Crashworthiness Design of a Light Commuter Rail Vehicle Operating on Secondary Lines

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Summary

A newly designed rail vehicle in Europe must fulfill the requirements specified in the European standard EN15227 to prove sufficient and acceptable crashworthiness. A vehicle designed as a so-called Light Commuter Rail Vehicle (LCRV) refers to a lightweight railcar operating on secondary lines. Lightweight is necessary for modern engineering design. Although it has many benefits, it creates difficulty in the crashworthiness design. An LCRV has low longitudinal structural strength that affects the ability of the energy-absorbing devices. It is only a single unit; its weight is comparable with large road vehicles like trucks. A collision with them can be dangerous to LCRV. With the Aachener Rail Shuttle (ARS), a totally innovative design is introduced, and the restrictions to crashworthiness are even more brutal. This paper describes the crashworthiness design process, its problems and limitations, and possible solutions for this type of rail vehicle. The ARS's crashworthiness concept is presented as a design example. The crashworthiness design process consists of three main procedures: developing the crashworthiness concept, analyzing the collision behavior in one dimension, and finally, in three dimensions. The goal is to fulfill the three primary requirements of the European standard: the deceleration limit, the overriding protection, and the survival space.

Keywords: Crashworthiness, Light Commuter Rail Vehicle, Rail Vehicle Design, Collision

1 Introduction

Germany aims to reopen disused short-distance railway lines to promote rail transportation in the countryside, [1-2]. More than 95% of these lines are shorter than 30 kilometers connecting small cities to mainline railways, known as secondary lines. Conventional trains like diesel or electric multiple units (DMU or EMU) may not fit in these very low-passenger density routes in terms of cost efficiency. Therefore, an innovative lightweight rail vehicle smaller than conventional regional trains seems to be more suitable for this type of railway line, [3]. The idea of this kind of rail vehicle is initially known in Germany as a railbus (Schienenbus). The idea was developed over time and later known as LNT (Leichter Nahverkehrstriebwagen). This type of railway vehicle is designed with low longitudinal stiffness of the vehicle frame but has a good braking performance comparable to tram vehicles. It operates in mixed traffic with mainline vehicles in urban and regional areas. The crashworthiness design of this type of rail vehicle is challenging because the low longitudinal stiffness causes difficulty in meeting the present crashworthiness requirements in secondary line operation.

At present, a newly designed rail vehicle's passive safety is analyzed according to the European standard EN15227. [4-6] The standard defines the crashworthiness requirements for rail vehicles based on their operational type and possible collision scenarios. A rail vehicle operated on secondary lines has several requirements because it is considered to run on an open line that shares routes with other types of rail vehicles. Besides, this type of operation can encounter level crossings so colliding with road vehicles is possible. Therefore, the crashworthiness requirements are strict because many types of obstacles are possible.

The Aachener Rail Shuttle (ARS) project aims to introduce an innovative light rail vehicle operating on low demand/non-used secondary lines. [7] The vehicle belongs to the so-called Light Commuter Rail Vehicle (LCRV) class. It is a single wagon and very light. However, its low longitudinal stiffness affects the ability of the energy-absorbing devices, which limits the crashworthiness design. The comparable weight to large road obstacles raises doubt about safety in case of a collision. Moreover, a unique design concept of decoupling between the chassis and the passenger compartment is proposed. This leads to a special challenge to protect the passenger compartment which should not bear external loads.

2 Crashworthiness design process

The chosen crashworthiness design process consists of three main steps (developing crashworthiness concept, one-dimensional analysis, and three-dimensional analysis) as shown in Fig. 1.

