*Acta Polytechnica CTU Proceedings* **43**:117–125, 2023
https://doi.org/10.14311/APP.2023.43.0117


# COOPERATION OF ACTIVE STEERING CONTROL OF WHEELSETS WITH SUBSYSTEMS OF AN AUTONOMOUS URBAN RAIL VEHICLE

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Abstract. The paper presents the motivations for the application of actively controlled elements in the running gear of a rail vehicle and the challenges that need to be addressed before deploying vehicles with actively controlled elements in real operation. Furthermore, the paper presents the design of an active element concept and its control for steering the axles of an urban rail vehicle to improve the vehicle's passage through small radius curves. The design takes into account the fundamental issues of cost and safety of the application of active elements, which are addressed in the presented control design by using data from autonomous driving subsystems such as the environmental database or the anti-collision system.

Keywords: Active element, actuator, rolling stock, autonomous driving, tram, running gear.

## 1. Introduction

Routes for urban rolling stock, especially trams, usually run through city centers, where directional curves with very small radii (less than 25 meters) are often used for historical reasons. Curves with even smaller radii (around 15 meters) can often be found in depots, see example in Figure 1. When a vehicle passes through such a small curve, the lateral clearance of the wheelsets in the track is exhausted and large slip forces are generated at the wheel-rail contact. These longitudinal and transverse forces lead to undesirable phenomena in the form of high wheel and rail wear and noise and vibration emissions. The wear of wheels and rails results in high costs for both the infrastructure manager and the vehicle operator, who has to arrange for machining of the worn wheel profile and subsequent replacement of the wheel tyre. Wheel reprofiling, which has to be carried out regularly due to the wear of the wheel profile, and the subsequent replacement of the wheel tyre are the largest maintenance costs for tram vehicles and thus contribute substantially to the service component of the LCC (life cycle cost).

Figure 1. Demonstration of high wear of rails and turned material from vehicle wheels in tram depot [1].

Improving the passage of trams through small radius directional curves has been the focus of much attention from researchers and vehicle designers around the world for many decades. Improvement of small-radius curve passage of tram vehicles can be achieved by only mechanical solutions in the form of optimisation of the rolling stock running gear, for example longitudinal stiffness and primary suspension design, use of pivot bogies, lubrication of the flanges or the articulated tram vehicle concept itself. Another possible purely mechanical solution to improve the passage through the curve is the use of wheelset with independently rotating wheels (IRWs), whereby the torsional link between the individual wheels of the wheelset is unbound compared to conventional wheelsets, see Figure 2. This solution allows the wheels to rotate at different angular speeds and deals to minimisation of longitudinal slip forces. The use of independently rotating wheels (IRWs) is only widespread in tram vehicles, because of the ability to pass through curves of very small radii and also because of the possibility to achieve a fully low-floor vehicle without ramps or steps over the bogies. The use of IRWs has a great advantage in the design of low-floor vehicles passing small radius curves, but on the other hand, vehicles

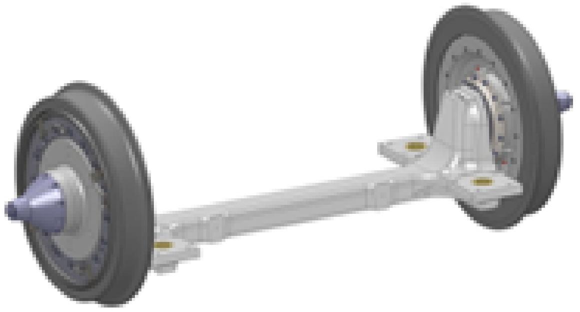


Figure 2. Tram wheelset with independently rotating wheels [3].

Figure 3. Electro-hydraulic actuator.

with IRWs have poorer running characteristics on the straight line [2] and at higher speeds. The lack of torsional coupling between the wheels prevents the IRWs wheelsets from performing the sinusoidal motion that conventional wheelsets perform, which ensures more even wear on the wheel surface.

Due to the long development in the mechanical parts of rolling stock running gear, a major advance in the improvement of sharp curve negotiating can no longer be expected. For this reason, a great deal of interest and research capacity has been devoted in recent decades to the use of actively controlled elements in rolling stock running gear. The first active elements in locomotive running gear were already used in the 1950s to achieve a mechanical optimum. However, the rapidly developing fields of electrical engineering, sensorics or controllers in the last decades allow the use of active elements on a much wider scale and thus support the quest for faster, more comfortable, more economical and ultimately safer rolling stock (hereafter referred to as RS). However, despite several decades of research and development in the field of active elements applied to rolling stock running gear, it is not possible to claim that their use in new rolling stock running gear is more widespread.

