# Master Thesis Assignment: The Computational Structural Mechanics of Driving Busses and Vibrating Doors

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## 1 Introduction

The future sustainable growth of cities and urban areas will increasingly rely on means of mass transport. All major bus manufactures are therefore studying new types of mini-vans, city busses, coaches, double deckers and mono-rail systems. It suffices to browse the webpages of the major bus constructors to gain an understanding of the transition in this market. This development increases requirements of the door systems. Bus door systems are expected to become lighter, more responsive to passenger via sensors and electronics and more adaptable to the changing market.

Ventura Systems BV is worldwide the market leader is the manufacturing of bus doors. It is a very successful Dutch high-tech family business that employs hundred people at their plant in Bolsward in Friesland. Ventura Systems maintains contacts with all of the main bus manufactures. Ventura discusses with these partners the predictive maintenance, the condition based monitoring and the data analysis to obtain low maintenance door systems. Ventura Systems is part of Innovatie Cluster Drachten (link to Innovatie Cluster Drachten) in which various companies collaborate.

Ventura Systems has acquired a solid world-wide reputation over twenty-five years of operation. The doors manufactured by Ventura Systems are mounted in busses carrying passenger in almost all European cities, in North America and in Asia. Met by new challenges from the market, the company is eager to engage in the mathematical modeling and numerical simulation of the products it manufactures. The company wishes to gain understanding on factors such as weight reduction and the enlargement of glass surfaces impacts factors such as the live cycle of door systems and the production process.

## 2 Mathematical Modeling and Numerical Simulation

During a bus ride, loads on the bus transfer to the doors. This is schematically represented in the left of Figure 1. The aim of this assignment is to gain insight into how the motion of the bus results in the distribution the displacements, the strains and the stresses on door system. The term *door system* is here meant as rather genetic term. It refers the assembly of the door and the door suspension-and-drive system and its attachment to the bur frame. The door consists of a metal frame and a glass surface surrounded by a rubber seal. The door suspension-and-drive system consists of a motors, hinges and bars attached to the frame of the bus. The strain and stress distributions can be integrated over surface and volumes to obtain the force and the torque on the door and the door drive. Forces and torques can subsequently be used to gain information on the deformation and vibration of the parts. These quantities will serve as a guide in the optimization of the design in terms of strength, stiffness, size, weight and durability of these systems. More information is available in the company website.

We will target the plug sliding door system that Ventura sells most. This system are well known for their use on passenger trains. It consists of two outward revolving door leaves and is shown in the right of Figure 1. The results of in-house simulations by Ventura this system is shown in Figure 2. The figure shows the distribution the von-Misses stress. This assignment invites to build and solve mathematical models for door systems mounted on the bus subject to various loading conditions. This assignment can be developed in various directions that we describe further below.

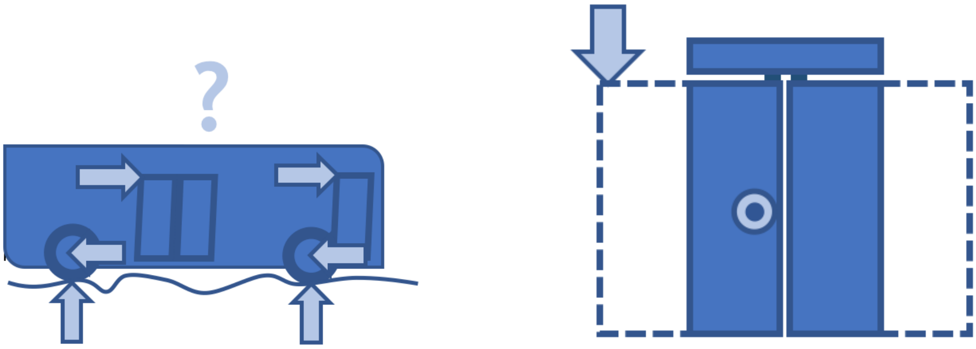

Figure 1: Schematic of bus driving over a bump (left) and two-leaf plug sliding door system (right).

