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Measurements of Structure Gauge Limits on German Railways

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Summary

Knowledge of the gauge limits on operating railway lines is essential for safe railway traffic, as defined by the train timetable. The article presents, from a historical perspective, the development of diagnostic measurements. The first designs of measuring vehicles, which systematically reduced the time for diagnosing railway lines, including tunnels, are also presented here. The engineering and technology progress allowed the development of new surveying methods, successively implemented by upgrading diagnostic vehicles. Such measures simultaneously affected the quality of measurements, allowed measurements to be taken at increasing speeds, as well as to automatically create a gauge limit database on the DB AG network. This data is used, inter alia, for the codification of railway lines for the purposes of intermodal transport and special shipments.

Keywords: rail transport, DB AG railways, structure gauge, measuring wagons

1. Introduction

The first ordered information about structure gauges on German railways appeared in the "Work Regulations for Main Railways in Germany" of 1892 [1]. The second paragraph of the document contains provisions on the need to maintain a free space between the train and various structures, devices or machines, together with an indication of the need to maintain appropriate distances (Table 1). Annex A (Fig. 1) to the document shows the structure gauge for the tracks on the route and tracks at the train entry and exit stations, and Annex B shows the structure gauge for the remaining tracks at stations.

Table 1

Certain requirements from 1892 for structure gauges on German railways [1]

No.	Requirements
1.	All tracks on which trains run must be free of construction equipment and stored objects at least up to the limit of the free space necessary for the free passage of trains on the tracks, including within the stations for the entry and exit of passenger trains (Annex A) and on the side station tracks (Annex B). This must take into account track widening and lifting of the outer rail. In the case of tracks used for the entry and exit of military trains, a deviation from the free space limit (Annex A) in relation to the maximum step height above 0.760 metres is permitted at stations.
2.	Immovable objects protruding up to 50 millimetres above the top rail edge must generally remain at a distance of at least 150 millimetres from the inner edge of a rail head; if the distance from the running rail remains unchanged, it may be reduced to 135 millimetres. Within the track, their distance from the inner edge of a rail head must be at least 67 millimetres, but this distance may be progressively reduced to 41 millimetres in the middle of the mandatory track. On curved sections with track widening, the distance of immovable objects coming out of the track from the inner edge of a rail head must be greater by the size of the track widening than the above-mentioned dimensions.
3.	Depending on the type of application, the supervisory authority may authorize the limitation of the free space on the load tracks.
4.	The extent to which deviations from the prescribed space limit are permitted shall be determined by the Federal Council.

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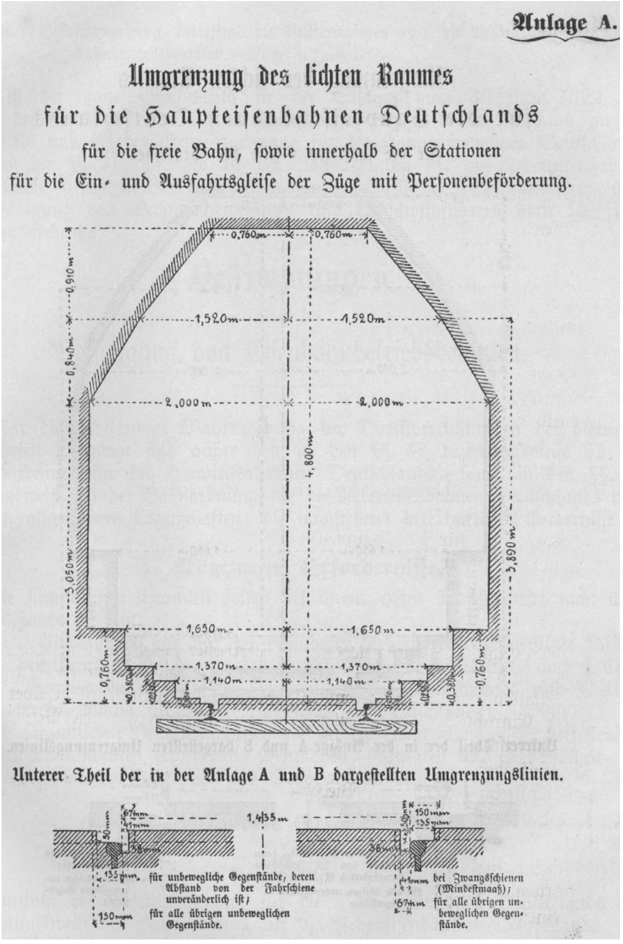

Fig. 1. The German railway structure gauge from 1892 [1]

Despite the development of railway technology, train traffic safety is also affected today by ensuring an appropriate structure gauge. As the line is operated and upgraded or track and subgrade aligned, situations may arise as continuous or point gauge limits[2]. In order to ensure the safe and optimised routing of trains with intermodal transport loading units and special shipments, it is particularly important to know the track geometry, the topology of individual railway lines and the inventory of this topography. A key criterion for safe train traffic is a free space between the trackside infrastructure and the train so that the train can run without obstacles. The knowledge of such limits on railway lines is essential for:

- Codification of lines for intermodal transport;
- Codification of lines for the transport of special (overgauge) shipments;
- Maintaining the distance of the platform edge from the track axis, defined by regulations, which is related to the gap size affecting the safety of access to a train.