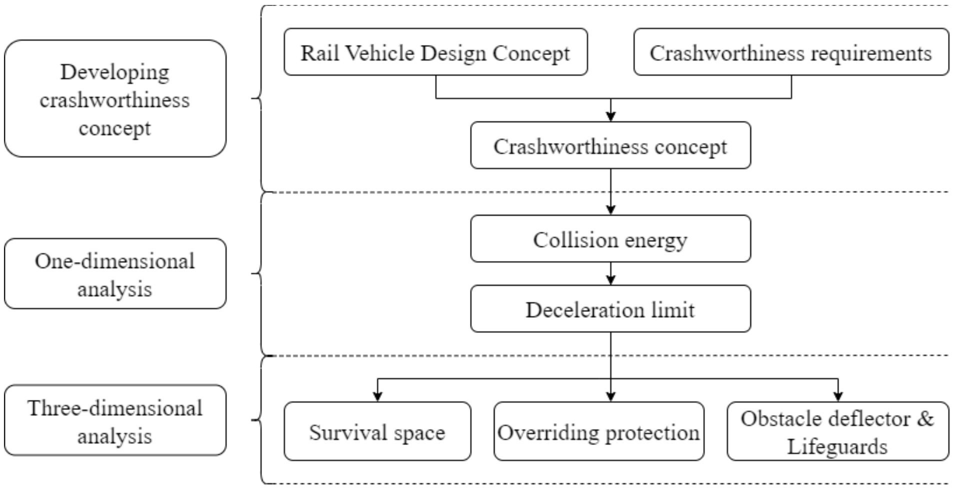

Figure 1: Crashworthiness design process

The process begins with defining the crashworthiness concept. The requirements from the rail vehicle design affecting the crashworthiness concept are gathered and summarized. Besides, the crashworthiness requirements according to the European standard EN15227 are listed. Then, these two aspects are considered together to elaborate the crashworthiness concept for the rail vehicle.

The crashworthiness design relies heavily on numerical simulations to prove the crashworthiness performance. The simulation ranges from a simple one-dimensional analysis to a sophisticated three-dimensional simulation of the designed vehicle. The one-dimensional collision study is performed by analyzing the differential equation of motion and using the commercial software (LS-DYNA). First, the collision energy is calculated for each design collision scenario to identify the worst collision scenario in terms of required energy absorption. It will be used as a reference scenario to evaluate the deceleration limit. Next, the conventional analysis performs a fundamental calculation, before further sophisticated simulation by the commercial software. At this step, the energy-absorbing elements are defined regarding technology and characteristics. Later, the result from the actual crash experiment is used to improve the simulation. The final step is three-dimensional analysis. The other design collision scenarios are investigated to evaluate survival space and overriding protection, and obstacles & lifeguards according to the requirements from the standard.

3 Developing crashworthiness concept

The ARS vehicle has unique design characteristics. A list of requirements from the design concept and its impact on crashworthiness design can be summarized in Tab. 1.

Table 1: Design concept and impact on crashworthiness design

Characteristic	Impact on crashworthiness design
Operation on secondary lines	Crashworthiness category C-III (EN15227)
Passenger vehicle category P-III (EN12663)	Static buffer load is limited to 800 kN
The passenger compartment should not be subjected to any external force	All collision force is taken by the chassis via energy absorbers
No center coupling	No central energy absorber
Compact design	Crumple zone is kept as short as possible
Single wagon	Symmetric design on both vehicle ends

The ARS vehicle falls into the crashworthiness design category C-III according to the European standard EN15227. The standard aims to guarantee the passive safety of rail vehicles in four aspects: Overriding protection, Survival space, Deceleration limit, and Obstacle deflector and lifeguard. The obstacles in a collision could range from small obstacles like debris on track to large obstacles like heavy trains. The standard defines four major design collision scenarios to validate all four aspects of the crashworthiness requirements. The crashworthiness requirement for category C-III is shown in Tab. 2.

Table 2: Crashworthiness requirements for category C-III according to EN15227

Crashworthiness requirements for category C-III	Design collision scenarios				
	S1	S2		S3	S4
		S2-1	S2-2		
	Identical train	80 t freight train	129 t regional train	15 t deformable obstacle	Leading end impact with a low obstacle
Overriding	●				
Survival space	●	●	●	●	
Deceleration limit	●	●	●		
Obstacle deflectors and lifeguards					●

