# The Use of Terrestrial Laser Scanning for Post-Accident Deformation Evaluation of a Train Wagon

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**Keywords**: Terrestrial Laser Scanning, 3D model, Change and Deformation

## SUMMARY

Terrestrial laser scanning (TLS) surveying has been successfully used in recent years for crime scenes and accidents enabling to obtain a complete 3D topographic documentation of the location and the objects present, including metric information and images. The purpose of the project described in this paper is to produce a digital record of a railway accident and provide high accuracy geometric information so that the causes of the accident can be explored as well as the restoration of the damage. Specifically, the paper describes a recent rail accident which involved a train from the Urban Rail Transport Company of Athens, Greece. The unique, complex shapes of the damage on the wagons made capturing and analyzing the full geometric detail of the deformations using traditional methods such as tape measures and mechanical profilometers very difficult. The use of terrestrial laser scanning was implemented and the workflow of the data capture and processing is described. An examination of a dataset from a damaged wagon is presented along with some results illustrating the modelling opportunities that are possible. From the detailed high accuracy 3D model of one train wagon geometric analysis results due to deformation are also presented.

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## 1. INTRODUCTION

Accident reconstruction analysis is very helpful for experts of different types of vehicle accidents because it contributes towards the determination of the factors causing the accident. Through the analysis of vehicle accidents essential information concerning the vehicle is obtained which can be of help in modifying the structure in order to improve its future safety.

Recovering a vehicle scene accident can be of two types; in situ documentation of the actual accident scene immediately after the accident and a post-accident mapping of the vehicle being involved. The former type involves usually automobile traffic accidents where it is very advantageous to know the condition or state of a car and to analyze data of, for example, acceleration, angular velocity, etc. of the vehicle at the accident occurrence time. Transitory events, e.g., accident scenes in particular, must be accurately and quickly recorded in situ prior to the removal of the affected vehicles for purposes of later reconstructing the relative position of various features and objects and their relationship to fixed positions at the site. The second type refers to the detailed mapping of vehicles after their transfer from the scene of the accident to special repair sites. In the field of accident reconstruction, it is often important to measure the deformation after a crash has occurred usually of large sized vehicles (e.g. train, truck). The measurements must be of high detail and accuracy and can lead to conclusions including whether the vehicle is repairable, what kind of repair is needed and whether it is effective. Also the data provide useful information including energy calculations for speed loss, measuring roof or other structural deformation, analyzing seat or seat belt component positions, frame or unitized body structure deformation, and for estimating the actual post crash condition of a vehicle prior to the damage.

The traditional methods of reconstructing accidents manualy are the “baseline” (or “baseline/offset”) method in which an imaginary grid or coordinate system is established overlying the accident scene with a first axis which was fixed between two permanent objects and were utilised as control points (e.g. traffic signs, utility poles and the like) and then manually a series of distances along the first axis to establish various positions (e.g. the abscissa) are measured. The resulting “x, y” values can then be utilized to reconstruct the accident scene on a grid for subsequent investigation. An alternative technique is the “triangulation” (or “range/triangulation”) method which requires that a pair of fixed object or position control points also be selected and the distance between them established by manual measurement. The distance to both of the control points for each point of interest (e.g., the left front tire of the first vehicle, the right front tire of the second vehicle, and the like) is measured and the resultant data are utilized to calculate the “x, y” position of the various points with respect to the control points. Reconstructing accidents by using the above methods are time consuming and inaccurate at times (e.g. Martinez, 1985).

Current commonly used tools include total stations and laser rangefinders. Satellite positioning techniques are successfully used as well, however, only in areas where there are no obstructions. With the advances in computer vision, 3D measurements are used offering the possibility to analyze and evaluate visual information gained from accidents scenes in a more faster and accurate way. Close-range digital photogrammetric systems and terrestrial laser scanning can provide fast and accurate data acquisition enabling 3D documentation of the accident site in a much safer manner, since data are collected from a remote location, which enables uninterrupted work of other units at the scene (e.g. Varkonyi-Koczy et al., 2014; Behring et al., 2011; Randles et al., 2010; Fraser, 2008). The most attractive attributes of both methods are that the accident scene can be recorded in a very short time and that the acquired data provide a permanent archival record that will support further measurement after the incident. These methods are nowadays used widely in countries such as Australia and US to map accident scenes. In practice however, police departments of various countries use different types of measuring equipment depending on the scene complexity. For example, the methods of reconstruction used by state police agencies at the US national level are in the order of 39% for traditional methods, 36% for total station surveying, 12.5% for laser scanning and 12.5% for photogrammetry (Watson 2005).