In the past, before each special shipment, the railway management boards studied the conditions and transport options, determining the size of a carrier at the same time. Since such a procedure was not attractive to railway customers due to its duration, labour consumption and cost, the International Union of Railways (UIC) started work in 1984 to simplify it. It was then agreed that individual railways would define the conditions of transport on the lines for shipments with defined profiles by introducing the so-called gauge contour method, assigning specific codes to individual lines. A shipment reported by a customer was only required to be assigned to the correct pattern and to check the transport possibility on a particular route.

The development of railway line codes for the transport of special shipments required an inventory of gauge limits and building gauge records on lines intended for freight or mixed traffic. The gauge structure inventory consisted of locating it in the field and unambiguously determining the contour of all objects located next to or above the tracks, which violated the structure gauge, making it impossible to transport shipments with the maximum code [11]. The intermodal transport loading unit code had to be compared with the code numbers of the line sections on which the shipment was to be transported. Shipment transport was possible when the code number of the loading unit was lower or equal to the code numbers of individual line sections along the transport route [11].

With the development of measurement techniques, various methods for obtaining information on structure elements that violate the gauge contour have developed. From the historical point of view, the following methods can be distinguished:

- Manual – flawed with a very large measurement error, which affects both the accuracy of the measuring instruments used and the skills of those carrying out the measurements;
- Mechanical – using simple measuring devices (reference frames, protractors, etc.), usually placed on track geometry recording trolleys or wagons;
- Automatic, where, depending on the techniques used, the following solutions may be applied:
  - Photogrammetric, in which pairs of images are used;

[2] The gauge limits include: design of tunnels and bridges, platform edges, platform shelter roofing, fences and noise barriers, buildings (continuous limits) and semaphores, distant and shunt signals, indicators, pylons, footbridge supports and bridge pillars, switchpoint lamps, etc. (point limits).

- Light profiles set by laser light and recorded by a high-speed digital camera, and
- The use of a laser rangefinder or a laser scanner.

There are two measurement methods:

- Static – a measuring device is immobilised at the measuring point;
- Dynamic – measurements are taken while a diagnostic vehicle is moving.

Structure gauge measurements in Germany have been performed since the construction of the first railway line. Over time, both the railway network and stations have expanded. The rapid growth of trackside railway infrastructure made manual methods for measuring structure gauges insufficient. The current railway infrastructure (Fig. 2) requires accuracy and speed of measurements. This can be provided by the measuring equipment of diagnostic vehicles.

Fig. 2. With a developed railway infrastructure, it is easy to breach the structure gauge [3]

In order to use the measurement results for various operational solutions, they should be collected in a special database. Such a database was created back in the 1990s at the DB Netz AG branch in Mainz, where both the first solutions for measuring gauge limits and, on their basis, the principles of coding railway lines for intermodal transport and special shipments were developed. The aim of the article is to describe these measures on German railways together with a demonstration of the development of diagnostic vehicles for measuring gauge limits.

2. The beginnings of gauge limit measurements

In the first period of railway operation in Germany, the structure gauges were measured manually. No photos of such measurements have been preserved from that period. Static methods were characterized by low accuracy, high time consumption and manual registration of the results obtained. For this reason, it was not possible to create a database for the gauge limits on the individual lines. However, it is worth remembering that manual methods, using modern measuring instruments, are still used for single point measurements of gauge limits, when economic conditions do not prevent the use of modern measuring vehicles (Fig. 3).

The measurement of continuous limits in tunnels was a major problem on German railway lines. For this purpose, a vehicle based on the VT3802 railbus, decommissioned in 1960, was developed. After its

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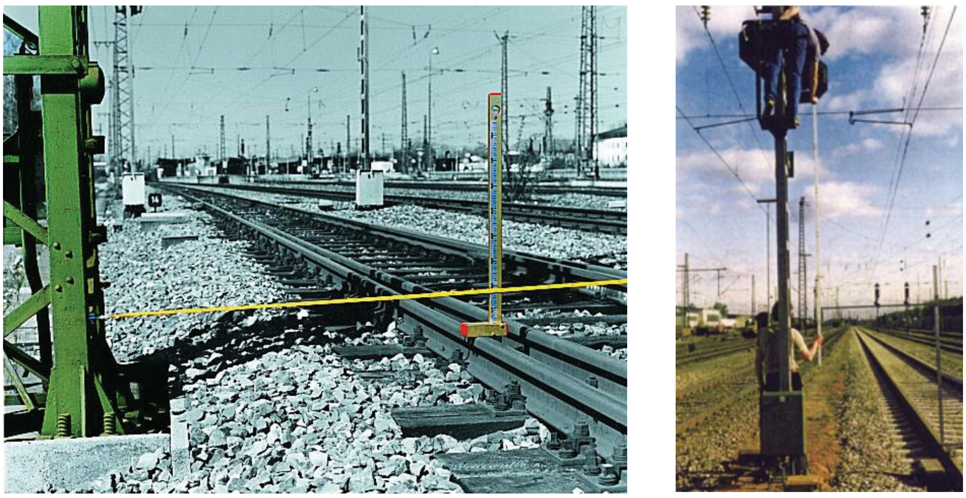

Fig. 3. Examples of manual measurement of gauge limits: a) pylon position [12], b) emaphore signal position [photo: Deutsche Bahn AG, Geschäftsbereich Netz]

adaptation to a measuring wagon, it was recommissioned in September 1965. The layout of the doors and windows remained unchanged during the adaptation work. In order to install mechanical measuring components, the wagon was extended by 1170 mm and 55 retractable and rotating probes were mounted on the elongated part to create working profiles. For this reason, it was colloquially called the "tunnel hedgehog." The probe mount design made it possible to remove and fold the probes if they were caught in the tunnel structure. The repositioning of the probes was transmitted to the measuring room by means of a cable system and recorded. In addition, the vehicle was equipped with a working pantograph (grounding), which was also used to determine the position of the traction wire (Fig. 4).