According to the standard, the different obstacles result in different collision positions at the vehicle front. Side buffers are installed for a collision with a freight wagon. A center buffer is usually installed for a collision with a regional train. Generally, the energy absorber for the center position is part of a center coupling; however, the design concept of ARS intends to omit a center coupling. The reason is that the ARS vehicle is planned to operate solely on secondary lines without coupled wagons. Hence, the ARS design does not include a center buffer and uses only side buffers as a primary energy absorber. The standard defines a collision with a center coupling as the design collision scenario S2-2 (a collision with a regional train with a center coupling). The 129 t regional train has a center coupler of a total deformable length of 475 mm. Even though the ARS vehicle has no center buffer, the designer aims to stop a collision with a regional train before its center coupler reaches the safety zone of the ARS vehicle. Detailed analysis is explained in Chapter 4. Besides, obstacle deflectors and lifeguards are separate devices from the main energy-absorbing elements and have independent validation methods. This paper does not focus on them. Hence, the design collision scenario S4 will be neglected in this paper. Then, the crashworthiness concept is designed as in Tab. 3.

Table 3: Crashworthiness concept design

Crashworthiness requirements for category C-III	Design collision scenarios				**Crashworthiness concept**
	S1	S2-1	S2-2	S3	
Overriding Protection	●				Equipped with Anti-climber
Survival space	●	●	●	●	Energy absorbers absorb all collision energy
Deceleration limit	●	●	●		Appropriate force-deformation characteristics
Crashworthiness concept	Side buffers with anti-climber	Only side buffers	No intrusion of center coupling into survival zone	No intrusion of obstacle into survival zone	

Four design collision scenarios (S1, S2-1, S2-2, and S3) are used to validate the ARS's crashworthiness. The ARS's crashworthiness concept is summarized as follows:

- The energy-absorbing elements will be two side buffers equipped with anti-climber at both vehicle ends.

- The buffers can absorb all collision energy with a limited collision force at 800 kN.
- There is no intrusion of the collided obstacle into the survival zone (the passenger compartment). The crumple zone is limited to energy-absorbing element length and is designed to be as short as possible.

4 One-dimensional analysis

4.1 Collision energy

The train collision is assumed to be a perfectly inelastic collision. The collided objects will stick together after a collision. While the total momentum is conserved during the collision, a part of the total kinetic energy is absorbed by the collision elements. This dissipated energy from a collision is called collision energy. It can be computed from the mass of collided objects and their velocity according to eq. 1.

$$E_c = \frac{m_1 m_2}{2(m_1 + m_2)} (v_1 - v_2)^2 \tag{1}$$

The collision mass of the colliding vehicle is the design mass in working order plus 50% of the mass of seated passengers following EN15663, [8]. All standardized obstacles are un-braked and stationary ($v_2 = 0\ \mathrm{km/h}$). In Tab. 4, the result shows that the design collision scenario 2-1 (a collision with a freight train) generates the highest collision energy of 462 kJ. Thus, it will be used as the reference scenario for verifying deceleration limit.

Table 4: Collision Energy

Design collision scenarios	S1	S2-1	S2-2	S3
ARS mass, m_1 (ton)	25.2	25.2	25.2	25.2
Obstacle mass, m_2 (ton)	25.2	80	129	15
ARS velocity, v_1 (km/h)	25	25	10	25
Collision energy, E_c (kJ)	304	462	82	227

4.2 Deceleration limit

One aspect of passenger safety during a collision is ensured by limiting the train's deceleration. The deceleration limit will decrease the severity of the secondary impacts on the passengers. According to the standard, the deceleration limit is set to two criteria. The first criterion is that rail vehicles must have a mean decelerate below 10g (98.1 m/s^2) during any 30 milliseconds collision period. The second criterion is that a mean deceleration must be below 5g (49.05 m/s^2) during any 120 milliseconds collision period.

After the crashworthiness concept and the reference collision scenario have been defined, the collision analyses are performed to design suitable energy-absorbing elements. One-dimensional crash analysis is performed first to determine the force-displacement characteristic of the energy-absorbing elements, which is essential to achieve the desired safety. It defines how the collision energy is absorbed. One-dimensional analysis simplifies all complex geometries of rail vehicle components by rigid bodies/point masses. It limits many degrees of freedom of the rail vehicles into one degree of freedom in the longitudinal direction (train running direction). This simplification makes the analysis faster and more easily repeatable. The design collision scenarios generally involve a moving train colliding with another stationary object. The collision can be simplified using a spring-mass system, as in Fig 2.