This paper deals with accident reconstruction after a crash has occurred in order to measure the deformation of the vehicle using terrestrial laser scanning. Laser scanners offer a highly effective method for collecting massive volumes of precise, high-resolution 3D information for deformation monitoring applications. Unlike traditional surveying techniques that collect hundreds of discrete data points over a period of several days, laser imaging is capable of capturing several million 3D points in just a few minutes. The specific example described herein refers to a recent rail accident in the Urban Rail Transport Company of Athens, Greece whereby a stationery train at the main parking and manoeuvring area got loose and rolled at a speed of about 40km/h past a safe wall and onto the main street killing one pedestrian and injured several more. The unique, complex shapes of the damage on the wagons made capturing and analyzing the full geometric detail of the deformations using traditional methods such as tape measures and mechanical profilometers very difficult. The use of terrestrial laser scanning for the data capture and the creation of a high accuracy 3D model of the train is described. Section 2 provides information about the train accident details and Section 3 describes the data capture and modelling. In Section 4 results regarding the deformed wagon are given between pre- and post- accident in 2D and 3D. Finally, concluding remarks are given to summarise the use of this technology in complex accident investigation applications.

## 2. TRAIN ACCIDENT BACKGROUND

Trains remain one of the safest ways to travel in Europe, where millions of euros have been sunk into rail safety and infrastructure. Based on the European Railway Agency, trains are far safer than most other forms of transportation within Europe and about as safe as air travel, as seen in Table 1 (European Railway Agency, 2013).

| **Transport mode used by user** | **Fatality risk (2008-2010)<br>Fatalities per billion passenger km** |
|---|---|
| **Airline passenger** | 0.101 |
| **Railway passenger** | 0.156 |
| **Car occupant** | 4.450 |
| **Bus/coach occupant** | 0.433 |
| **Powered two-wheelers** | 52.593 |
| **Vessels passenger** | N/A |

Table 1. Fatality risk of passenger using different mode of transport (2008-2010) (ERA, 2013)

The same study by the European Rail Agency of the train accident rate within the European Union over time shows that the rate of fatal incidents has been declining steadily and is currently hovering around one incident per billion train kilometers travelled and the majority of these involving cars crossing train tracks and not mass derailments such as the rail accident in Spain on July 2013. In fact, train incidents are classified in three groups: collisions with objects (i.e. grade-crossing incidents), single train events (i.e. derailments), and train-to-train collisions (Jacobsen, 2008). However, an interesting point is that unlike in the car industry, there are no European safety regulations covering vehicle design in the railway industry.

There is little understanding of how the different parts of train structures actually stand up to crashes, and there have been few detailed international safety standards that train operators can specify to the builders of their vehicles (Pereira and Ambrosio, 1995). All countries conform to the recommendations of the International Union of Railways on crashworthiness, but they adopt different structural specifications which all pay little attention to the effects of one train riding over another in a crash, one of the main causes of passenger injuries. Trains have in most cases been designed to crumple in a crash, to dissipate the enormous amount of energy released by the impact. This has meant that trains are usually very unfriendly places for people in crashes. Railway companies are, however, increasingly insisting on designs to high safety standards, and various proposals have emerged in recent years for how trains should stand up to impacts. Within Europe, the requirements to ensure the structural integrity of coach bodies comes mainly from the International Union of Railways (UIC) and the affiliated European Railway Research Institute (ERRI). For example, British Rail proposed that the energy of a collision should be absorbed first by deformation of the end wall of a vehicle before other parts deform.


Figure 1. The train accident on 22 February 2008 (Pireas, Greece)

The specific passenger train accident described herein occurred on the 22nd February 2008 at 12.30 pm, in the depot (parking and maneuvering) Station of Piraeus in Greece. The train of the Urban Rail Transport Company of Athens comprised six carriages and was stationery and was undergoing its routinely cleaning internally the carriages. Due to human error the lever -brake of the train was released and the train started moving and changed track lines covering a distance of about 300m. Then it started cruising uncontrolled at a speed of 40km/h and collided to a wall fence. The train dragged part of the wall and continued its unregulated course towards a busy street with cars and pedestrians (Fig. 1). The end result of this was the human loss of one pedestrian, injury of six cleaners working in the train and serious damages on the protective wall and the train itself.