In tunnels with a traction line, the measurements were much more difficult. Frequent tunnel measurements with this system (referred to as TUM) were intended to identify places where dimensions changed over time. This was possible by comparing the results with previous measurements. In 1994, the measuring wagon was decommissioned and is now stationed at the Bochum Dahlhausen Museum Depot as an antique rail vehicle.

Improvement of measurement methods in terms of the speed and accuracy of measurements has resulted in the replacement of contact methods with non-contact methods. Before the decommissioning of the described measuring wagon, it had been replaced (since 1993) with the then modern measuring vehicle PROM, used to measure the profiles of continuous structures (tunnels, viaducts, bridges, and platforms). The vehicle was equipped with a laser measuring device, which in 1994 was supplemented with a mechanical template to reach areas inaccessible to laser technology. The template was pulled out by a sliding door in the vehicle wall. The pantograph of the vehicle (Fig. 5) had the same functions as in the previous vehicle.

Fig. 5. PROM gauge limit measuring vehicle (marked as 712 002) [photo: Erik Rauner]

The basic measurement system was based on a laser scanner with a beam distribution time available for different ranges. An industrial computer archiving the data was attached to the scanner. The measurements were performed at the speed of 8 km/h, which was a significant improvement in relation to the static methods used.

3. LIMEZ vehicles[3]

The improvement of measurement methods enabled implementation of the stereo photogrammetric DOLIM gauge measuring system. In 1994, a prototype of the new LIMEZ I measuring vehicle was developed as a result of collaboration between DB AG Netz in Mainz and FEW Blankenburg.

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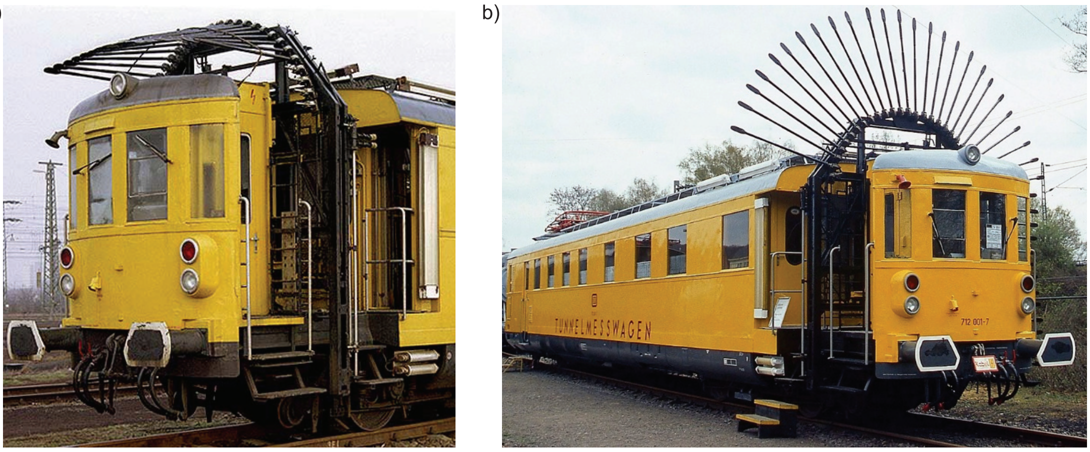

Fig. 4. Tunnel and trackside trench measuring vehicle on mountain lines (marked as PELIM 712 001): (a) folded top and side probes for tunnel contour measurement [10], (b) folded side probes and unfolded top probes [15]

[3] The name of the system is an acronym for the German name *Lichtraumprofil MessZug* (profile/contour/gauge measuring train).

Between two decommissioned diesel locomotives that were being rebuilt for a new measuring device, a special construction frame was built in, equipped with flasher lamps (night work), special-design cameras for taking pictures in all weather conditions and video cameras. The photos covered the gauge sections perpendicular to the track axis. Gauge limit measurements could be made at 20 km/h, and after the reconnaissance run recorded with video cameras, at 60 km/h. A measurement sheet printout recorded by the LIMEZ I vehicle devices is shown in Figure 6 [11], while the measuring vehicle is shown in Figure 7.

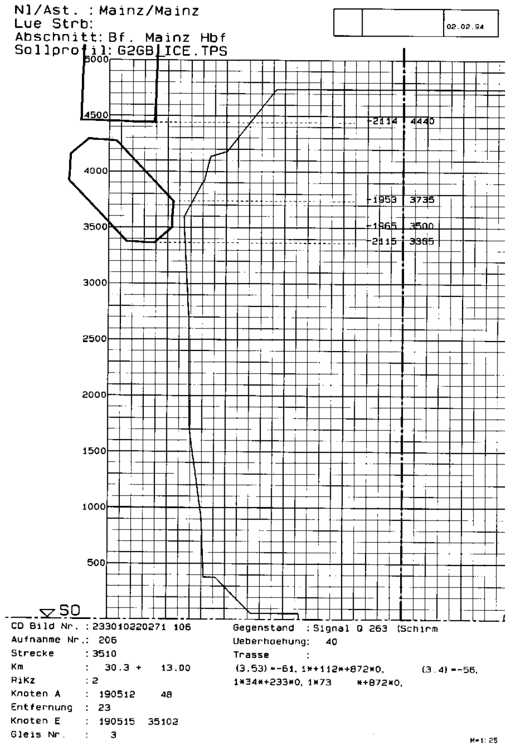

Fig. 6. Gauge limit measurement sheet made by LIMEZ I [11], during a run demonstrating the measurement principles [with the participation of the article's author (1994)]

