rope dynamics are implemented by means of a Force User Routine. Furthermore, as shown in Fig. 4, the user routine includes a simple contact model for calculating the interaction forces $q(s, t)$ between the rope and the bull wheels. Here, the contact force is determined by assuming that there is no slip between the bull wheel and the rope. However, with this approach, it would also be possible to apply more general contact models in cases where the interaction forces are a function of longitudinal slip.

> **"With SIMPACK, subsystems with internal dynamics can be included..."**

Theoretically, it would be possible to model the interaction between the rope and the sheaves using a similar method. However, since RAPM usually contain several hundred sheaves, a different approach has been chosen in order to increase numerical efficiency. Instead of modeling the sheaves as rigid bodies with assigned rotational joints, the sheave inertias are incorporated as additional entries in the rope's mass matrix. The resulting mass matrix is asymmetric and time-dependent, but band-diagonal. Hence, the unknown relative rope accelerations can be determined efficiently at each time step using the Tridiagonal Matrix Algorithm (TDMA).

In addition, the sheave's rolling resistance is considered as an additional external force on the rope. This is important because the collective rolling resistance of all of the sheaves is the main energy dissipation factor in the overall system.

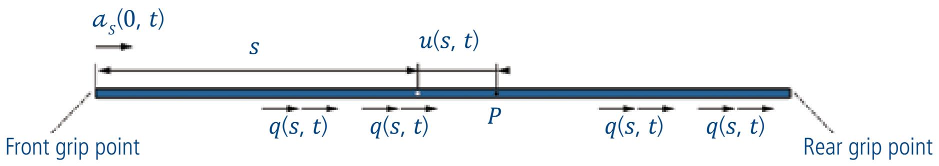

Fig. 3: One-dimensional approach for the calculation of rope dynamics [1]

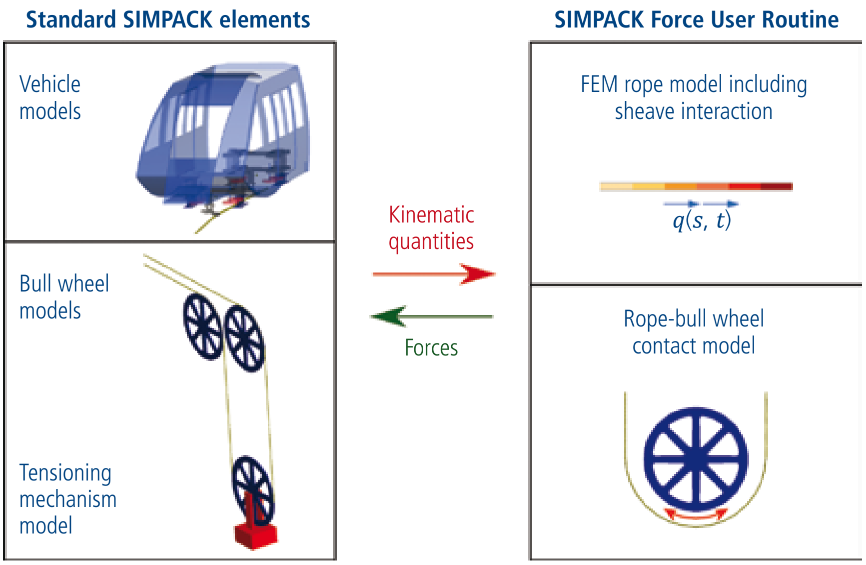

Fig. 4: Implementation of the rope model into SIMPACK [1]