## 3. DATA COLLECTION AND PROCESSING

From the six carriages of the train involved in the accident the first three suffered major damages which were not repairable, the fourth suffered extensive damage but was repairable, and the last two had no damages. For this reason, it was important to have a full geometric documentation of the exterior and interior of the fourth carriage and provide a deformation model in order to assess the damages.

The geometric documentation of the damaged train carriage performed with terrestrial laser scanning. A total number of four scans were acquired from different stand points by using a Leica Scanstation 2 scanner. In particular, three scans were acquired from the ground, whereas for remaining one the sensor was placed on the roof of a building close to the investigated scene. The use of reflective targets placed on the surface of the carriage enabled the georeferencing and registration process of the collected data (Fig. 2). Also, it is seen in Figure 2 that in order to avoid gaps and noisy data in the final model due to the large number of window openings, these were covered by paper. The scan acquisition was accomplished within 5 hours, obtaining a global number of about 9 million points.

The scan registration was performed in a fully automated way using the proprietary software Cyclone with precision of 3mm. The processing includes the transformation of all point clouds from the local scanner coordinate system into the common coordinate system supported by the use of targets as tie points. This is achieved by a 3D Helmert transformation without a scaling factor. The registered point cloud of the object is shown in Figure 3.

The modelling process was performed in the proprietary software Geomagic. The first step involved the filtering by removal of outliers and noise from the dataset. Redundant information is also removed at this stage. For the noise removal, the free form shape algorithm was chosen after several trials. The statistics for the noise removal were for the maximum distance 0.0116m, the average distance 0.0011m and the standard deviation 0.0009m. The full point cloud was also resampled by about 10%. This essentially reduces file sizes and ultimately lowers processing times for modelling algorithms.

Figure 2. Reflective targets placed on the damaged train carriage

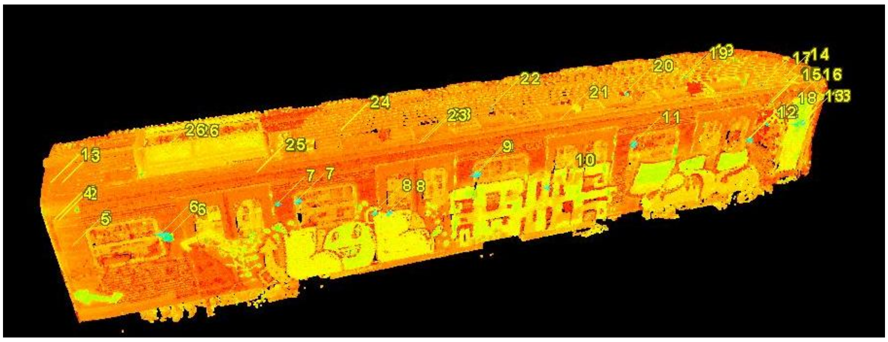
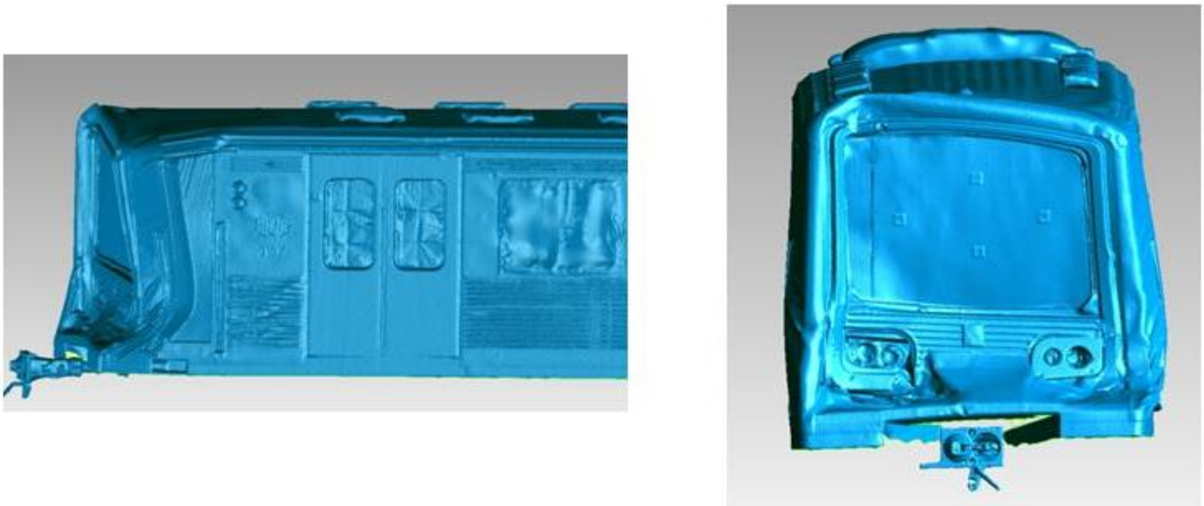