The second significant development trend in rail transport, and again especially in urban RS, is the development of autonomous vehicles and their gradual deployment in operation. Currently, fully autonomous metro vehicles are already routinely deployed. Moreover, partial systems leading to future fully autonomous driving for trams are developed and tested in operation. An example of such a subsystem for autonomous tram driving is the deployment of an anti-collision system (ACS) on current tram vehicles to improve operational safety.

A number of synergies can be found between these two development trends, both in terms of the interconnection of the vehicle control itself and therefore the active elements, and in terms of the sensors that provide the input variables for the control algorithm of the active element in the running gear and the vehicle as a whole.

The aim of the article is to briefly introduce the reader to the possibilities of using active elements in the RS running gear. The paper also describes the proposed concept of an active element in the tram vehicle running gear for the purpose of turning the wheelset into a curve and its control. The proposed concept emphasizes on trying to solve some basic issues of the application of active elements in the RS running gear, such as cost or safety, by linking the control of the active element with the sub-systems of the autonomous control of the tram vehicle. This linking can lead to a reduction in the cost of the active element application due to the use of sensors that are primarily placed on the vehicle for other purposes, and to an increase the safety of the control by verifying the input variables by two independent sources.

## 2. Active elements in RS running gear

The active element (actuator) is a force element used in the construction of the rolling stock, with the help of which we can actively influence the driving and force effects of the rolling stock in interaction with the track. An example of an electro-hydraulic actuator is shown in Figure 3.

### 2.1. The collision scenario: the frontal impact of two identical trams

The classification of the use of active elements can best be made according to their location in the running gear of the rolling stock into active elements used in secondary suspension and in primary suspension. As a special subcategory of elements in secondary suspension, it is possible to classify active elements used to tilt the carbody or the concept of placing active elements between the carbodies of a multiple unit train or articulated tram in the vertical or lateral direction.

#### 2.1.1. Classification by purpose of use

A different approach to the classification of active elements is presented by Stichel et al. [4] according to the purpose of their use. Thus, active elements can be divided into four categories:

- active elements isolating the vehicle body from track irregularities (increasing ride comfort),

- active elements controlling the bogie kinematics (ensuring the driving stability),
- active elements steering and guiding the wheelset (radial positioning of the wheelset),
- active elements for other special purposes (tilting of the carbody, more even loading of the bogies, leveling of the floor height in relation to the platform, ...).

#### 2.1.2. Classification by source of force

Actuators can also be divided into pneumatic, hydraulic, electro-hydraulic or electric actuators in terms of the initial source of force they exert. Information regarding their characteristics or technical maturity can be advantageously drawn from the field of civil aviation, where the use of actuators is much more widespread and where the use of hydraulic and electro-hydraulic actuators is still predominant. However, the electro-mechanical actuator is increasingly being used because of its good characteristics [5].

Hydraulic actuators are very often used in aviation due to their technical maturity, high power density or good safety in case of failure. Usually, actuators are powered from one central pump producing a constant oil pressure and controlling the oil flow by means of servo valves (the so-called "Fly by wire" concept) [5].

Another frequently used actuators are electro-hydraulic actuators, which operate according to the "Power by wire" concept, where each actuator has its own servo motor controlling a pump that produces pressure and fluid flow according to the current need. This solution brings weight reduction as it eliminates the need for manifolds, oil reservoirs or valves [5].

The electro-mechanical actuator is the least technically proven, but very promising for future use. This type of actuator is the best controllable, lightest, least demanding for maintenance, but it can cause mechanical jamming if the ball screw malfunctions. This type of actuator is used, for example, in electrical multiple units for carbody tilting [5].

The actuators presented are applied as linear actuators and thus influence the behaviour of the vehicle on the track by means of their extension. A different approach is the torque control of traction motors that drive independently rotating wheels. Each traction motor is thus individually controlled by its own traction converter and when passing through small radius curves, the angular velocity of the outer wheels is increased in the case of IRWs wheelsets. Moreover, the wheels may be also braked on the inside of the curve. This has the effect of ensuring the necessary difference in rolling distance between the inner and outer wheels and thus improving the passage of the rolling stock through the curve. In this case, the traction motor can therefore be considered as the active element.

