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# Inefficient design: Sensitivity analysis and numerical investigation of load cases from EN 12663-1 on railway car bodies

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## Abstract

Railway car bodies for passenger trains in Europe are designed according to EN 12663-1 but the load assumptions contradict the goals of designing light and energy-efficient car bodies. Hence a sensitivity analysis is carried out to determine the influence of the load cases of EN 12663-1 on the overall vehicle structure to identify the relevant loads. The load cases of EN 12663-1 are examined for their sensitivity to the system response with the help of design of experiments. As an essential parameter for the design of railway car bodies the weight force is identified. The longitudinal force at the buffer level is described as a dimensioning load if it is applied at the maximum level. However, an operating situation with this load magnitude is not known. Furthermore, load cases are uncovered that are not relevant for future designs due to their redundancy with other load cases. Over-dimensioning can be assumed as a result.

**Keywords:** rail vehicle, sensitivity analysis, EN 12663-1, design of experiments, longitudinal load cases, vertical load cases.

## 1 Introduction

Future rail vehicles should be designed to be as light, safe and energy-saving as possible [1]. Therefore, the load assumptions have to correspond as precisely as possible to the real structural loads of rail vehicles in order to dimension them according to the requirements [2]. With EN 12663-1:2015-03 ‘Railway applications

– Structural requirements of railway vehicle bodies – Part 1' [3] the (quasi-) static loads on the car bodies of passenger rolling stock and locomotives are defined, however some loads originated many decades ago without any verifiable or recognizable scientific justification [4]. Changing operational conditions as well as the introduction of new materials and manufacturing methods throughout the last decades are not reflected in the current state of the EN 12663-1, which is why over-dimensioning cannot be ruled out. Figure 1 gives an overview of the longitudinal loads for the most conservative vehicle category 'P-1', e.g. passenger cars.

In order to achieve a scientific basis for a revision of this standard, it will be necessary to determine the real loads through complex measurements or multi-body simulations. A revision can mean that new loads or load combinations are added and/or the current load amplitudes are adjusted. The sensitivity analysis carried out in this study should make it possible to identify the loads of the vehicle category 'P-1' of EN 12663-1 that have the greatest influence on the car body or are covered by other loads.

The loads in the standard are subdivided into longitudinal (vehicle longitudinal axis), lateral and vertical loads. Longitudinal and lateral loads partly depend on the mass and must be superimposed with weight forces depending on the operating situation. Vehicle-specific equipment and aerodynamic loads are not examined.