Figure 3. Registered point cloud of the damaged train carriage

The creation of the TIN (triangulated irregular network) was performed automatically in Geomagic, but the resultant surface had many gaps and other irregularities. For this reason, a process is followed which fills the holes taking into consideration the complex geometry for specific parts of the object. The final model was also reduced further in size by 20% totalling to about 3.3 million triangles. Views of the final wagon model are shown in Fig.4. Figure 4a presents a side view and Figure 4b gives the front part of the wagon which suffered most of the damage.



(a) (b)

Figure 4. Views of the 3D wagon model

## 4. DEFORMATION MEASUREMENTS

In traffic accident reconstruction, one of the main objectives is to study the deformation of the damaged vehicle in order to establish useful parameters, for example the pre-impact velocity and trajectory. But due to the variety, complexity and instantaneity of the vehicle accidents, the precision of the quantitative analyses using manual methods is fairly low. For this reason and with the availability of computer simulation models the deformation analysis is based usually on the theory of elasticity–plasticity. Many researchers also consider the use of finite elements and neural networks in the processing software (e.g. Zhang et al., 2007; Zhong, 1993). Clearly, for all the above analysis an accurate model of the damaged vehicle is required and terrestrial laser scanning can provide the necessary data in order to create a 3D model.

The 3D model created for the wagon was used in a post-damage analysis to quantify crush by measuring a limited number of profiles and sections. Crush along one horizontal axis and front-end shift or longitudinal bowing in a side impact are also measured. Also, the measurements from the model were compared with respective conventional measurements. The conventional measurements were carried out by the experts of the Urban Rail Transport Company of Athens (ISAP) in 2D by using tape measures and mechanical profilometers at specific sections along the wagon and height differences in specific parts of the frame. For each section, two measurements were taken, one at the lowest point (noted as ‘a’) of the wagon frame and the other at the top part of the wagon frame just before the start of the curvature of the roof (noted as ‘b’). In Table 2, a comparison is given for the values of ‘a’ and ‘b’ for ten sections between the measurements provided by the 3D model and the ISAP.

| | **3D model** | | **Conventional** | | **Differences** | |
|---|---|---|---|---|---|---|
| | a(m) | b(m) | a(m) | b(m) | a(m) | b(m) |
| 1 | 2.745 | --------- | 2.758 | ----------- | -0.013 | -------------- |
| 2 | 2.742 | 2.573 | 2.748 | 2.576 | -0.006 | -0.003 |
| 3 | 2.747 | 2.58 | 2.751 | 2.579 | -0.004 | 0.001 |
| 4 | 2.751 | 2.563 | 2.749 | 2.578 | 0.002 | -0.015 |
| 5 | 2.749 | 2.579 | 2.749 | 2.574 | 0.000 | 0.005 |
| 6 | 2.739 | 2.567 | 2.749 | 2.574 | -0.010 | -0.007 |
| 7 | 2.756 | 2.581 | 2.75 | 2.574 | 0.006 | 0.007 |
| 8 | 2.749 | 2.562 | 2.75 | 2.573 | -0.001 | -0.011 |
| 9 | 2.752 | 2.565 | 2.748 | 2.575 | 0.004 | -0.010 |
| 10 | 2.747 | 2.566 | 2.75 | 2.575 | -0.003 | -0.009 |

Table 2. Comparison between conventional and 3D model measurements

The maximum difference is 1.3cm and the rms is 0.008m. It is seen that there is a fairly good aggreement of the results considering that there is difficulty in identifying the exact sections between the two methods of measurements. It is noted here that the obtained differences between the conventional method and the laser scanner model may not be representative of those encountered during actual reconstruction practice. The conventional method of measurement is performed manually and is dependent on the individual examining the vehicle and the way  the location of the points are determined.

