A Method to Optimise Semi-Trailers with the Use of FEM Analysis and Durability Tests with a Road Simulator

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Abstract. This paper presents a method developed by Wielton company – a manufacturer of trailers and semi-trailers – for the optimization of semi-trailer’s construction, supported by FEM analysis and the modern road simulator – a test stand included as part of the method for optimising semi-trailers. The aim of the research was to optimize the process of developing a technical measure in terms of shortening the time of implementing new products while guaranteeing high durability and functionality of the products. As a result of the optimization of the construction with the use of FEM analysis and the road simulator, the semi-trailer as a new product for sale is delivered quickly and possible defects of construction are eliminated on early stage of new product development. The method assumes the following stages of the development process: determination of input data to the process, development of a 3D model, FEM numerical analysis (static and dynamic), development of an optimized 3D model based on numerical analyses, construction of the first prototype, prototype validation tests using the road simulator and other test stands. Important feature of the developed method to optimise construction is connected with specific data achieved from FEM analysis and used in tests with the road simulator. The effect of using presented method is the elimination of 98% errors in construction and technology. These errors concern not only the key parts of the semi-trailer, i.e. the body and the frame, but also less important components, i.e. fixing of tanks and boxes, ladder, spare wheel basket, extinguisher mounting. The method to optimise semi-trailers developed in Wielton have many advantages, such as: limiting the risk of launching breakthrough solutions on the market, faster increase in vehicle competitiveness, optimizing vehicle construction, reduction of production time and costs, and as a consequence - faster implementation of new products, reducing the number of complaints and service costs, increasing the value and prestige.

1. Introduction

Providing new, innovative construction solutions in the field of manufacturing commercial vehicles for transporting, among others trailers and semi-trailers is a difficult and long-lasting process. New vehicles must meet a number of requirements in terms of safety, durability and reliability [1][2]. The final stage associated with the introduction of a new vehicle on the market are validation tests, which carried out in a traditional way on roads can consume a lot of time and generate additional costs. Wielton company developed and propose alternative way for final validation of product. A special method of validation has been developed, which bases on FEM analysis and a mechatronic test stand.
for validation of prototypes. A road conditions simulator, which is located in the Wielton’s R&D Center, enables validation testing of prototype products in a much shorter time.

Mechatronic test stands for vehicle structures, the so-called road simulators enable fatigue and durability tests of vehicles and their components. Road simulators are widely used research devices in the automotive industry [1][3][4]. However, they are not widespread when tests are carried out on vehicles such as semi-trailers and trailers. On the base of our research Authors would like to state that this type of research equipment bring tangible benefits to manufacturers of commercial vehicles, i.e. trailers and semi-trailers. With reflecting the real road conditions on the test stand, after registering road profiles on the measuring devices Authors of this paper would like to show how to accelerate the research process, which in turn will cause faster introduction of the new product to the market. The most important thing is to check, identify as fast as possible and eliminate potential threats and design problems that may occur during the long-term use of semi-trailers and trailers in various road conditions and different "culture" of vehicle use. It seems obvious that there is no better method to detect defects or weaknesses in the construction of complete vehicles than to simulate reality. Combination of FEM analysis and the MTS 320 road simulator [5] make it possible to map the vehicle movement observed while driving on different roads, regardless of the quality of their surface. The technical possibilities of the road simulator allow to simulate extremely different road conditions with high efficiency, from small vibrations to very strong impacts caused by road potholes. However such approach is not easy, because of complexity of the problem [6][7].

2. Simulators of road conditions in the automotive industry
The use of road simulators when introducing cars to the market is generally popular. With such test devices vehicle manufacturers are able to carry out the following tests (Figure 1) [3][5]:

- Vehicle durability testing through fatigue and durability tests allowing to assess the complete vehicle structure, components and subassemblies already at the prototype construction stage, improve reliability and performance while maintaining high quality, reduce costs and reduce the time of new implementations.

- Quality testing at the end of production stage, the "first road" in a controlled and repeatable environment (established road profiles) where, after successful testing, the vehicle is handed over to the end user (customer). Without a road simulator, a manufacturer who wants to sell products that meet the quality requirements must perform expensive, unique tests carried out in changing weather conditions on special test tracks, which will not allow for the elimination of potential irregularities.