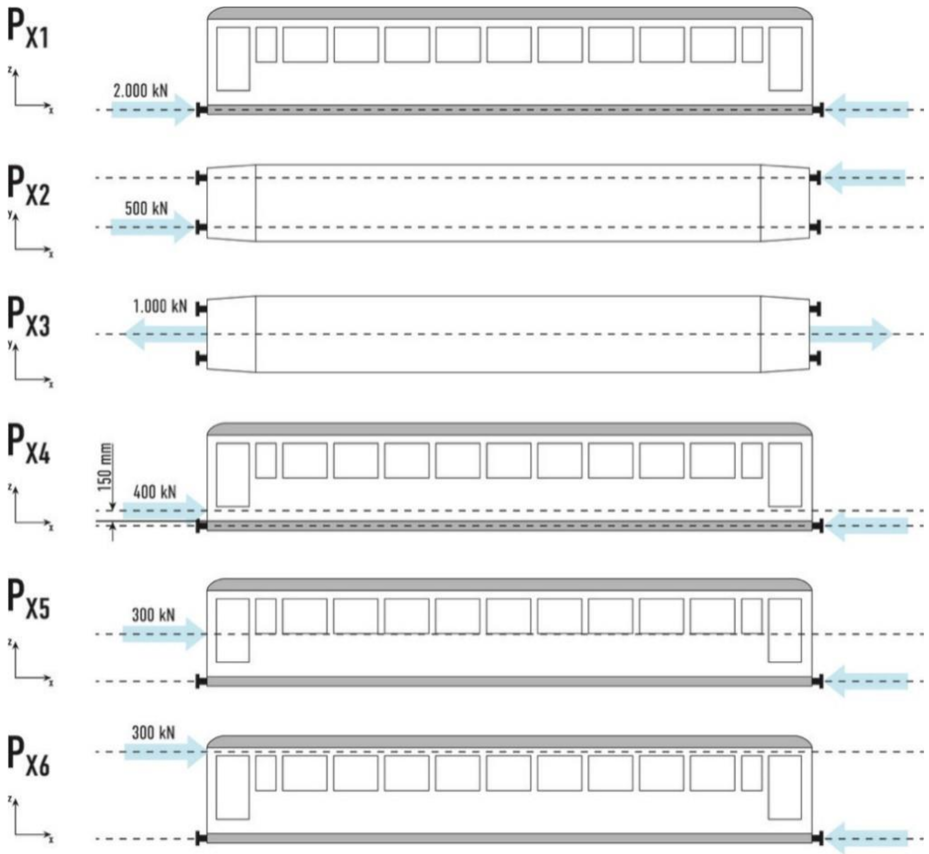


Figure 1: Longitudinal loads according to EN 12663-1 [3]

Fatigue loads due to dynamic excitations are considered by quasi-static equivalent loads and rail vehicles are designed in the fatigue endurance limit [5].

The loads are applied to a generic car body model (Figure 2), which is constructed in a differential construction with steel. Due to the central buffer, the diagonal compressive force $P_{x,2}$ is omitted and the loads $P_{x,1}$ and $P_{x,3}$ have the same force application.

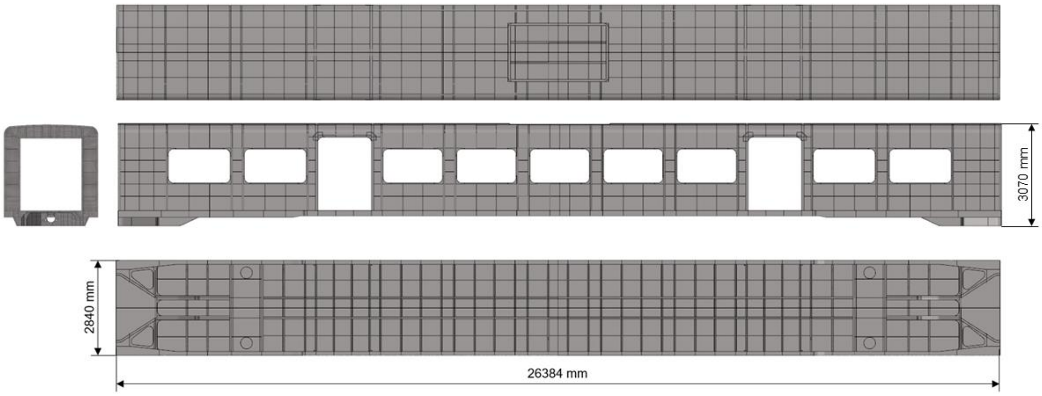


Figure 2: 4-side view of the generic car body model

## 2 Methods

The level of the variation in the system response (here: stress distribution) due to a change in the input parameters (load amount) is defined as the sensitivity of the parameter [3] [6].

The sensitivity analysis can be subdivided into three consecutive steps (Figure 3).

(1) The *factor screening* reduces the totality of variables $E_m$ to the essential parameters $X_i$ by qualitative observation. The variables are applied to the system individually with maximum value. Combinations of variables are not considered [7]. Similar modes of action of variables are identified and initial relationships are developed.

(2) In the *local sensitivity analysis*, the system response to changes in the parameters is quantitatively investigated. The parameters of an operating point are applied and one parameter is varied between levels, for example 10% and 100% of the maximum load value. If the model is linear, two levels are sufficient. All other parameters are kept constant. Thus, the sensitivity of a parameter at different operating points can be shown and correlations of the varying parameter can be determined when it is superimposed with different parameters at different conditions. Interaction effects are neglected but, in case of a linear relationship between the system response and the parameters, the local sensitivity analysis is well suited for a first overview [7].

(3) The *global sensitivity analysis* investigates the interrelationship of loads within a load case by simultaneously varying all parameters $X_i$ independently

over their levels. The global approach further clarifies the interaction of the parameters on the system response and allows the significance of each parameter to be assessed. Interactions with three or more parameters have a negligible influence on the system response [8]. The full-factorial experimental designs used consider all possible combinations of the level setting of the parameters and thus calculate all main and interaction effects [9]. An experimental design for two-level parameters can be divided into three areas (Figure 3, number 1 – 3). First, the columns of the parameters with the respective levels in all possible combinations. Next, the columns of the interactions and thirdly the determined system response.