Another disadvantage of the 2D deformation retrieval is that only specific points in the model are examined. Thus, the detection of changes directly in the 3D high density point clouds is more advantageous as it provides information about the deforming areas from the entire object’s surface. For this reason, the deformed wagon model was compared with the undeformed model of the same wagon. As there was no available point cloud data of the wagon before the accident, a model was constructed based on the ISAP plans for the specific type of wagon. Initially the two models (undeformed and deformed) were aligned using six identifiable correspodence points.

A comparison between the two models in the form of deviations is given and shown in Figure 5. The example shown in the figure was performed in Geomagic but there are open source software suites that provide similar tasks (e.g. Cloudcompare). The statistics of the 3D comparison gave a maximum difference of 0.4m with a standard deviation of 0.0507m. The colour variation provides the deforming regions in the front part of the wagon.

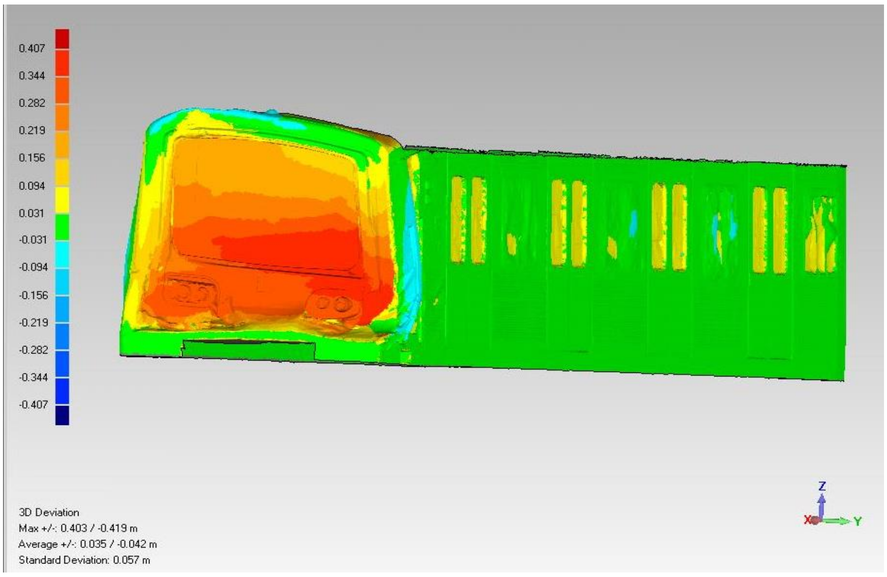



Figure 5. The 3D deformation regions on the front part of the wagon

In order to examine in more detail the deformed object a number of profiles and sections were constructed along a predefined axis (Figure 6). The result is a 2D representation measurement in the vehicle X-Y plane at prescribed heights. This method of vehicle measurement conforms with those set forth by the Society of Engineers and those used in vehicle damage analysis (SAE, 1980). In Figures 7a and b the longitudinal profiles of lines 1 and 2 (cf. Fig 6) are given and in Figures 8a and b the cross sections of lines 1, 2 (cf. Fig 6) are shown.