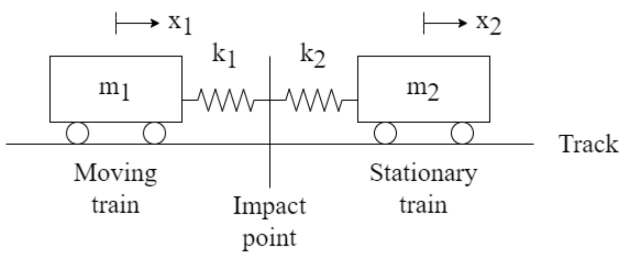

Figure 2: One dimensional trains collision model

Springs represent energy-absorbing components without a damping effect. The collision is assumed as a perfectly inelastic collision. Therefore, the collision can be analyzed by the differential equation of motion with initial conditions [9-10], as in Tab 5. The design collision scenario 2-1 is investigated. The analysis aims to find the energy absorber's characteristic (spring's characteristic, k_1) that complies with the deceleration limit. The conventional analysis provides fundamental results, which guide further detailed simulations by commercial software.

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Table 5: One dimensional crash analysis equation

Description	Equation	
The spring's characteristics	$k_{eff} = \frac{k_1 k_2}{(k_1 + k_2)}$	(2)
The differential equation of motion	$m_1 m_2(\ddot{x}_1 - \ddot{x}_2) = -(m_1 + m_2)k_{eff}(x_1 - x_2)$	(3)
Initial conditions	$x_1 = x_2 = 0$ $\dot{x}_1 = v_1 , \dot{x}_2 = v_2 = 0$	(4)
The relative acceleration	$a_{rel} = \ddot{x}_1 - \ddot{x}_2 = -\omega v_1 \sin \omega t$	(5)
The angular frequency	$\omega = \sqrt{\frac{(m_1 + m_2)}{m_1 m_2} k_{eff}}$	(6)

Conventional analysis and commercial software show similar results. It verifies the accuracy of the simulation model. The impact force is limited to 800 kN, and the spring's characteristic (k_1) is set to 738 kN/m; the acceleration-time relation of a collision with a freight train can be seen in Fig. 3.

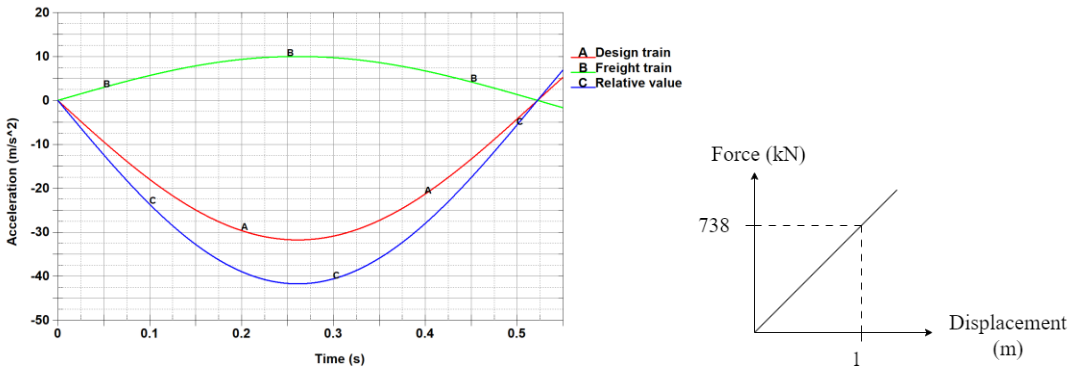

Figure 3: Acceleration-time diagram of the design collision scenario 2-1 (left), spring's characteristic (k_1) (right)

The maximum deceleration of the designed train is 31.7 m/s^2. Hence, it fulfills the deceleration limit. However, this spring's characteristic needs considerable deformation length. It requires more than 1084 mm. Thus, the designers aim to minimize this length as much as possible to fulfill the compact design concept.