#### 2.1.3. Classification according to the input variable of the active element control

In the past years, many control algorithms have been developed and described in the literature, which control individual actuators in the rolling stock running gear and thus control the steering of the wheelset into a curve, or control individual traction motors driving the IRWs. In particular, two categories of control method can be defined in terms of the variables entering the control algorithm.

The first method of active element controlling is the feedback control based on the knowledge of the lateral position of the wheelset in the track. This method was introduced in the works of, for example, Lu et al. [6], Oh et al. [7] or Ahn et al. [8]. However, this control method is very problematic for practical application on real rolling stock, since the measurement of the lateral deflection of a wheelset is very difficult to perform in an operationally demanding environment such as a RS running gear. Hyundai Rottem applied this method of active torque control of the IRWs to a test tram vehicle, and a reduction of up to 30 % in lateral wheel-rail contact forces was achieved when the vehicle was driven on a test track [9].

The method of controlling the active steering of the wheelset based on the radius of the currently negotiating curve seems to be much more applicable. The radius of the curve can be sensed by sensors on the vehicle (automatic rail curvature detection from LiDAR or camera sensed data), or the information can be retrieved from a track database on the vehicle based on the current position of the vehicle on the track. This input variable has been used to control actuators by authors such as Hur et al. [10], Stichel et al. [11], and for active control of IRWs by Čapek [2]. A commercial application of active wheelset steering designed in this way was presented by CRRC on Cetrovo metro vehicles. The steering of the wheelsets is performed by electro-hydraulic servo actuators. First tests in operation show a significant reduction of the steering forces in wheel-rail contact and also a reduction of noise emissions [4, 12].

### 2.2. Active element application into RS running gear

The positive effect of properly selected and controlled active elements in the running gear of a rolling stock on the reduction of wear of wheels and rails, noise and vibration emissions when passing small radius curves, increase in driving comfort or increase in maximum vehicle speed can be considered sufficiently proven. Nevertheless, a wider expansion of active elements into the running gear of rolling stock has not yet taken place. Exceptions are, for example, some Pendolino electric multiple units with active tilting of the carbody in order to reduce the lateral forces acting on the passenger when passing through a curve, or an active element placed instead of a yaw damper in the secondary suspension of Vectron locomotives in order to actively steer the bogie when passing through a curve [13]. The author of the paper discusse in detail the research on the use of active elements in RS running gear in [14]. From the conducted research it is evident that the most attention is paid to active elements improving the vehicle's passage through the curve and in particular to active elements located within the primary sus-pension and actively controlled IRWs.

The wider spread of active elements in the RS running gear is hindered by unresolved issues, including in particular the question of safety of their use in normal operation, cost or maintenance requirements. Another relatively unresolved issue may be the relative movements of the wheelset and the drive or brakes. Unresolved issues for actively controlled independently rotating wheels are primarily the magnitude of the needed steering torque when passing a small radius curve [2], the cost and number of traction converters, or finding the right steering algorithm to avoid wheel climbing on the flange during track irregularities or at curve transition.

## 3. Autonomous driving systems

In general, rail vehicles have a significant advantage over road vehicles in terms of autonomous driving in terms of directional guidance in the track and thus have one less degree of freedom. As mentioned in the introduction, autonomous driving, particularly of metro vehicles or similar transport systems, is a commonly deployed technology. Autonomously controlled trains are also being tested and the implementation of ETCS on European railways can also be seen as a major step towards autonomy.

Certain uniqueness of trams compared to road vehicles, but also compared to other types of rolling stocks, leads to the need for specific development of some autonomous driving subsystems. These specific systems are mainly the anti-collision system (ACS) and the track map information database. Due to the operation of trams in urban areas, the issue of sufficiently accurate vehicle localisation on the track must also be taken into account. For the other sub-systems of autonomous driving, it can be assumed that it will be possible to adopt them for autonomous tram vehicles from other RS.