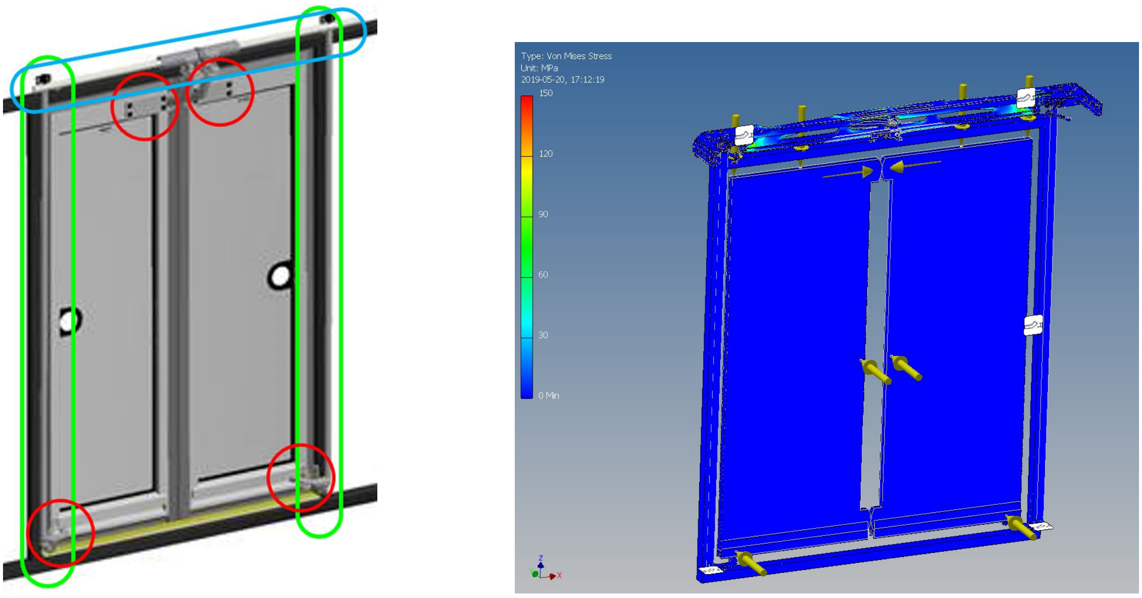


Figure 2: The two-leaf plug sliding door system. At the left-hand side of the figure: attachment (or suspension) of the door leaves to the door frame. At the right-hand side of the figure: sample result of a finite element simulation of the door system. The figure shows the von-Mises stress to be large at the top of the figure. The stress is shown to be large in areas in which the excitation is large. These areas at marked by arrows. In these areas the door frame is attached to the bus frame. Further illustrations can be found in the manuals of the products that Ventura sells.

## 2.1 Modeling of the isolated door system subject to load

In a first stage of the project, the door system in the absence of the bus can be modeled.

The two door leafs can be modeled as single bodies (plate assemblies) consisting of glas plane glued and bolted onto a aluminum profile. The glue can be modeled as 2mm thick and 10mm wide EPDM rubber strip encircling the glass plane. The bolts can be modeled by considering the aluminum frame to exist as a single entity.

The attachment (or suspension) of the door leafs to the door frame is shown in the left most figure of Figure 2. At the top and the bottom, the door leaves are attached to the door arms and to vertical door bars, respectively. Both the door arms (top) and the attachment to the vertical door bars (bottom) are encircled in red. At the top, the door arms are connected to a strong horizontal round bar mounted across of the door opening. This round bar is encircled in blue. The vertical door bars are encircled in green. The vertical door bars are kept in place by the drive system mounted on top of the door. The door bars serve to limit the liberty of motion of the door leaves. The drive system with the over-center mechanism and actuator is not shown in the figure.

The objective of this assignment is to analyze how the door system deforms with subjected to a load. The load with in part cause the deformation of the door leafs and in part be transferred to the door suspension mechanism. It is of interest to study the location of the large deformation and the level of the stress on the suspension mechanism. In the absence of the bus, the outer edges of the suspension mechanism is assumed to form a fixed reference frame.