The LIMEZ I train measuring system proved its worth on lines outside railway stations, but was not used to measure gauge limits at stations. The photogrammetric system used in this vehicle had the following characteristics [4]:

1. Short object detection time; there was no need to stop to parameterise the gauge limit. The parametric description could be assessed at a later time, based on images obtained in a given location. The required photographic material was prepared in seconds while the vehicle was in motion. Thanks to this, the measurements were not inconvenient for the line operation.
2. High accuracy (accuracy was provided by measuring cameras).
3. High degree of measuring point density registration selection.
4. Option of measurement documentation archiving in the form of films and photos.
5. Non-contact measurement, eliminating troublesome bottleneck marking, which was characteristic of other, existing measurement techniques.

These features led DB AG to consider the photogrammetric method of the time to be the most relevant for measuring gauge limits on railway lines.

In 1997, METRONOM Gesellschaft für Industrie Vermessung mbH undertook the development of a new version of the measuring vehicle, called LIMEZ II, commissioned by DB AG railway. The vehicle had a motor car (712 101 5), equipped with two driver's cabins, a computer room, a workshop, a room for equipment, sanitary facilities and a lounge for the measuring team. The vehicle could carry 10 people. A measuring wagon (713 001-6) was attached to the motor vehicle. The measuring set is shown in Figure 8.

It was assumed that the vehicle would be the primary source of data on gauge limits on the DB AG rail network and on the traction wire height on electrified

a) b)

Fig. 7. LIMEZ I measuring vehicle: a) view of the frame with measuring instruments, b) vehicle view [photo: author's

Fig. 8. LIMEZ II measuring set: a) screen frame of the measuring wagon [photo: Thomas Linberg], b) equipment of the measuring wagon frame [photo: Thomas Linberg], c) general view of the LIMEZ II measuring set [8], d) tunnel measurement [14], e) front of the drive unit of the LIMEZ II measuring assembly [photo: Thomas Linberg]

lines. For this reason, the vehicle was equipped with the latest image registration technology devices. These include, for example, colour video cameras on the wagon roof to record the route, and other cameras to orient the measuring frame of the vehicle to the track axis. All image signals were marked with a time code (time marker), allowing synchronization of all recorded signals, and the measurements were supported by a computer system. In addition, strong halogen headlamps were installed in the vehicle for use after dark or in tunnels. Measurements with this vehicle started in 1998.

The measuring wagon was a specially-designed platform with measuring devices, which included: video cameras, two digital cameras and a track axis measurement system. These devices were connected to the computer on which the readings were recorded with special software. As described in [9] (…) *Synchronized calibrated small format cameras were at* *a distance of about 2.5 m. They were equipped with lenses with a focal length of 31 mm and a grid*[4] (…). *At a distance of 11 m from the cameras, there was a frame with 22 adjustment points placed on it, located in three planes to the photogrammetric base. Objects located 3 m in front of and 3 m behind the frame with photo control points farthest from the cameras were measured in the photos, in a 20-cm strip inside and outside the gauge contour projected onto the photos. The location of a possible obstacle referred to the track axis in relation to the route chainage (reading from a video camera). The photos were measured semi-automatically, with the use of PICTRAN L software specially adapted to the gauge measurement* (…), [Figure 9]. *Grid crosses, adjustment point signals on the frame and homologous points in the area of interest were measured. The final verification of potentially colliding objects was performed by the operator, marking it with a contour added to the gauge vector. The result of the measurement was a database containing, among other things, information on the type of collision structure, its location along the track, photo numbers, etc.* (…). A full description of the measurement principle and result recording is discussed in some articles [4, 9].

Already at the moment of the LIMEZ II vehicle being commissioned, work was underway on another, upgraded version of the measuring wagon, called LIMEZ III[5]. In 2006, two 614 wagons (045 and 046) were converted into a gauge limit measuring train (719 045/046), Figure 10.

The LIMEZ III vehicle is used to measure the structure gauge contour with free space limits above and beside the tracks that may restrict train traffic. The measurement results were used to check and possibly verify the line codes for intermodal transport and special shipments that exceed the loading gauge. The vehicle is equipped with two laser measuring scanners, which are fitted to the front of the 716 046 wagon and allow measurements to be taken at train speeds up to 100 km/h. In 2012, the vehicle was equipped with additional devices for measuring the traction line and the track geometry [12] for more economical measuring.

Fig. 10. LIMEZ III measurement train [9]

The standard measuring device is (…) *a rotating phase scanner, scanning in a plane, with a distance measurement accuracy of < 6 mm, measuring 3600 points per profile. When using a double-mirror scanner with a single head, the measuring density is 300 profiles per second, with 4 heads it can reach 1200 profiles,*

Fig. 9. Left and right image created by the LIMEZ II photographic system [13]

[4] The grid allows the orientation of the measuring camera to be determined and reduces image deformation.

[5] German railway enthusiasts have not yet found out why the working name LIMEZ III has never appeared on its body.

which, at the maximum train speed, gives profiles every 2÷3 cm. The system also includes video cameras which record the measurement course and identify collision structures, location of profiles, or stereo measurement of selected structures (…) [9]. The vehicle front with the measuring system equipment is shown in Figure 11.