ACS is mainly used on tram vehicles on the German market, but is gradually becoming a part of domestic vehicles as well. The system's task is to detect an obstacle in the vehicle's passage profile (by using a camera, radar, LiDAR, etc.), to alert the driver with a light or sound signal and, if necessary, to directly intervene in the driving of the vehicle. Anti-collision systems developed at the same time often work on inputs from LiDAR and cameras, supplemented by an IMU unit that records vehicle movements. LiDAR data is usually used for obstacle detection and camera

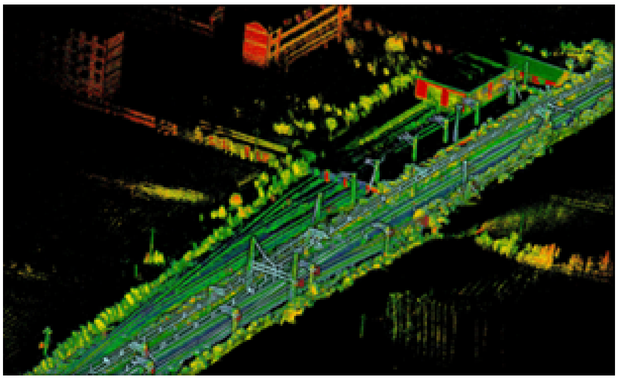


Figure 4. HD map of the railway track [17].

data is used for obstacle type recognition by image processing [15].

The environment database contains a static map database and thus provides the vehicle information about, among other things, the vertical and horizontal profile of the track, the track surroundings or the infrastructure along the track. The second part of the vehicle environment database can be described as dynamic, as it is modified in real time based on data from other vehicles in the system, dispatching, etc.

Today, localization is often solved by RFID and odometry technology for tram vehicles. However, for the use of autonomous vehicle localization, the technology of combining GNSS with odometry and IMU unit seems to be more suitable. By combining these signals, a relatively very accurate vehicle location can be achieved even in built-up urban areas within centimetres [16]. Another recently much discussed solution is the use of HD map technology, where the surroundings of the tram line are first scanned and stored in the vehicle environment database. The vehicle then scans its surroundings while driving and determines its location based on matching with the same objects in the database. This method is particularly suitable for urban environments, which are diverse in terms of objects and also have the risk of poorer GNSS signal reception. This method can thus refine positioning to GNSS [17]. This method of localization can be advantageously used for vehicles with an anti-collision system based on LiDAR data, as the same sensors can be used for obstacle detection and localization. A sample HD map of the railway track is shown in Figure 4.

## 4. Conceptual design of active wheelset steering control

As already mentioned in Section 2.2, the use of active elements is hindered by the issues of price, reliability and, last but not least, the safety of their application. These key factors have been taken into account in the design of the control concept for active elements in tramway running gear for the purpose of steering individual wheelsets into a curve. When travelling on a straight track, the actuator in its nominal position will be used to transfer the traction and braking forces from the wheelsets to the bogie frame.

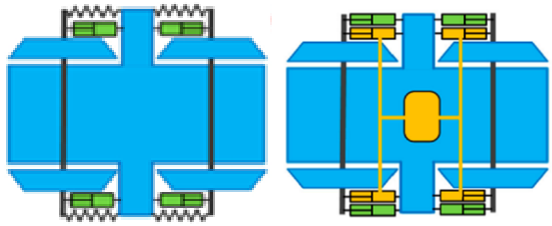
The design is based on the assumption that the active elements will be applied to the running gear of a tram vehicle equipped with an anti-collision system operating on the basis of object detection in the vehicle's running profile. For obstacle detection, it is assumed to use one or more LiDARs mounted on the front of the vehicle in combination with an IMU unit mounted on the same part of the vehicle. In addition to obstacle detection, the LiDAR data will also be processed to make the position of the vehicle on the track from GNSS more accurate by automatically searching for matches between the imaged surroundings and the surroundings stored in the HD map in the track database. Based on the found matches, the distance of the vehicle from objects, buildings, etc. will be evaluated and thus the position of the vehicle on the tram line will be determined unambiguously and accurately enough.

### 4.1. Location and type of active element

For the design of the active element control and its application, an active element is considered on each side of the wheelset located within the primary suspension with the function of steering the wheelset into a curve and transferring the driving and braking forces. In parallel with the active element, a passive primary longitudinal suspension is considered. This solution increases the requirement for the force exerted by the actuator and thus increases its weight and dimensions, which makes it more difficult to incorporate the active element into the running gear, but the main advantage is to ensure safe driving of the vehicle in the event of a failure or deliberate removal of the active element from service. In the event of a failure of the active element or its control, it is thus considered that the vehicle will be able to reach the currently serviced line at a reduced speed and then leave for a service operation in the depot.