The SSB/TSS ratio (Sum of Squares Between Groups / Total Sum of Squares) is the variance of the system response caused by the parameter $X_i$ normalized with the total variance of the system response. It describes the sensitivity independent of level width and value range [9].

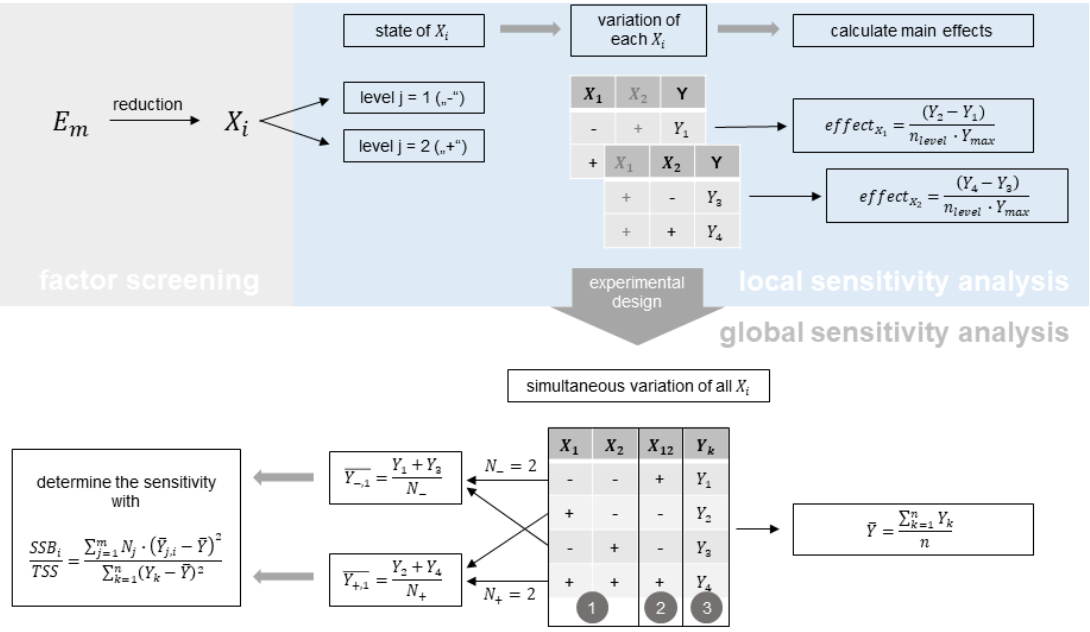


Figure 3: Schematic process of the sensitivity analysis with two levels

# 3 Results

The maximum stresses and the stress at three fixed positions, expected to be exposed to a high stress level, of the car body are evaluated (Figure 4).