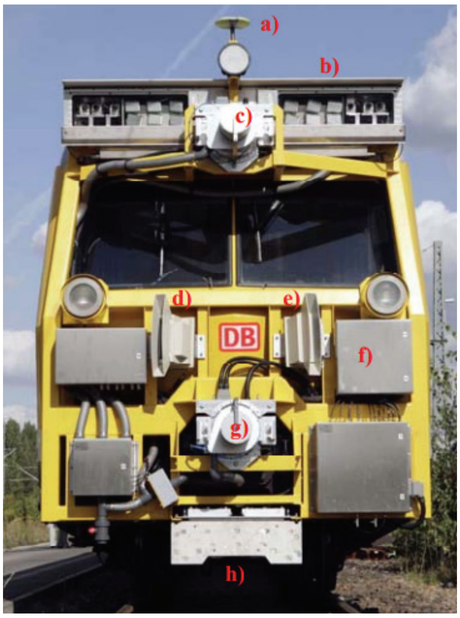

Fig. 11. 3D scanning system in a measuring wagon [2]: a), f) GPS and INS systems b) video and stereo photogrammetric system, c), g) dual laser scanners, d), e) distance scanners, h) track marker

The measurement method for the gauge limits uses several important elements, such as the profile contour adopted in the calculation rule (Figure 12) and the measurement principle of coordinate system tracking (Figure 13). The measurement system is equipped with the latest versions of GPS and INS (the positioning system uses a laser gyroscope and accelerometers), which enables measurement result localisation with an accuracy of a few centimetres.

The diagnostic vehicle system provides the following accuracies [7]:

- Track measurement: width measurement accuracy: 2 mm, height: 2 mm, gradient: 1 m/1 km, radius: 1%.
- Ambient measurement: width measurement accuracy: 40 mm, height differences: 4 mm, relative: 20 mm.

Despite the fact that the measurement speed of track-side elements by two laser scanners is very high and a gigantic number of measuring points is generated, the system cannot capture all narrow structures. Objects, such as indicator signals several millimetres thick, may be in "dead gaps" where it is not possible to measure with the main laser scanners. To fill this measurement gap, an additional system based on video cameras is used for photogrammetric evaluation (stereo system). It is composed of four digital black and white cameras each with a resolution of two megapixels. Each of the two cameras is matched with identical image areas on the right and left side of the track (Fig. 14).

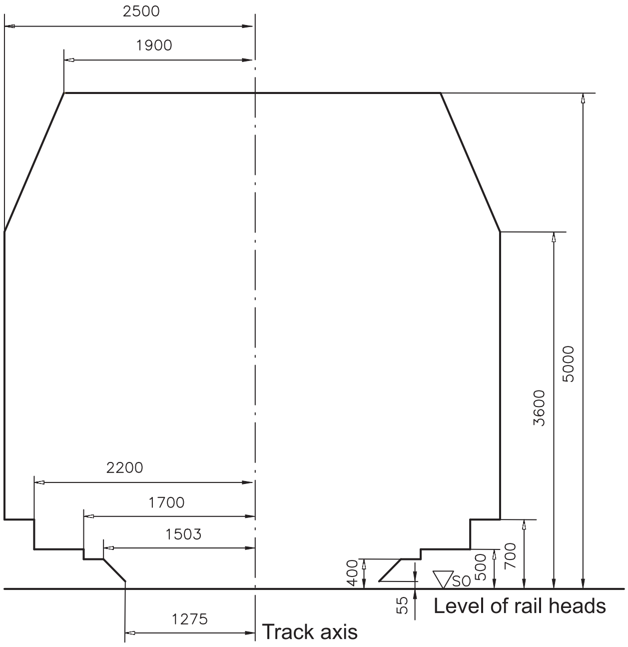

Fig. 12. Outline of the profile calculation rule; author's study based on [5]

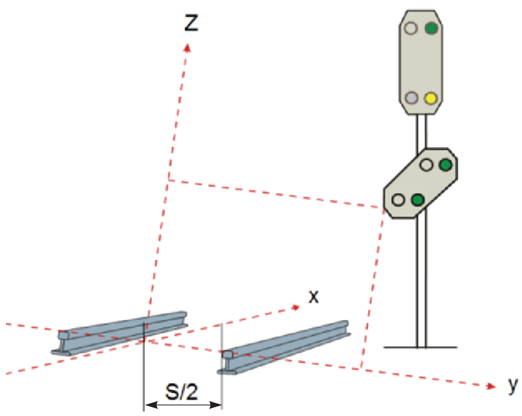

Fig. 13. Coordinate measuring system [5]

The digital colour camera with a resolution of two megapixels, a wide-angle lens, and cameras for route recording, used during measurements, support the evaluation of the laser scanner data. The colour camera is installed at the other end of the vehicle, so that it always takes pictures in the direction of travel (front and rear of the measuring vehicle), making it possible to identify any infrastructure located near the railway track. Black and white photos are taken every 2 m, and colour photos every 4 m.