Fu and Bruni [5] discussed in detail the comparison of dif-ferent concepts of placement and types of active elements in the primary suspension of the RS from the safety point of view. Their suggestion of the most suitable solution is shown in Figure 5 on the right and represents a variant where each actuator is duplicated by a different type of actuator in case of failure. Hydraulic and electro-hydraulic actuators are used. Although this solution appears to be the safest, it is doubtful whether it can be applied to the running gear of conventional RS, let alone trams, where the problems of incorporating new elements are compounded by the low floor level. Apart from the large installation dimensions, the high cost of the application and the complicated and demanding servicing of two different types and twice as many actuators can be expected.

The parameters of the selected actuator type will also enter the active element control algorithm. Based



(a). (b).

Figure 5. The considered concept of placing active elements in the tram bogie (A), the concept evaluated as the safest according to [5] (B).

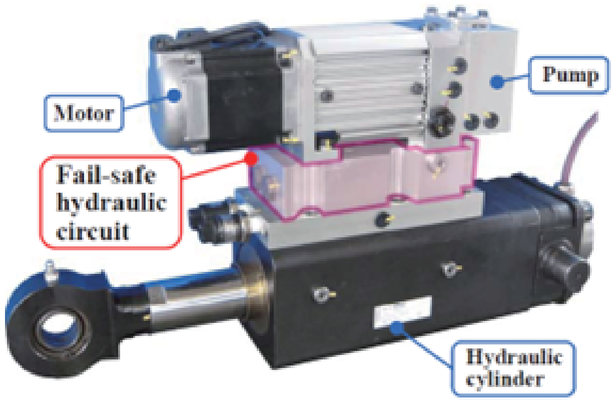



Figure 6. Solution of electro-hydraulic actuator with fail-safe hydraulic circuit [18].

on the actuator characteristics described in Section 2.1.2, an electro-hydraulic actuator can be tentatively considered. This appears to be a compromise between simplicity of control, installation dimensions, maintenance requirements and the ability to ensure safe operation of the actuator. Although the electromechanical actuator has the above mentioned characteristics better, it may cause mechanical jamming if the ball screw malfunctions, which will make further operation of the vehicle impossible. This is unacceptable in a tramway system, as the inability to operate one vehicle can block the entire transport system.

On the other hand, a safety circuit can be added to the elec-tro-hydraulic actuator to ensure that the actuator is taken out of operation if necessary. The design of an electro-hydraulic actuator with a fail-safe function has been addressed by Umehara et al. [18], see Figure 6.

### 4.2. Active element control

#### 4.2.1. Input variables into active element control

In terms of the cost of the active element application, a large part of the cost can be attributed to the sensors that need to be fitted to the vehicle to obtain the input variables needed for the active element control algorithm. Similarly, the issue of safety is largely linked to the correct sensing of input quantities. Algorithms based on the measurement of the lateral position of the wheelset in the track are difficult to apply in practice, due to the near impossibility of reliably measuring this quantity in such a demanding urban tram operation environment. For this reason, the control design of the active element is performed only with input quantities that can be obtained from the track environment database, i.e. the current radius of the passing curve, or with quantities that are already sensed on the current conventional vehicles – the vehicle speed. Vehicle speed is a quantity that is normally sensed with sufficient accuracy already on current vehicles and thus there is no need to install additional sensors. The radius of curve will be obtained from the track environment database based on the vehicle position, which will be obtained using HD mapping and GNSS. Thus, the same sensors located at the front of the vehicle for the ACS are used to locate the vehicle and there is no need to use additional sensors to obtain input variables for controlling the active element.

The design also assumes that other parameters of the track, obtained from the environmental database, could be input to the control algorithm of the active element. In particular, the track lateral clearance, track gauge (in small radius curves these parameters are often extended), superelevation or track quality (influence of vertical and lateral irregularities). Based on this information, the steering of the wheelsets will be controlled and the vehicle speed will be regulated. In order to obtain such detailed information about the infrastructure, it is necessary to find a tool that is able to map the track and its surroundings in sufficient detail.

#### 4.2.2. Basic active element control relations

As input variables to the control of the active element, the easily obtainable variables of the instantaneous vehicle speed and the radius of the directional curve $R$ will be input. In the next phase of development of the control algorithm, the plan is to include information about the gauge $g$ or clearance in the track $\sigma$ in the control of the active element. The optimal displacement of the actuator $\Delta L$ can then be expressed as:

$$\Delta L = \frac{a \cdot b}{R} + f(g, \sigma)\,, \tag{1}$$

where $2b$ is the wheelbase of the bogie and $2a$ is the lateral distance of the actuators steering the wheelsets, see Figure 7 [5].