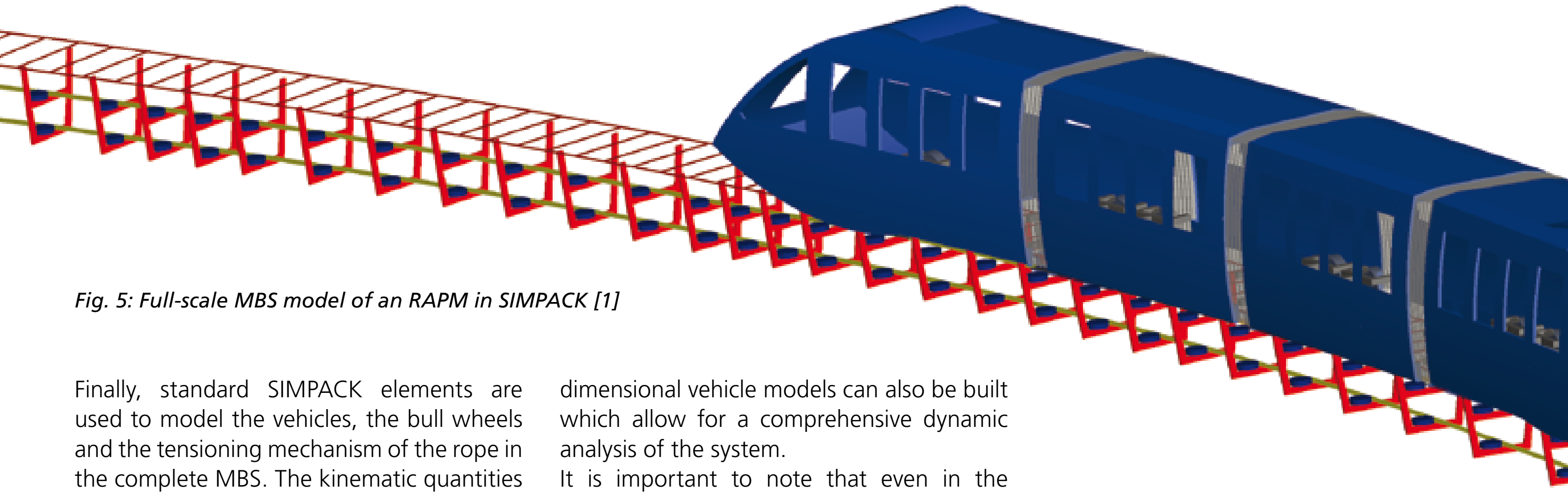

Fig. 5: Full-scale MBS model of an RAPM in SIMPACK [1]

Finally, standard SIMPACK elements are used to model the vehicles, the bull wheels and the tensioning mechanism of the rope in the complete MBS. The kinematic quantities of these subsystems are passed to the user routine which generates the corresponding forces on the rigid bodies.

Implementing the rope model in SIMPACK offers the advantage that the model depth of the vehicles and other facility components can be varied as desired. Thus, on the one hand, it is possible to generate simple models with real-time capability which only represent the longitudinal dynamics of the train. On the other hand, detailed three-dimensional vehicle models can also be built which allow for a comprehensive dynamic analysis of the system.

It is important to note that even in the three-dimensional MBS, the rope dynamics are treated as a one-dimensional problem. The spatial motion of the vehicle grips only affects the boundary conditions of the rope model.

VERIFICATION

A physical RAPM was used to verify the modeling technique for the rope. For this purpose, a three-dimensional model of the facility was built in SIMPACK (Fig. 5). The model contains rigid bodies for the bull wheels, the rope tensioning mechanism and the vehicles. The vehicles are guided by a three-dimensional rigid track.

In order to generate data for the model verification, various experiments were conducted at the physical RAPM facility. During these tests, special attention was paid to emergency stop situations which generate the maximum values with regard to system dynamics.