There are two main types of energy absorbers (reversible and non-reversible energy absorption elements). After a collision, the reversible type is reusable, while the non-reversible type will be damaged. However, the non-reversible type requires a shorter length to absorb the same energy level. Therefore, using non-reversible energy absorbers is considered. If the non-reversible energy absorber can absorb energy perfectly, the deformation length can be calculated from absorbed energy and impact force as in Eq. 7.

$$E_{absorb} = F_{impact} \cdot L_{deformable} \tag{7}$$

The analysis reveals that the required deformable length is about 542 mm for non-reversible energy absorbers. The one-dimensional simulation shows that the maximum deceleration of the designed train is still at 31.7 m/s^2, as in Fig. 4. The designers decide that the energy absorber will use non-reversible energy absorbers.

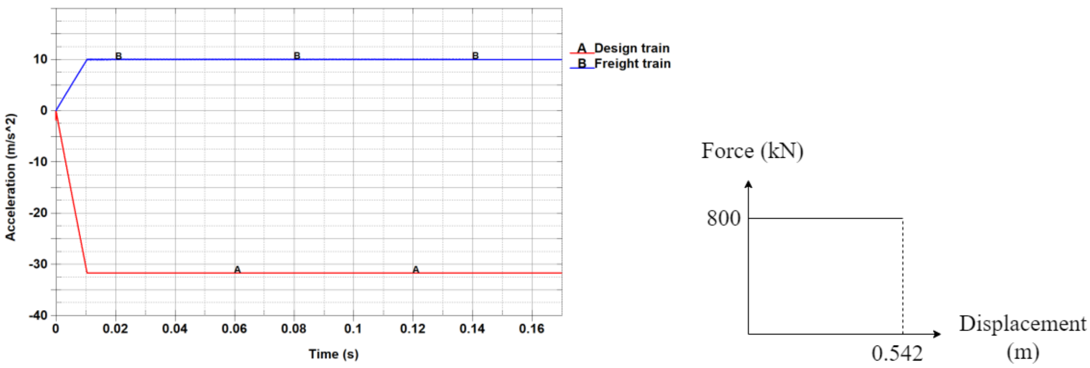

Figure 4: Acceleration-time diagram using non-reversible energy absorber (left), energy absorber's characteristic (right)

4.3 A collision with the standardized regional train

A collision of the ARS vehicle with the 129 t regional train generates a collision energy of 82 kJ, as in Tab. 4. The designed side energy absorber can absorb this collision energy within a deformable length of 102.5 mm. The collision must stop before the center coupler of the regional train reaches the safety zone of the ARS vehicle. In that case, the side energy absorber should absorb all the collision energy for this scenario as well. Hence, the crumple zone (a permissible deformable area) of the ARS vehicle requires a length of at least 577.5 mm (the length of the center coupling of the 129 t regional train plus a deformable length of the energy absorber of the ARS vehicle).

5 Three-dimensional analysis

5.1 Survival space

According to the design concept, there shall be no deformation in the passenger compartment. However, the obstacle in the design collision scenario 3 (a collision with a large road obstacle) has a particular shape and conditions. The crash simulation with the standardized model of a large road obstacle exhibits that the obstacle will tip over the designed train, as in Fig. 5. It hits directly at the passenger compartment, which is unacceptable. Therefore, three proposed solutions are investigated to handle this impact.