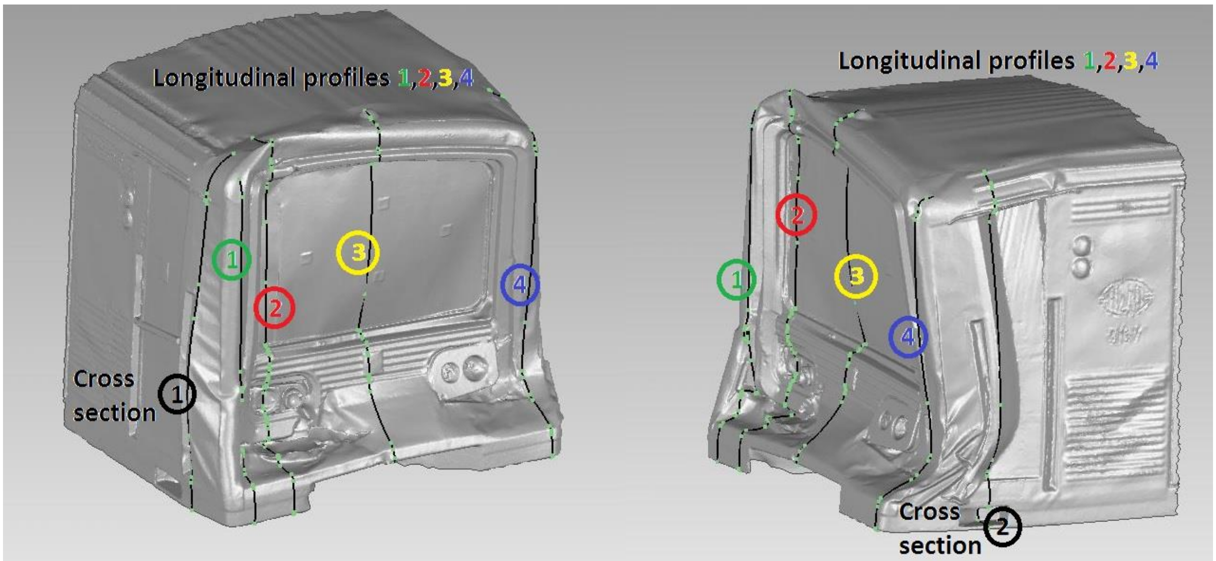
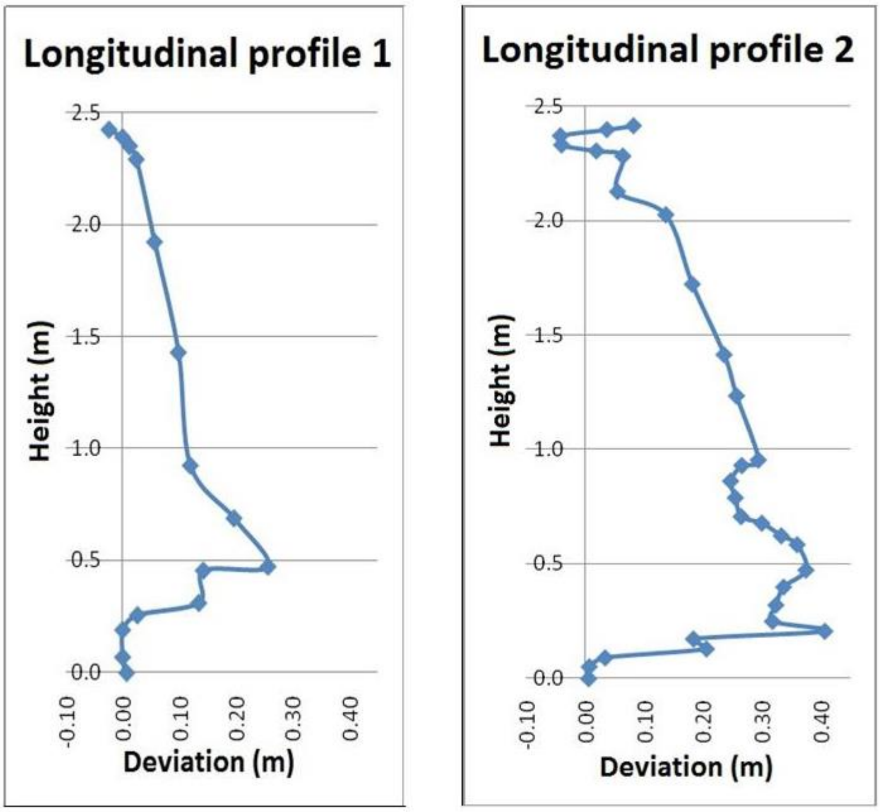



Figure 6. Positions of sections and profiles




(a) (b)

Figure 7. Example of longitudinal profiles

The x-axis represents the height of the wagon from the bottom point of the model up to the top (cf. Figure 6) and the y-axis represents the deformation profile. Based on these measurement sets, it appears that terrestrial laser scanning is appropriate for accident reconstruction and damage analysis and clearly, such type of qualitative information is difficult to be retrieved using conventional ways of measurements.