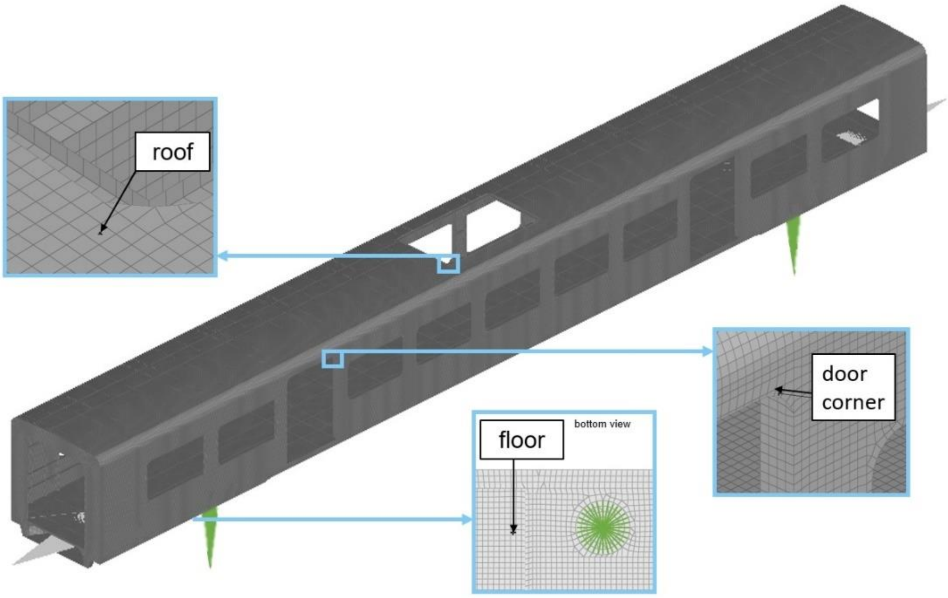


Figure 4: Evaluated positions

The stress values of the weight forces increase with growing payload over the entire car body. Due to the linearity, for load cases that differ only in the weight force, only the one with the larger weight force needs to be verified.

The superposition of the compressive force $P_{x,1}$ = 2000 kN and weight with exceptional payload is the most critical with an influence of $P_{x,1}$ of 59.9% on the maximum system response. The sensitivity due to $P_{x,1}$ is 3.3 - 5.6 times higher, than the sensitivity due to the tensile force $P_{x,3}$ = 1000 kN. A higher mass always results in a higher system response, the longitudinal load dimensions the system response starting from 1000 kN (Figure 5).

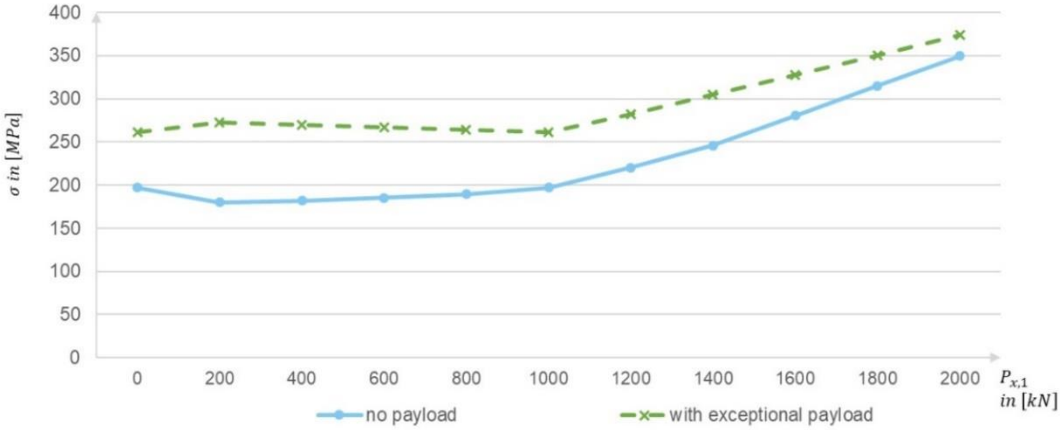
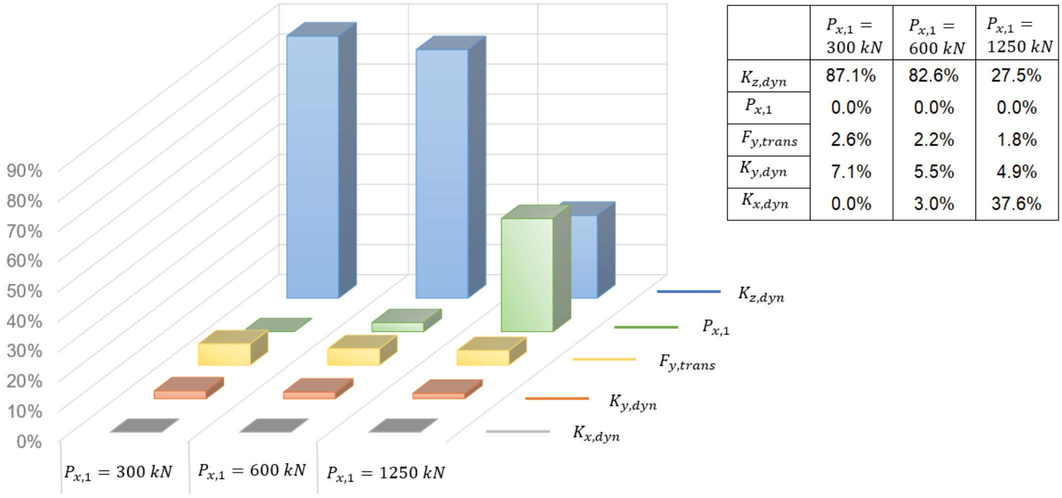


Figure 5: System response for two loading conditions superimposed with $P_{x,1}$

The load $P_{x,1}$ is reduced to 300 kN [5], 600 kN (light buffer impact) and 1250 kN, according to [4] sufficient for the design, and superimposed with the lateral force

$F_{y,trans}$ (transverse shock of the bogies) and the quasi-static equivalent loads (Figure 6).