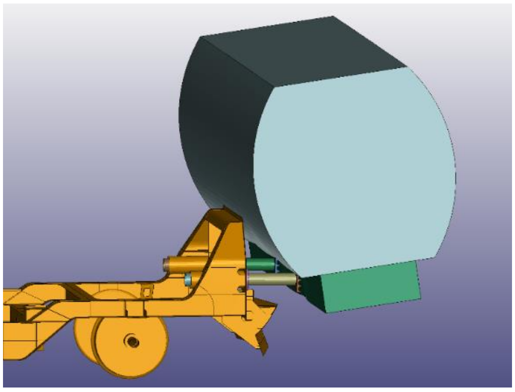

Figure 5: Collision with the standardized large road obstacle

5.1.1 Strengthening chassis and installing additional energy absorber

The obstacle's most outer point (MO) height is 2200 mm above the top of the rail level (TOR). The obstacle's center of gravity (CG) height is 1750 mm above TOR, as shown in Fig. 6. Secondary energy-absorbing elements should be installed at a chassis structure around these heights to protect the passenger compartment. It needs a revised chassis design to support the additional energy absorbers, which may result in a larger and heavier chassis. The length of the crumple zone is also an essential factor. The primary energy absorber is at a height of 1000 mm above TOR, according to the standard. It needs at least 550 mm to contact the lower part of the standardized obstacle. Otherwise, the secondary energy absorber may collide with the obstacle before the primary energy absorber and function as a main energy absorber. It needs a sufficient length of the primary energy absorber, sizeable secondary energy absorbers, and robust support structures. All these requirements disagree with the design concept of lightweight design. Moreover, the higher chassis could result in smaller or no front windows area. As a result, this option is not viable.

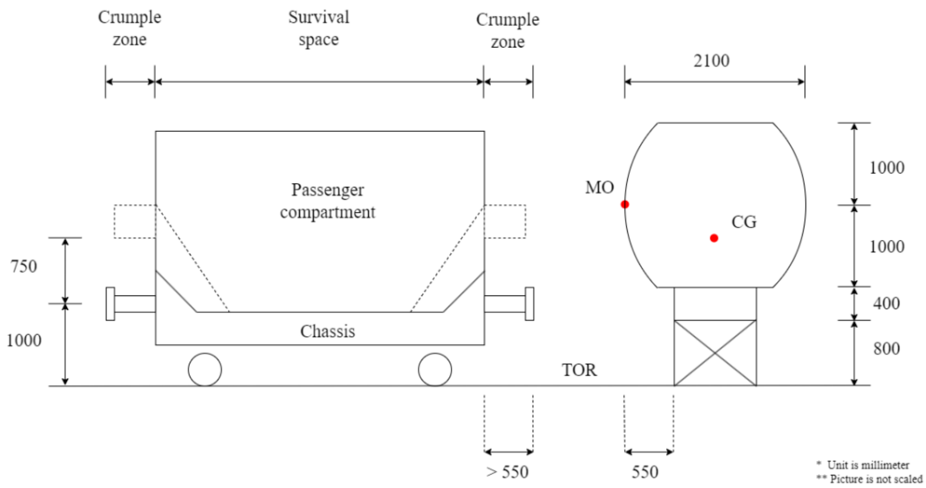

Figure 6: Dimensioning of the design collision scenarios 3

5.1.2 Strengthening passenger compartment

The obstacle will collide with the front end of the vehicle at a height that hits the passenger compartment directly. Typically, this impact will encounter the front-end structure of the conventional rail vehicle, which is designed to be deformed in a controlled manner to absorb the collision energy. This solution requires a sufficient deformable length at the front-end structure to absorb collision energy and a durable passenger compartment to provide safety space. Since the ARS vehicle is compact and has no driver cab, the required deformable length and more robust structure could result in a heavy passenger compartment with small safety space. It disagrees with the ARS's design concepts. It requires a more sophisticated design for the passenger compartment. This option is not viable for the time being.

5.1.3 Reducing vehicle's velocity at level crossing

The significance of the design collision scenario 3 depends on the existence of level crossings, the operating speed, the emergency braking rate of the train, and the sighting distance. The design collision scenario 3 is obsolete if the LCRV can stop reliably within the sighting distance. The stop distance consists of the sum of the covered distance from the point where the driver can see the obstacle until he reacts, called reaction distance, and the brake distance, which depends on the vehicle itself with its brake system.