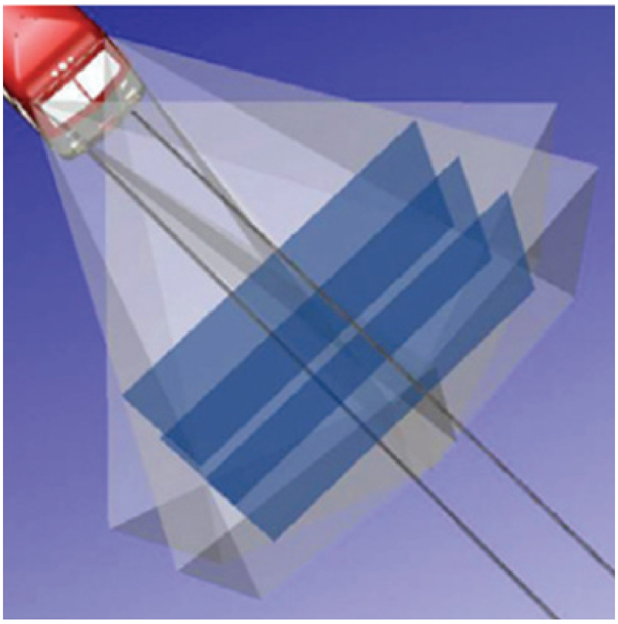

Fig. 14. Video measuring system recording configuration [16]

In order to minimise blurring at a measuring vehicle speed of 100 km/h, i.e. approximately 28 m/s, the measurement must be performed with a very short exposure time (less than 1/1500 s). This requires adequate lighting both during the day and at night as well as in tunnels. Lighting in the human visible light frequency band is excluded, as this means, for example, dazzling passengers on the platforms with a measuring vehicle. Necessary lighting is provided by special infra-red diodes, which are used as flasher lamps (working in pulse mode), synchronized with the cameras taking pictures. A dedicated adaptive exposure control sensor [16] has also been developed to accommodate different lighting situations.

The LIMEZ III diagnostic vehicle also uses: two VDS cameras located at the front and rear of the vehicle taking 20 images per second with a 16 × 5 field of vision, and two VMS cameras at the vehicle front, showing a wide range of terrain in front. Overlapping images from these cameras enable stereo measurement. Light scanning was used to measure the rails, where the light profile (for each rail) is recorded by CCD cameras [7]. The video measurement range is shown in Figure 15, while the scan of the rails to determine the track axis (track marker) is shown in Figure 16.

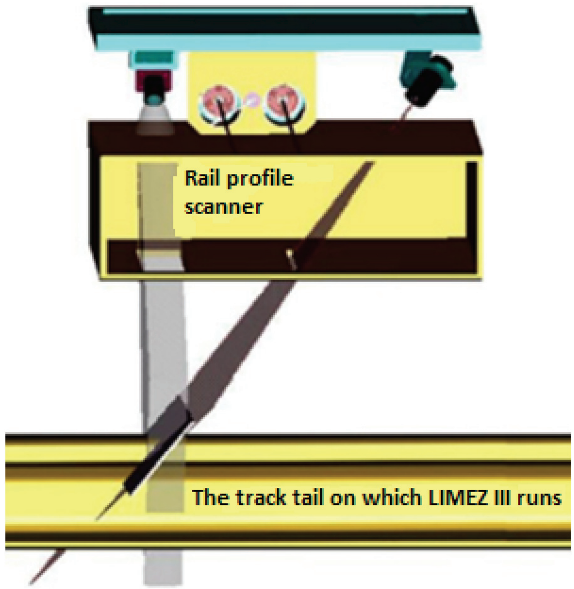

Fig. 16. One of two rail profile scanners for determining the track axis [16]

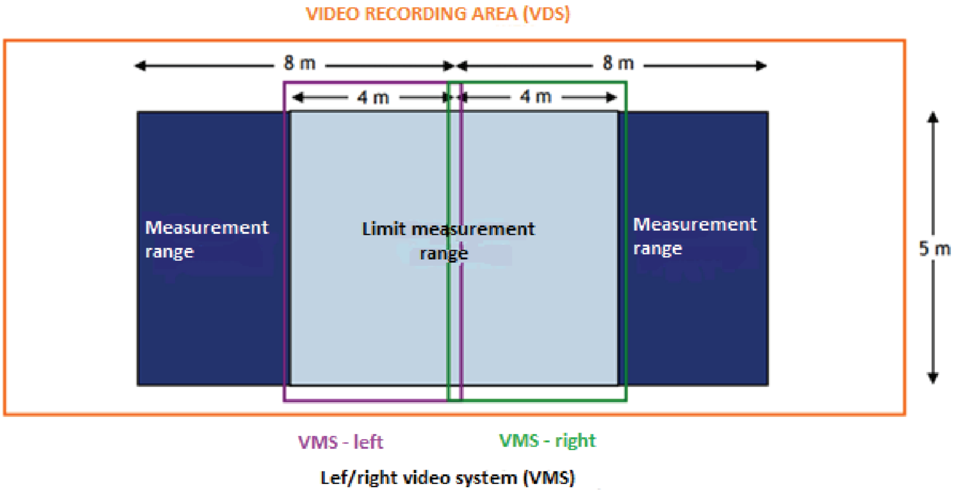

Fig. 15. Video measuring range (recording area) [5]

Two rail profile scanners, referred to as track markers, attached to the lower part of the vehicle underframe, are used to determine the track axis. Laser triangulation sensors are permanently installed in one housing. Two rails are marked with a thin laser line. The special camera maps the laser line at a known viewing angle, providing automatic evaluation of images and positioning the measuring system to a precisely defined (1 mm) track axis [16].

In addition to the readings taken by the video-assisted rotating laser scanners, measurements are also taken by two side laser scanners, directed outside both sides of the track (Figure 17). The video measurement configuration is shown in Figure 18 and the video measurement device in Figure 19.

Figure 20 shows several results obtained during measurements with a diagnostic vehicle. The surveyed object is marked with a yellow arrow.