With increasing load $P_{x,1}$, their sensitivity increases, whereas the other sensitivities decrease. At $P_{x,1}$ = 1250 kN, it exhibits the highest sensitivity of 37.6%, whereas previously it has only little influence. This shows that above 1000 kN the longitudinal load has the dimensioning influence and otherwise the weight force strongly influences the system response. In real operation, where the load is usually less than 1250 kN (see above), the longitudinal load is no longer dimensioning. The transverse force $F_{y,trans}$ and $K_{y,dyn}$ cannot be neglected.



| | $P_{x,1} =$ 300 $kN$ | $P_{x,1} =$ 600 $kN$ | $P_{x,1} =$ 1250 $kN$ |
|---|---|---|---|
| $K_{z,dyn}$ | 87.1% | 82.6% | 27.5% |
| $P_{x,1}$ | 0.0% | 0.0% | 0.0% |
| $F_{y,trans}$ | 2.6% | 2.2% | 1.8% |
| $K_{y,dyn}$ | 7.1% | 5.5% | 4.9% |
| $K_{x,dyn}$ | 0.0% | 3.0% | 37.6% |

Figure 6: Operating situations with adjusted load $P_{x,1}$

In studies on the acceleration force of the bogies the stresses near the running gear are influenced 1/3 by the accelerating load and 2/3 by the superimposed weight force. In all the other areas the system response is almost exclusively influenced by the weight force. The same applies to the loads $P_{x,4}$ – $P_{x,6}$ (Figure 1), which causes a high sensitivity only at their force application.

The evaluation of the other load cases confirms the dimensioning influence of the weight force with a sensitivity of mostly more than 90%, whereas the longitudinal and lateral loads has with a maximum of 5.5% considerably lower influence.

## 4 Conclusions and Contributions

The influence of the loads and load cases on the overall vehicle structure of EN 12663-1 was worked out using a sensitivity analysis in three steps. The evaluation of fixed elements showed that the basic findings obtained from the evaluation of the maximum stresses remain valid. The weight force was identified as the major parameter influencing the system response, which is also confirmed by further literature [10], whereas the sensitivities of the system due to longitudinally and laterally directed excitations usually are very low. The lateral loads show at the same magnitude higher sensitivities on the system due to the lower opposing resistance.

Redundant load cases in EN 12663-1 make the design of railway car bodies inefficient. Among other things, EN 12663-1 requires verification of static weight forces of different magnitudes superimposed with static longitudinal loads of different magnitudes acting at the same point for a car body with center buffer coupling. Due to linearity, it is sufficient to verify only the load case with the largest loads in terms of magnitude. This is the superposition of the buffer force $P_{x,1}$ with the weight force from the exceptional payload. The topicality and the force application areas of the longitudinal loads is often unclear, whereby the force application has a negligible influence on the global sensitivity. If the load $P_{x,1}$ is reduced to realistic magnitudes, a relevant influence only occurs from an absolute value of 1000 kN. The relevance of the longitudinal loads is therefore to be regarded as low in relation to vertical loads. It should be noted that the compressive force at buffer level $P_{x,1}$ as a single load is not alone the decisive dimensioning load as described in the literature [4]. Related to the roof structure, the load at top flange level is the dimensioning load and the influence of the weight force is not neglectable. The superposition of the compressive force $P_{x,1}$ and weight with exceptional payload is shown as the most critical in this study.

It can be assumed that the basic findings also apply to other types of car bodies and that EN 12663-1 is not fully appropriate for the development and demand-oriented design of new rail vehicles due to redundant load cases and non-transparent load assumptions or topicality of loads. Thus, more detailed viewing in the dimensioning of rail vehicles should be considered in the future.

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