The ARS vehicle is equipped with a disk brake, an electromagnetic brake, and a regenerative brake using the engine for recuperation. The brake system provider investigates the braking performance regarding standard EN14531, [11]. In full braking performance and with a reaction time of 1 second, the vehicle can stop from the operational speed of 100 km/h within 174 m, as in Fig. 7. The stop distances sink at lower speeds radically and meet the high requirements for the deceleration according to §36 BOStrab, [12]. For this reason, reducing the speed at level crossings with the highest possible deceleration is an option to avoid a collision. It causes a slight loss of time, so the effect on the timetable is limited. This option is more viable than other solutions for the time being.

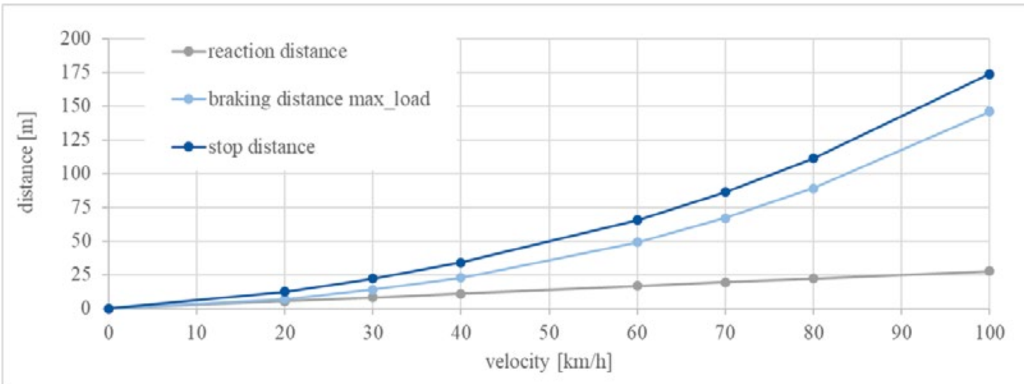

Figure 7: Stop distances at different velocities

5.2 Overriding protection

The overriding of collided trains is one of the main crashworthiness requirements because it could result in catastrophic and dangerous damage to vehicles and passengers. The standard requires a train equipped with an anti-climber device to prevent an overriding during a collision. However, an anti-climber device has no specific standard. It is designed according to the industry's know-how. It is usually a wave-shaped plate installed at the tip of the energy absorber, as in Fig. 8. During a train collision, the wave shape will lock with each other and provides contact in the vertical direction. Hence, the vehicles cannot be lifted easily about each other during a collision. Typically, the energy absorber equipped with anti-climbers can withstand a vertical force of around 100 kN. The collision simulations are performed according to design collision scenario 1 (a collision with an identical train) as in Fig. 9. A low pass filter of 180 Hertz filters the simulation results in Fig. 10. The simulation shows that the vertical collision force at one side fluctuates within the limit of 100 kN. The maximum lifted wheel is still within the requirement of 75% of the flange height, which is 24 mm. The anti-climber devices stay fully engaged during the collision simulation period of 120 ms. Therefore, the vehicle fulfills the requirement of overriding protection.