Based on the optimal actuator extension, the required actuator force can be expressed as:

$$F = \left(k_x \cdot \Delta L + \frac{F_{t\_dv}}{2}\right) \cdot K\,. \tag{2}$$

The actuator must be dimensioned based on the requirement for the actuator displacement $\Delta L$, the longitudinal stiffness of the primary suspension $k_x$ and

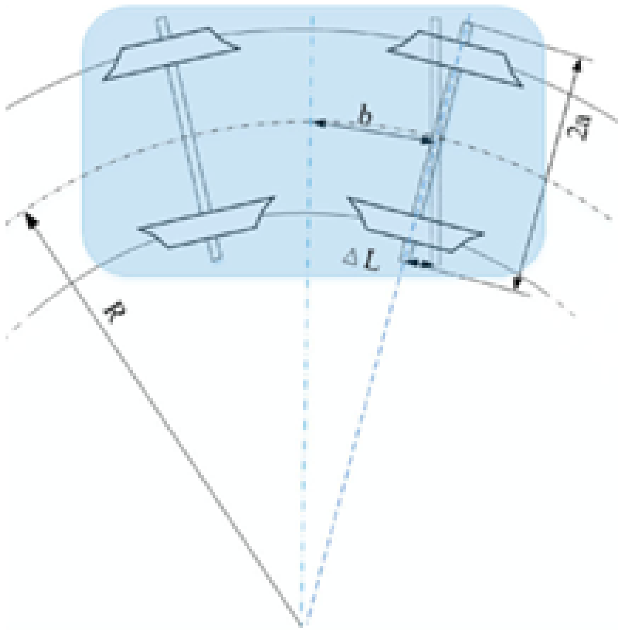



Figure 7. Bogie with actively steering wheelsets passaging through a curve [5].

then the transfer of the maximum traction force of the vehicle to each driven wheelset $F_{t\_dv}$, which will be transferred from the wheelset to the bogie frame via the actuators. The coefficient $K$ can be seen as a safety coefficient, the value of which will be further investigated to guarantee safe steering of the wheelset in any operating situation (empty/fully loaded vehicle, high/low coefficient of adhesion, etc.), but at the same time not over-dimensioning the actuator. Oversizing the actuator leads to an increase in its size and weight, making it even more difficult to place the actuator into the vehicle running gear.

Due to the positioning of the ACS sensor on the front of the vehicle, the individual wheelsets will need to be steered with a delay depending on the vehicle speed and vehicle dimensions (vehicle front length, bogie axle and wheelbase distances, length of individual articles). The extension speed and other actuator parameters will also have an influence and will be included in the control algorithm.

At the current design stage, the control is intended to be forward, which appears to be a suitable solution for this task. It has the advantage of being able to better adapt to different boundary conditions that may occur during operation [11]. The detailed design of the active element control will be developed in the next phase of the research.

### 4.3. Safety issues of active element application and its control

For the evaluation of system fault tolerance, inspiration can be drawn from the aerospace industry, which is significantly further along in this field. Comparisons in terms of risk priority number and based on the proposed methodology [5] of how to assess fault tolerance can be used. The risk priority number is determined based on two main criteria, the severity of the failure in terms of economic loss or personal injury and the probability of failure. A third additional criterion may be the ability to detect a failure using a monitoring system.

From the point of view of the safety of vehicle operation, the following factors and operating situations appear to be particularly problematic:

- Correctness of control input information (sensors),
- Actuator malfunction status:
  - ▷ Inactive actuator,
  - ▷ Actuator stuck in utmost position.
- Control algorithm error:
  - ▷ Maximum extension of both wheelset ac-tuators in the opposite direction,
  - ▷ Extending only one wheelset actuator in the opposite direction.

All these states need to be considered in the design of the active element, its control and the whole vehicle and then the system needs to be evaluated using, for example, the methodology mentioned above.

As in aviation, in the case of the design of the control of an active element, it would be advisable to obtain the key variables entering its control from two sources. The correctness of the main input information of the control algorithm, i.e. the curve radius, will thus be verified by comparing the value stored in the vehicle environment database based on the knowledge of the vehicle position with the measured and automatically evaluated value using sensors placed on the front of the vehicle primarily for the purpose of obstacle detection. This mechanism should prevent the vehicle from derailing due to a bad steering input variable. If these two values differ, the active element will be set to the nominal position and the vehicle will drive through the curve at a reduced speed. The leading of the wheelset shall be still provided by a active element, which, however, will not steer the wheelset.