- Driving comfort test that is conducted to compare with competing vehicle models. During the tests, it is possible to monitor the effects of changing test parameters, which cannot be carried out during tests on special test tracks, including in addition subjective opinions from the driver and passenger, which are insufficient for a correct assessment. The road simulator allows for high accuracy, repeatability and simplicity of driving comfort assessment. It is possible to recreate exactly the same conditions for each vehicle multiple times, stopping, visual inspection and restarting the test. Engineers are able to observe and evaluate, and then introduce changes to a design.

- Assessment of noise (buzzing, squeaking, rattling noise), which is perceived as a very important feature, has nowadays become the basic indicator of vehicle evaluation for both manufacturers and customers. Temperature, humidity, age and road conditions are the main factors that have the greatest impact on vehicle wear, which lead to the occurrence of the above defects, so some manufacturers decide to place the road simulator in special chambers that almost 100% reflect the real conditions in which vehicles are moving.

- A racing vehicle test, in which it is possible to very accurately simulate the dynamics of a vehicle that occurs during competition by adjusting the height, roll, inclination of the vehicle and allows to precisely simulate the aerodynamic load effects on the vehicle.
However, an important research problem is the development of a test stand that allows testing of large and long (more than 12 meters of length) vehicles such as trucks, buses, semi-trailers, and truck trailers. Therefore Wielton, as a producer such type of long and big vehicles, had to elaborate own
mechatronic road simulator for specific conditions. Development process have been realised in cooperation with MTS company, and a final results are presented in this paper.

3. The road simulator for trailers and semi-trailers in Wielton company - construction and application

The stand for testing commercial vehicles, i.e. semi-trailers and trailers at Wielton, known in the literature as “road simulator”, is currently the most modern test stand that allows to determine various static and dynamic characteristics and, most importantly, to precisely determine the durability of the entire structure of the vehicle and its components in real conditions road loads. The stand for durability tests (understood as fatigue tests on a real object) at Wielton consists of six hydraulic cylinders placed on an active damping mass (Figure 2). The cylinders create a vertical force on all the tires and the saddle plate of the trailer. The configuration of the stand enables the testing of single-axle vehicles with a coupling, two-axle vehicles (passenger cars, agricultural trailers), and three-axle vehicles (buses, semi-trailers, military vehicles). It is possible thanks to the steel structure of the floor with interchangeable, configurable elements, which enable different settings of the distance between: axles, vehicle wheels, king pin (coupling) and the axle of a semi-trailer/trailer.

![Figure 2. Road simulator in Wielton company](image)

In the front part, the stand is equipped with a support, which allows connection of trailers and semi-trailers. This support can be hidden for testing other types of vehicles. The automatically retractable support attached to the damping mass, consisting, among other things, of two actuators, responsible for reflecting the recorded inputs in the front part of the semi-trailer or trailer, can be equipped with a standard fifth wheel or coupling, which are used in trucks depending on the tested vehicle, semi-trailer or trailer. Active damping mass with a mass exceeding 500 tons is suspended on pneumatic airbags.
Such a construction of the stand allows to limit the vibrations to the test field itself, damping the vibrations of the tested object, the weight of which may exceed 40 tons.

A specialized software package RPC (Remote Parameter Control) [9][10] is used for durability tests. It allows for a comprehensive analysis of the recorded loads of the vehicle in various road or terrain conditions and the selection of loads that will allow for the quickest determination of the actual durability of the vehicle.

At Wielton S.A., the road simulator is used for durability tests of curtain semi-trailers, tipper semi-trailers, container semi-trailers, center-axle trailers, trailers with a turntable and others. The use of this type of device offers the following advantages:
1. Reducing the risk associated with the introduction of breakthrough solutions to the market,
2. Faster growth of vehicle competitiveness,
3. Optimizing product design, reducing production time and costs and, consequently, faster implementation of new products,
4. Limitation of complaints and servicing costs,
5. Increasing the value and prestige of the Wielton brand.

4. New product development and optimisation method

Ensuring high-quality products offered on the road transport vehicle market (which is growing year-by-year [11]) requires comprehensive control throughout the design process. Improvements to currently offered products and the introduction of completely new products must be properly verified before they reach the customer. The final design of a new product is approved on the basis of positive results of verification tests (FEM analysis) and final validation tests (with the use of road simulator). Generally it is a long process, therefore at a continuous improvement during a design stage, the aim is to maximize the use of existing proven and correct solutions. However, after carrying out a certain number of such redesign iterations, a situation appears that further improvement of the technical means is associated with the introduction of significant changes, which in turn obliges to carry out a comprehensive re-verification of the product.