4. Summary

An overview of the operating systems used to measure gauge limits on railway lines in Germany shows that measuring tools have changed with the development of the railways. Knowledge of the gauge limits on railway lines has, over time, begun to affect the safety and capacity of railways, as well as the quality of service provided. The development of diagnostic devices has been focused on measurements performed by mobile diagnostic devices at increasing speed of measurement and maintaining high accuracy of the obtained results. In retrospect, it can be said that operating systems are based on three groups of methods [6]:

- A method using a laser rangefinder and laser scanner (LiDAR);

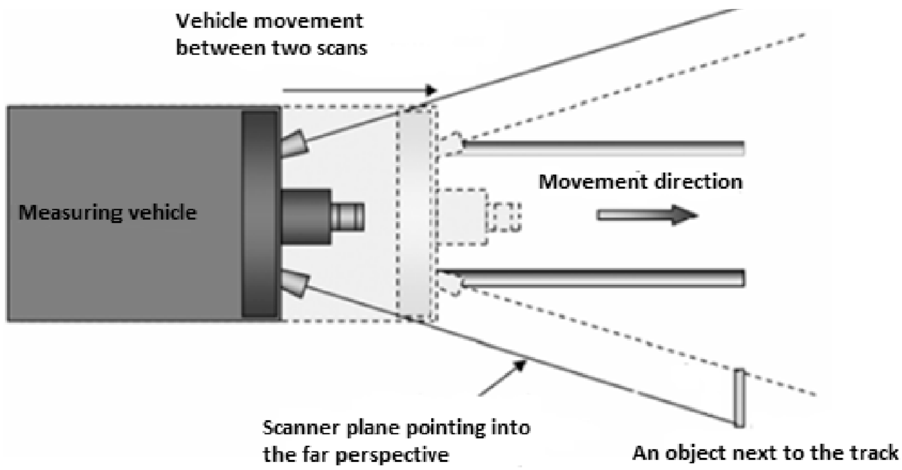

Fig. 17. Top view of the scanning system with side scanners covering the front of the measuring vehicle [2]

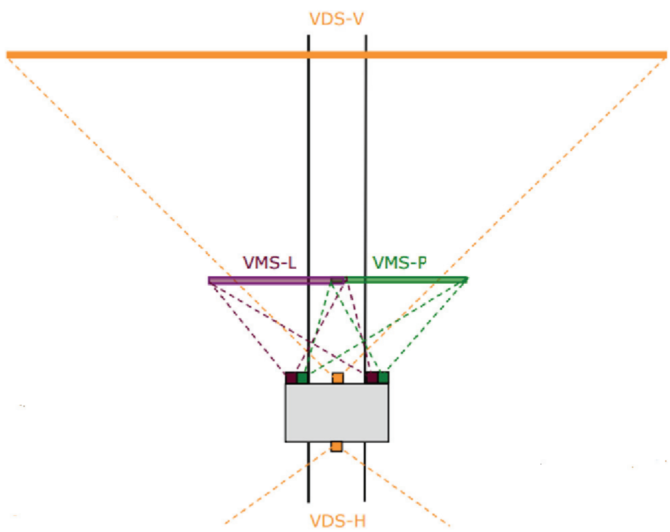

Fig. 18. Video measuring system (recording configuration) [5]

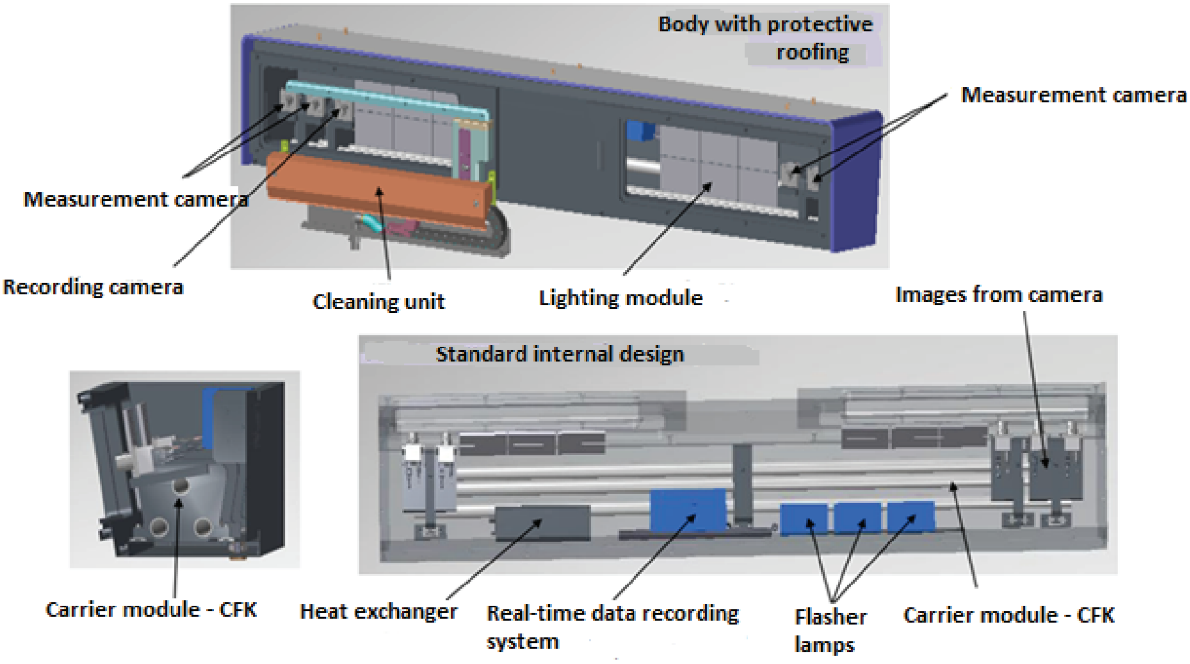

Fig. 19. Video measuring system device view [5]