In the event of a failure of the active element or its control, the actuator is disabled using the fail safe function. The leading of the wheelset is shall be provided only by a passive primary suspension designed with a longitudinal stiffness that allows the vehicle to pass safely through the curve with the smallest radius at a low speed defined by the derailment safety calculation. The longitudinal stiffness of the passive primary suspension shall be designed sufficiently large to allow a vehicle with a disabled active element to complete its service on the line (albeit at reduced speed and with accumulated delay) and to depart to the depot. At the same time, however, it must be taken into account that the higher the longitudinal stiffness of the primary suspension, the greater the force the actuator must exert in normal operation to overcome this stiffness when turning the wheelset into a curve. An increase in the required actuator force leads to an increase in actuator mass and volume and is therefore undesirable. Thus, the longitudinal stiffness of the primary sus-pension must be very carefully tuned to compromise the two described conflicting requirements.

## 5. Conclusion

In this paper, the design of the concept of controlling the active element in the tram vehicle running gear in order to actively steer the wheelset into a curve is presented. The aim of this application is to reduce the longitudinal and lateral slip forces at the wheel-rail contact when passing small radius curves, thereby reducing wheel and rail wear and noise and vibration emissions. The proposal attempts to reflect the problems that have so far discouraged the wider application of active elements in rolling stock running gear and outlines possible solutions that will be further addressed by the author.

For the control of active elements, it is proposed to use the subsystems of autonomous vehicles that are currently already installed on vehicles or can be expected to be installed on vehicles in the near future. These systems are in particular an anti-collision system, vehicle position detection using HD maps or the use of an environmental database. By exploiting these synergies, the cost of controlling the active elements is reduced, as there is no need for expensive sensors to measure the input variables, and the security of their use is also increased, as the input information is verified from two different sources. The aim is also to further supplement the forward control of the active element with additional track parameters that are stored in a detailed environmental data-base and have an impact on the vehicle's passage through the curve.

The article deals with the active steering of wheelsets using actuators located in the primary suspension of double-axle bogies of the classic concept of modern articulated trams. However, it can be assumed that future advances, in particular the reduction of the weight of the electric equipment and the mechanical parts of the vehicle or the autonomous driving will change the trend in the production of tram vehicles and will allow the creation of a light double-axle autonomous tram, where the actuator will have the function of steering the single-axle bogies when passing through a curve, and on the contrary, stabilizing the bogies when driving on a straight line. An example of such a vehicle concept is shown in Figure 8. In such a case, the design of the positioning of the element, which would probably be placed between the bottom of the vehicle carbody and the bolster or frame of the single-axle bogie, and the control algorithm would change, but the main ideas outlined in the paper remain valid. Inspiration for the design of a similar running gear can be drawn from the solution applied to the Cobra trams, see Figure 9.

In further research, the author wants to focus on creating MBS models of articulated trams of different

FIGURE 8. Possible solution for a two-axle autonomous tram presented by the company ŠKODA [19].

FIGURE 9. Running gear of Cobra tram [20].

concepts in the environment of suitable MBS software. The next step will be to create a detailed control algorithm for the active elements in Matlab Simulink and then link these two models. By cosimulation, it is possible to link the control of the active element to the vehicle model and to demonstrate the advantages of such a solution by simulating the driving of a vehicle with a controlled active element, to compare the lateral forces and wear during the passaging the reference track of vehicle with passive and active suspension, or to simulate failure conditions and evaluate their criticality. In the next phase, the failure states of the actuator and its control will be simulated by means of cosimulation and the safety of the presented design will be assessed.

The final goal of the research is to test the active wheelset steering design on an experimental roller rig.

## LIST OF SYMBOLS

$a$ half of the bogie wheelbase [mm]

$b$ half the lateral distance of the actuators [mm]

$g$ track gauge [mm]

$F$ actuator force required [N]

$F_{t\_dv}$ traction force transmitted by one wheelset [N]

$k_x$ longitudinal stiffness of the prim. suspension [N·m$^{-1}$]

$\Delta L$ required actuator extension [m]


## ACKNOWLEDGEMENTS

The research was supported by SGS21/112/OHK2/2T/12.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