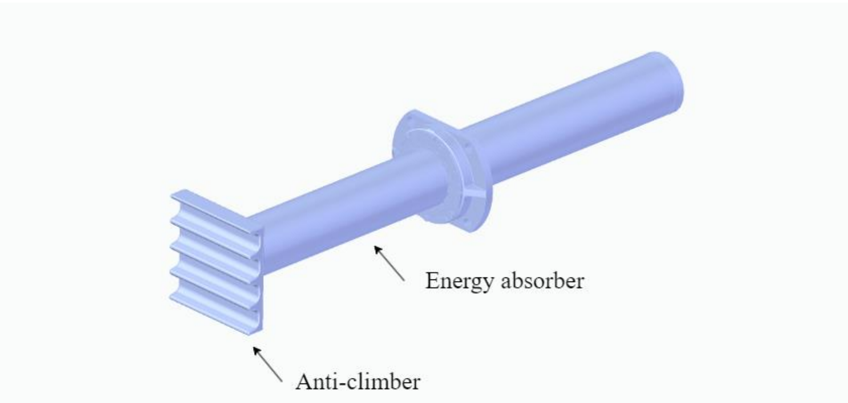

Figure 8: Energy absorber equipped with anti-climber

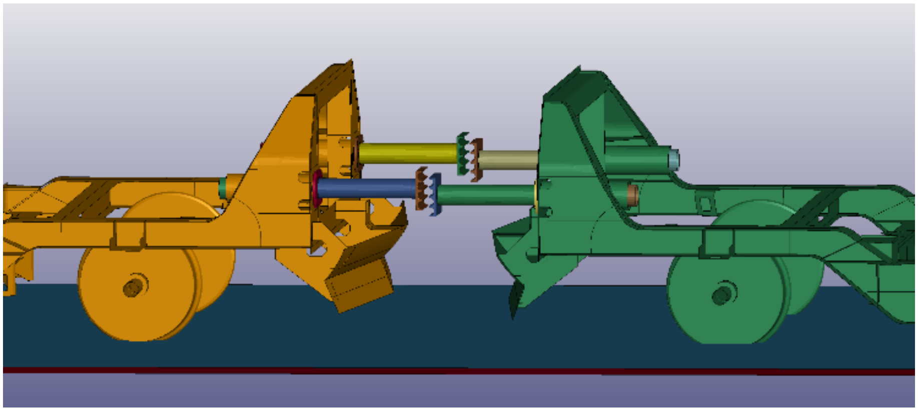

Figure 9: Collision with an identical train with a vertical offset of 40 mm

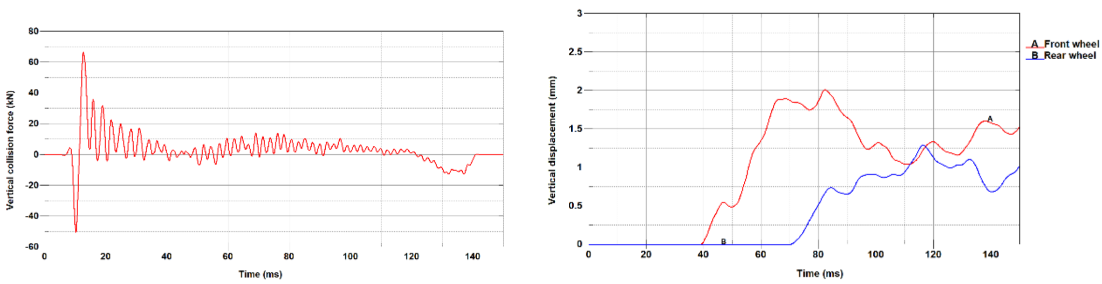

Figure 10: Vertical collision force (left), Wheel lifting (right)

6 Conclusions

Designing crashworthiness for a light commuter rail vehicle, as shown in the design of the ARS vehicle, is challenging. The vehicle is designed to be compact (single wagon) and light; therefore, it has low longitudinal stiffness. The passenger compartment should not be subjected to external forces. The vehicle will operate on secondary lines, which have railway crossings. A collision with other road obstacles is possible. This design concept causes difficulty in meeting the crashworthiness requirements.

The crashworthiness design begins with summarizing the rail vehicle design concepts and the related crashworthiness requirements. It leads to the design of the crashworthiness concept. The main crashworthiness characteristics of the ARS vehicle are:

- The crumple zone is limited to the energy-absorbing element's length. The passenger compartment (considerable here as a safety zone) shall not have any deformation.
- The energy-absorbing elements will be two side energy absorbers equipped with anti-climber at both vehicle ends.
- The collision force is limited to 800 kN.

The crashworthiness design is evaluated by one-dimensional and three-dimensional analysis to fulfill the three primary requirements in the European standard EN15227 (Deceleration limit, Survival space, and Overriding protection). As a result, the designed vehicle is recommended to use a lower speed at level crossing. The collision analyses define the characteristics and configurations of the two side energy absorbers as follows:

- Non-reversible energy absorber
- The collision force is limited to 400 kN (per side)
- The deformation length is 600 mm (considered from all collision scenarios)

7 Concluding part

Acknowledgment

We would like to thank the federal ministry of economic affairs and climate action for providing funding for the project “Flexibler Schienenbus für den Ländlichen Raum (FlexSbus-LR)”.

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