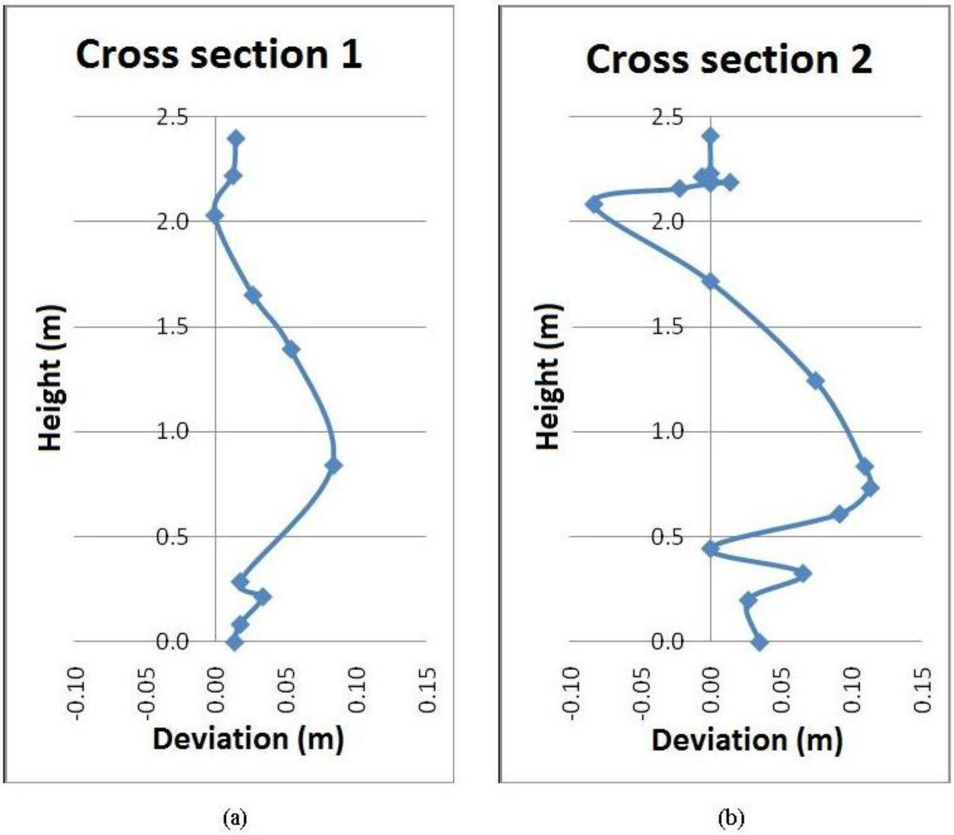



Figure 8. Example of cross sections

Both the 2D diagrams and the 3D model provide comparative results with respect the undeformed model of the train. It is important to emphasise that the undeformed model is lacking in reliability because it was created based only on design plans. The alignment of the two models is based on the identification of corresponding points in both models. Therefore, the high value of rms at 5.7 cm does not indicate the accuracy of the model. Nevertheless, the results show that this method has the advantages of high automation and 3D deformation quantification.

## 5. CONCLUDING REMARKS

The current technology for 3D recording using terrestrial laser scanning has reached a high level of development. The availability of this technique for the accident reconstruction area yields to several notable advantages with the main being that the created virtual model allows the investigator to look at the accident scene from different points of view and can be exploited to reproduce the event's dynamics. Also, the digital set of data is exempt from time consuming problem and can be used anytime and shared among different operators. On the other hand, the acceptance of this type of data as a valid and legal evidence is still to be completed in many countries.

The field survey is not a trivial task, especially in the case of large or complex scenes. This requires the presence of experts to plan and carry out an effective data acquisition. In the same direction goes the development of best practices, data interoperability and management and better understanding of the data quality needs for implementing terrestrial laser scanning for accident investigations.

It has been shown that the use of terrestrial laser scanning can add value to the achievable results. The good knowledge of the impact phenomena could not be achieved only by means of the traditional theoretical and analytical models used in crush analysis, because of the complexity of dynamic effects. Instead, the 3D models created by terrestrial laser scanning are able to virtually reproduce the bodies (vehicle, barriers, etc.), and to evaluate their deformations and dynamic actions exchanged during the crash.

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