As mentioned, the implementation of a new product is a complex and time-consuming process. New product development and optimisation process at Wielton is presented on Figure 3. It begins with traditional market research. Its purpose is to define the characteristics of a new vehicle. At the stage of defining the design assumptions, customer expectations as to the durability of the new product, its durability, maintenance costs and purchase price are taken into account. At the same time, activities are carried out to determine the possibility of using a new type of materials, design solutions and manufacturing technologies. In order to be approved for road traffic, the designed vehicle must also meet certain legal standards and approval requirements. They define certain functional characteristics of the vehicle, such as maximum overall dimensions, generated permissible axle loads, required safety systems. Taking into account the above requirements and based on over 20 years of experience in Wielton in the construction of semi-trailers, the first product model is prepared in the form of a CAD file. Then it is verified in numerical strength analysis (FEM). Their main purpose is to detect overstrained areas. Various load cases that may occur during the use of the semi-trailer in accordance with its intended use are investigated. Developed method for new product development bases in this step on results of previous validation tests on the road simulator MTS 320 for similar products. Places, where some abnormalities have been detected after tests on the road simulator in the past, are listed. Such list of places with increased risk is used for FEM analysis. In such places more detailed FEM static analysis is realised. In safe places less careful FEM static analysis is performed. However, if a too high stress distribution in the structure is detected, the model is redesigned until satisfactory analysis results are obtained. Results from tests with the use of the road simulator are used as well for FEM dynamic analysis.
Dynamic analysis is performed as last type of FEM analysis, just before first prototyping. As an input to dynamic FEM analysis, a reference 60-second mileage is implemented from exactly the same road profile which is used on the road simulator at the Wielton. FEM dynamic analysis is performed only for steel frame of semi-trailers. The simulation takes into account 8 input signals: 6 signals of vertical movement of the semitrailer wheels, vertical movement and torsional movement of the fifth wheel around the axis defining the vehicle’s driving direction. A reference simulation of 60 seconds is responsible for the cumulative fatigue damage of the material equivalent to a 15 km mileage. Finally these result are related to 400 000 km semi-trailer mileage, which is an equivalent of min. 3 years of a real exploitation of a semi-trailer. The results of FEM dynamic analysis are presented in the form of the damage accumulation factor. The accumulation factor of damage for welded joints is determined based on the SN fatigue curve according to PN-EN 1993-1-9-2007 Eurocode 3 for fatigue category 36 and the notch type corresponding to the weld with incomplete penetration (fillet weld). The adopted curve corresponded to the probability of failure of 95% for failure at the weld root. The SN fatigue curve of Strenx 700MC (which is typical material used for frames of semitrailers produced by Wielton) corresponds to a failure probability of 97.7%.

Positive results of FEM analysis provide the basis for manufacturing of prototype of a semi-trailer. It is being built to carry out further necessary tests, especially with the use of the road simulator, but not only. Functional tests check the performance characteristics of body elements (front wall, doors, side tarpaulins, roof) and chassis elements (bumper, support legs, electro-pneumatic system, boxes, buffers, etc.). This stage also controls the weight of the vehicle, the pressure generated on the fifth wheel and individual axles, and the tightness of the front wall and rear portal. Tensometric tests together with photogrammetric tests provide information on the strength properties of a new product and its components. Based on the recorded displacements, both methods determine the stress values in the structure. Such results are also used to define input boundary conditions for FEM analysis for next products. Tests are carried out for various load cases depending on the intended use of the product. Dropside and curtain semi-trailers are tested with a forklift simulating the loading and unloading process. In this way, the stability of the semi-trailer is checked, the strength of the floor and the functionality provided during loading (the possibility of opening/closing the tarpaulin, opening the door, lowering the sides). In turn, for example, tipper semi-trailers are tested in places such as gravel pits, quarries. On a semi-trailer equipped with appropriately placed sensors, the displacement of the side walls is measured depending on the type of the loaded material or the behavior of the entire structure at the time of the so-called tipping, i.e. dumping the load from the load box. The results obtained from such actual tests give an objective picture as to the correct functioning of the new product.