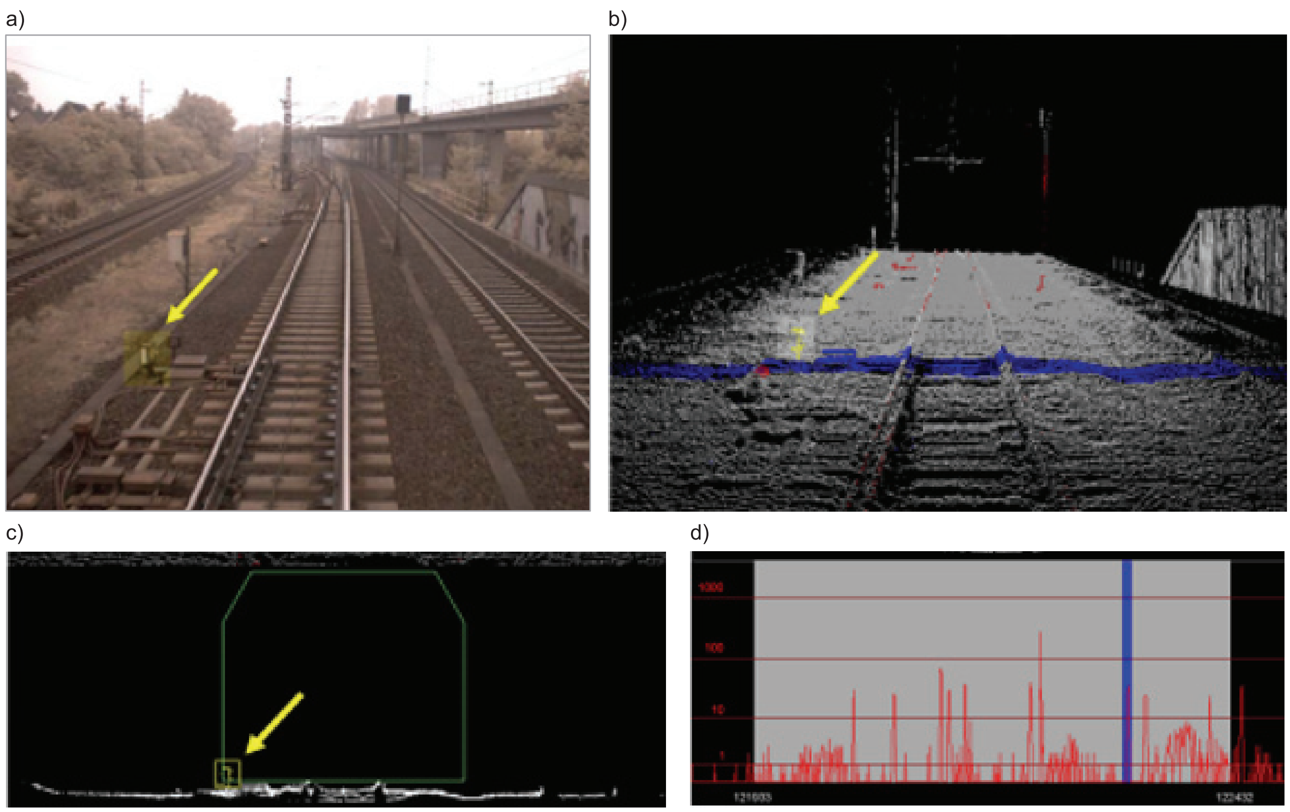

Fig. 20. Creation of measurement documentation [2]; a) video recording image, b) a 3D point cloud, c) view of a gauge contour with the surveyed structure, d) violation statistics with the number of points inside the reference profile

- A photogrammetric method using a stream of images, and
- A method involving light profiles projected by a light laser and recorded by a high-speed digital camera.

The most advanced systems combine these measurement methods. It is worth noting that (…) *the stereo photogrammetry method has practically reached its developmental end* (…). *Stereovision systems are* *characterized by high accuracy and, at the same time, by a lack of full measurement automation options. Photos must be viewed by a person who selects places to be measured on a stereoscopic model. Since the photos are taken in an interval of several metres, their number is large and the responsibility of the observer is very high* (…) [7]. The available literature shows that it has not yet been possible to effectively automate the process of developing stereoscopic images. It is very possible that this is due to the specificity of the railway track corridor, in which (...) *the structures being measured are relatively small, often slender, comparatively distant background is recorded between them, which rapidly changes the depth of the stereoscopic model* (...) [7].

The registration of laser profiles provides greater options for automating the procedure to determine gauge limits on railway lines. The profiles recorded in the images in this method are automatically vectorized and grouped into a sequence of sections, which then allows the detection of collision sites in the gauge plane. This method is currently used by many railway administrations, including Italian, French, Austrian, Swiss, Czech and Russian railways.

Among the many measurements of different railway parameters performed on DB AG, measurements of gauge limits were and are implemented with separate diagnostic equipment. So far, there is no information that this rule will change in the coming years.

A great deal of information concerning, among other things, the development of testing methods related to non-contact methods of measuring gauge limits is described in Polish publications [6, 7] and a lot of information is provided on German-language websites (*Photogrammetrische Messungen* – photogrammetric measurements, Lasermessungen – laser measurements).

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