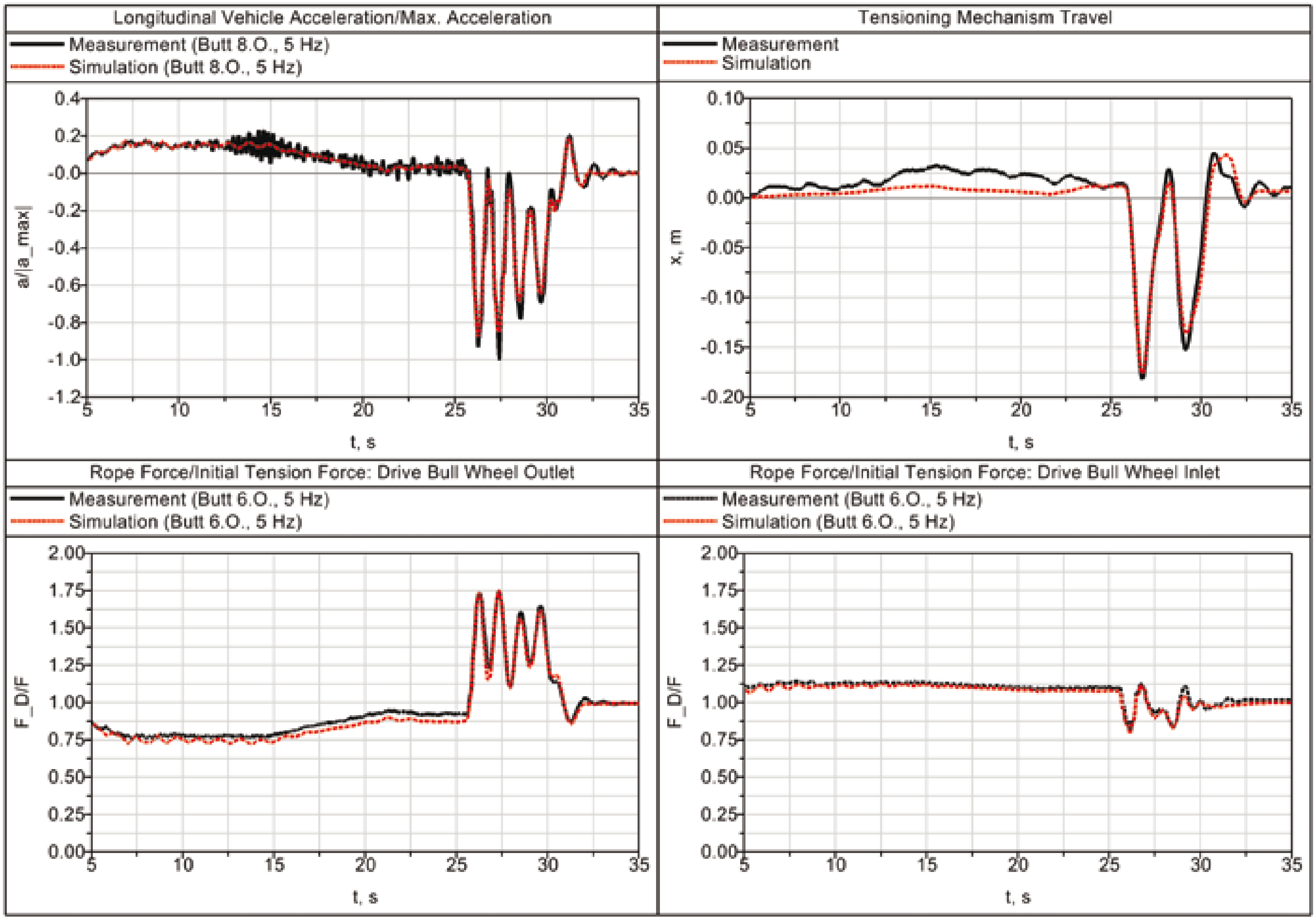

Fig. 6: Comparison of experiment and simulation in an emergency stop scenario

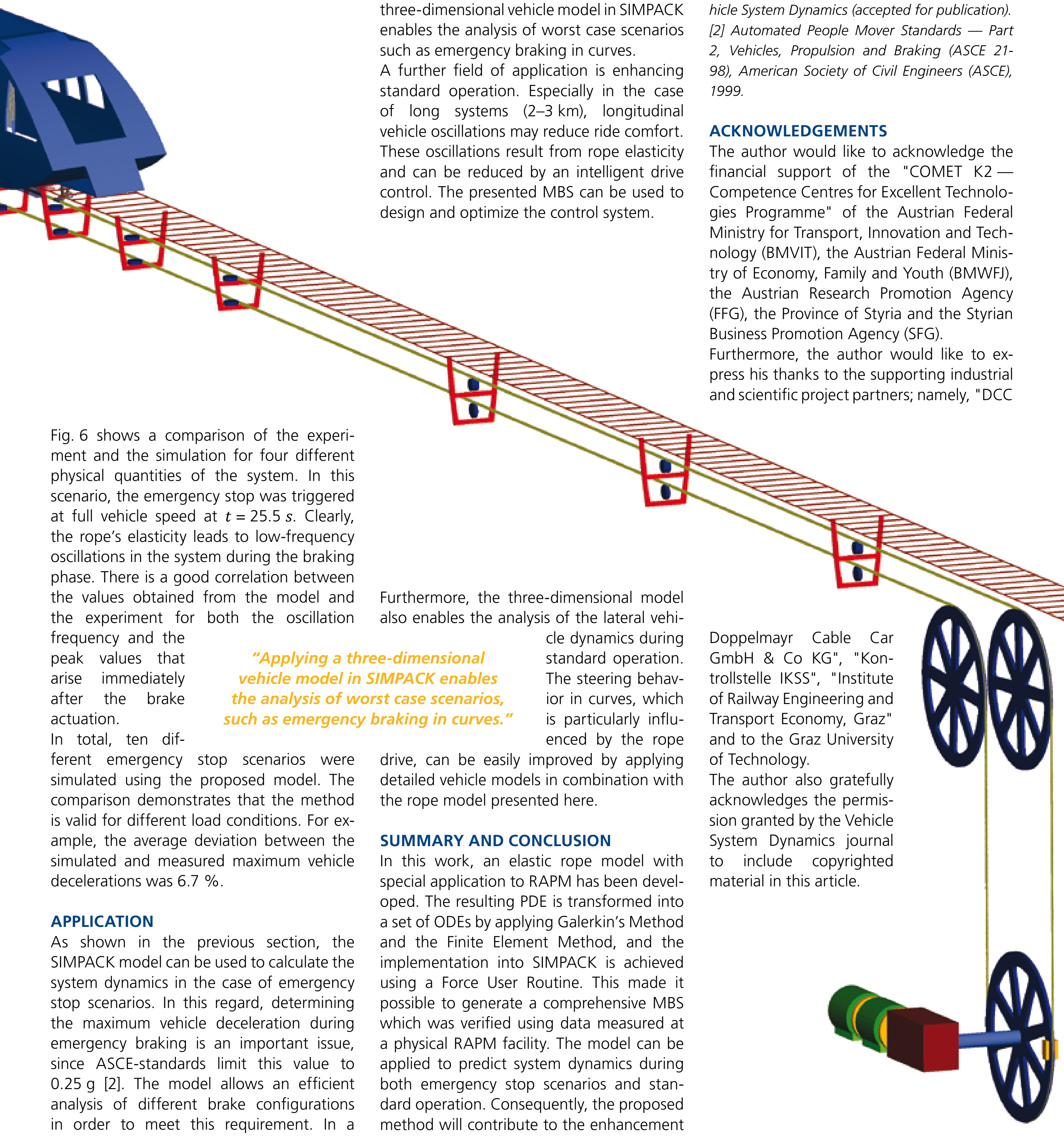

Fig. 6 shows a comparison of the experiment and the simulation for four different physical quantities of the system. In this scenario, the emergency stop was triggered at full vehicle speed at $t = 25.5\ s$. Clearly, the rope's elasticity leads to low-frequency oscillations in the system during the braking phase. There is a good correlation between the values obtained from the model and the experiment for both the oscillation frequency and the peak values that arise immediately after the brake actuation.

> ***"Applying a three-dimensional vehicle model in SIMPACK enables the analysis of worst case scenarios, such as emergency braking in curves."***

In total, ten different emergency stop scenarios were simulated using the proposed model. The comparison demonstrates that the method is valid for different load conditions. For example, the average deviation between the simulated and measured maximum vehicle decelerations was 6.7 %.

APPLICATION

As shown in the previous section, the SIMPACK model can be used to calculate the system dynamics in the case of emergency stop scenarios. In this regard, determining the maximum vehicle deceleration during emergency braking is an important issue, since ASCE-standards limit this value to 0.25 g [2]. The model allows an efficient analysis of different brake configurations in order to meet this requirement. In a further step, both the maximum tensioning mechanism travel and the dynamic rope forces that occur can be determined which are important inputs for the system design. Additionally, emergency stops generally lead to the maximum vehicle loads. Applying a three-dimensional vehicle model in SIMPACK enables the analysis of worst case scenarios such as emergency braking in curves.

A further field of application is enhancing standard operation. Especially in the case of long systems (2–3 km), longitudinal vehicle oscillations may reduce ride comfort. These oscillations result from rope elasticity and can be reduced by an intelligent drive control. The presented MBS can be used to design and optimize the control system.

Furthermore, the three-dimensional model also enables the analysis of the lateral vehicle dynamics during standard operation. The steering behavior in curves, which is particularly influenced by the rope drive, can be easily improved by applying detailed vehicle models in combination with the rope model presented here.

SUMMARY AND CONCLUSION

In this work, an elastic rope model with special application to RAPM has been developed. The resulting PDE is transformed into a set of ODEs by applying Galerkin's Method and the Finite Element Method, and the implementation into SIMPACK is achieved using a Force User Routine. This made it possible to generate a comprehensive MBS which was verified using data measured at a physical RAPM facility. The model can be applied to predict system dynamics during both emergency stop scenarios and standard operation. Consequently, the proposed method will contribute to the enhancement of the efficiency and ride comfort of Rope-propelled Automated People Movers.

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