The last stage of the verification tests are durability tests (in the literature also referred to as endurance tests, fatigue tests or mileage tests [12]). Conducted on the MTS road conditions simulator, they finally verify the new product in terms of durability of both the complete vehicle and its individual components. The entire implementation process, from the design stage to validation research, is iterative and continuous. The detection of structural defects at any stage causes the work to be returned to the design stage in order to introduce the necessary structural changes. After their application, 3D CAD model and then the prototype are tested again. Only a positive result of all tests guarantees that the product is free from defects and is ready to be placed on the market. The general scheme of the new product development process in Wielton is presented on Figure 3.

The developed method for product optimisation, which base on FEM analysis as well as on a road simulator allows to obtain a high convergence of the results of numerical analysis with measurements during tests on a test stand. Table 1 presents comparison of average values of normal stress for the same points on FEM analysis model and real prototype (measured during tests on the road simulator). In Wielton the acceptable level of difference is 6%. The main reason of such high convergence is that
data from a road simulator is used as an input for FEM analysis and dangerous areas detected during FEM analysis are identified and inspected during durability tests on the road simulator. Such integration is very beneficial and allows to eliminate 98% errors in new products. The remaining 2% errors that occur in the products concern only minor components (not connected with safety or the functionality of the product), supplied by partners and not tested (e.g. additional equipment attached to the trailer).

![Diagram of product development and optimisation process]

**Figure 3.** Method of new product development and optimisation used by Wielton

| Strain gauge | Normal stresses measured from experiment on a road simulator [MPa] | Normal stresses obtained from numerical FEM analysis [MPa] | Difference [MPa] |
|--------------|---------------------------------------------------------------|----------------------------------------------------------|-----------------|
| 1            | 410                                                           | 387                                                      | 23              |
| 2            | 389                                                           | 413                                                      | 24              |
| 3            | 381                                                           | 398                                                      | 17              |

**Table 1.** The comparison of results of the numeric and experimental research

5. **Product validation and verification using the road simulator**

The durability of the product has always been one of the key properties of each technical requirement. More than once, it played the role of the main criterion that guided the customer when buying a new machine or tool. There has also been a perception on semitrailers market that a "durable product" is a "heavy product". This reasoning is due to the fact that in the past, high durability was most often obtained by oversizing some key components of the machine. As a consequence, these actions increased the weight of the final product. Nowadays, the approach to product durability is a bit different. During the design process, the goal is to achieve the "golden mean" between a durable and a lightweight and cheap product. These criteria are used in optimisation process. The product lifetime has also been significantly shortened compared to similar products offered a dozen or so years ago.
However, one important fact should be noted. The products currently offered by manufacturers, also in the transport industry, are prepared for more effective work than the corresponding structures from previous years. The new generations of trailers are a good example. Thanks to the use of high-strength steels, such products are much lighter, but at the same time still durable. Hundreds of kilograms saved thanks to mass reduction of semi-trailers can be effectively used in the form of additional cargo that will be transported. The new technologies used for the production of semi-trailers, such as robotic welding, roll-forming, hydroforming, significantly affect the quality of the products offered. In order to maximize the potential of all these new solutions, it is necessary to use specialized tools to support the design process. It is possible to use CAD programs or environments used to numerically verify the durability of a new product. Modern tools used at various stages of the process of developing a new technical objects make it possible to determine the durability of the designed product with a certain probability. For this reason, validation tests are necessary to verify this feature of the new product.

Validation is a very important stage in the implementation process of a new product. The Polish standard defines it as a process that provides objective evidence confirming compliance with the requirements for a given use or application. The expression "objective evidence" refers to the test result, calculations or specific documents such as specifications, standards, procedures, etc. [13]. At Wielton, the validation process was carried out from the beginning on the basis of the results of a number of verification tests, including strain gauges, functional or utility. The latter were carried out at the customer's site during the trial period of operation. During this time, the recipient provided his own observations and comments regarding the product used. Additionally, after exceeding the set mileage, the semi-trailer underwent a detailed service inspection. They were inspected i.a. wear of the undercarriage components, the condition of the paint coating, the general condition of the main frame or the efficiency of power pneumatic systems. The time needed to test the trailer ranged from a few to several months. Nowadays, the key is to quickly introduce a durable and reliable technical measure. In order to meet the market requirements and to be able to compete with the largest trailer manufacturers, such as Schmitz Carbobull or Krone, it was necessary to implement modern tools that would allow for the elimination of defects at the early stages of the technical means development process. One of the basic tools used for this purpose are numerical strength analyzes. Basing on the method presented in this paper, thanks to the quick localization of excessively stressed areas, it is possible to properly modify the structure before building the prototype. Semitrailers and trailers are used in difficult conditions. Freight forwarding companies cannot afford to "waste" cargo space, which is why the trailers almost always move with the maximum permissible load. Their annual mileage reaches an average of 120 000 km, while for a passenger car they usually do not exceed 30 000 km. Loads occurring while driving constantly cause strenuous work of the entire structure. For this reason, it is crucial to correctly detect and remove even small, excessively loaded areas during the design process, as they may lead to later damage resulting from, among others, from the occurrence of material fatigue.

Correctly carrying out numerical analysis of complex systems such as semi-trailers is a difficult task. For this reason, it is necessary to conduct additional actual tests that allow to verify the correctness of the FEM model. The tool used for this purpose is the road conditions simulator MTS 320. The durability tests performed on this stand are the last tests carried out as part of the new product validation process. However, simulation with the use of road simulator must be properly prepared. In the first phase, sensors are installed on a prototype vehicle. Strain gauges providing information about displacements are placed in places that showed increased stress values in the numerical strength analysis. The accelerometers mounted on the trailer measure the parameters of the movement of the axles and the kingpin pivot. Additionally, sensors controlling the pressure in the suspension system and a GPS antenna are installed. Signals from all sensors collected during the reference run give a picture of the response of the trailer to real traffic forces. As part of the reference run, the prototype product travels a total of approx. 2000 km. Cases of driving without a load and with
the maximum permissible load are investigated. Data is collected from highways, main and local roads. This allows the behaviour of the semi-trailer to be examined in the event of various types of extortion. The next step is to prepare a road profile, i.e. a set of forces that will be applied on the simulator. Such information from test run is used also in FEM dynamic analysis. The main purpose of using the MTS stand in the product validation process is to precisely determine the durability of the trailer over a specified period of time and confirm correctness of previous analysis. At this stage, the key task is to prepare an effective road profile. Only such extortion allows the actual wear process of the semi-trailer to be accelerated, which translates into faster determination of its durability. A specialized RPC software package [9][10] is used for this purpose. Remote Parameter Control is an advanced simulation technique used to simulate and analyse repetitive inputs using a dynamic mechanical system in a controlled laboratory environment. The essence of the operation of the entire system is based on the continuous imposition of such extortion that the response of the tested object to this extortion is consistent with its response recorded in the reference run. Thanks to this, the correct mapping of road conditions is ensured, and several years of vehicle operation are achieved during several weeks of simulation on the stand. The use of the MTS stand as a validation tool allows for precise determination of the durability of the entire product and the detection of damage that may occur during normal operating conditions.

6. Conclusions

Market requirements force manufacturers like Wielton to shorten the time needed to implement new products as much as possible. Unfortunately, the prevailing trend of reducing the weight of vehicles while maintaining the required durability and reliability, additionally extends the design and implementation process of the new product. For this reason, there was a need to systematize the optimization processes of new products developed at Wielton.

The requirements for transport vehicles are higher each year. For this reason, the currently designed technical measures must be constantly optimized. Optimization includes economic, design (including strength), technological, operational and other criteria. Optimization of complex technical measures such as commercial vehicles, including semi-trailers, is a complex problem that requires systematization. There are different methods used in the various stages of the new product development process (from determining the need to the design and construction process, verification testing, etc.). These methods make it possible to optimize solutions with greater or lesser success. However, prototypes are often built in the final stages of the development of a complex technical objects (including semi-trailers) and subjected to further validation tests on advanced research stands. Only validation tests most often allow to confirm the correctness of the adopted solutions, especially from the point of view of the durability criterion.

In Wielton company a method for product optimisation within better durability has been developed. The method consists of some stages of the development process: determination of input data to the process, development of a 3D model, FEM numerical analysis (static and dynamic), development of an optimized 3D model based on numerical analysis, construction of the first prototype, prototype validation tests using the road simulator and other test stands. The most important feature of this method is an integration of data used for FEM analysis and validation test with the use a road simulator and real prototype of a product. Such approach allows the elimination of 98% of errors in construction and technology in faster way.

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