**Literature Study** We invite the student to perform literature study and become familiar with the mathematical modeling of representative mechanical systems. One could start by considered the partial differential equations for linear elasticity in two dimensions (Stokes equations) in stationary and transient regime, the boundary and initial conditions, the volumetric and boundary source terms. One can consider the weak or variational formulation, the meshing of the computational domain, the finite discretization and solution procedure. The modeling the impact of a falling weight on the door and the vibration of the door can be considered. One could extend the linear formulation to non-linear formulation to take into consideration non-linear material characteristic and/or large deformation. One could consider the extension to three dimensions. One could consider the modeling of fatigue and of the formation and propagation of cracks.

**Finite Element Simulations** After a literature study, the study can perform finite element simulations of the mechanics of the door systems. The door and the load can in a first instance be represented as a partially clamped flat plate and a point source, respectively [2]. Various weight distributions of the door and locations of the point source can be considered. Resonant frequencies and modes of vibration ought to be explored. Static and transient simulations can be performed. Various design of the door frames and the attachment of the door frames to the drive mechanism can be compared. We strongly encourage adopting the commercial finite element package Comsol Multiphysics (www.comsol.com) to efficiently prototype sufficiently detailed models. In a later stage of the project, it might be beneficial to adopt public domain alternatives such as FENICS (fenicsproject.org) or NGSOLVE (ngsolve.org). Possibly analytical computations can complement numerical simulations to some extend.

## 2.2 Modeling of door system subject to loads from within bus in stand-still

In a second stage of the project, one can consider the bus to be in stand-still and study how the door system deforms when a load is applied from within the bus. Both static and transient load cases can be considered.

Possible goals include the determination of the shock response of impact on thin plate representing the door lead and the design optimization to minimize the effect of this response. In optimizing the structure of the door, one needs to take into consideration the wish to extend the glass surface (esthetics) and to keep the trade-off between strength (stiffness) and mass into account. Below we describe two static load cases in more detail.

**First Static Load Case** The first static load case is the impact of a weight attached to the top of the door. It represents the act of vandalism of a 100 kg person hanging at the top end of an opened door. The geometrical complexity of the door and its suspension can gradually be increased. Ventura has modeled this case in-house and is keen to compare results with this assignment. We encourage the students to get in touch with Ventura to ask for details regarding geometry, material coefficients, location of impact on force and clamping on the door, prior modeling results in terms of stress and displacement, possible experimental validation in laboratory.


Figure 3: Schematic of construction safety test carried out by allowing a 50 kg sand bag to fall on the structure under an angle.

**Second Static Load Case** The second static load case is the impact of a falling weight on the door. It represent the side impact of a load in case of an uncontrolled event such as the bus suddenly breaking or turning causing a passenger to collide with a closed door. The door should comply with the norm NEN-6702 (see additional documentation). This norm defines a scenario in which a bag of sand weighing 50 kg falls on the door. This scenario is depicted schematically in Figure 3. The norm defines how much energy should be absorbed by the door. The sand bag behaves in a non-elastic manner upon impact with the door. The challenges thus resides in modeling the transfer of energy from the moving sand bag to the door in stand-still. Models of impact by collision can therefore be studied. Ventura has never modeled this case before and in eager to comment on the results obtained in this assignment. Valuable for Ventura is to obtain information on how the magnitude and direction of the forces propagate to the points of contact of the door leave with the door drive system. These points are encircled in red in the left-most figure in Figure 2. Results of the assignment will allow to optimize the design of these suspension points. We again encourage the students to ask Ventura for details on geometry, material coefficients, location of impact on frame or glass plain, expected results in terms of stress and displacement, modeling of glass planes and rubber sealing, etc.

**Assignment reformulation** Deformation of thin shell upon impact. Shock response analysis (see Comsol Blog below). (1/3) given configuration (2/3) configuration with modifications (3/3) automatic optimization of the configuration.

- `https://www.comsol.com/blogs/how-to-perform-structural-analyses-using-shock-respons`
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- `https://www.comsol.com/blogs/the-physics-of-tennis-racket-sweet-spots`

## 2.3 Modeling of door system subject to load externally transmitted from driving bus

In a third stage of the project, one can consider the bus to be driving and study how the loads on the bus frame are transmitted to the door leafs and the bus suspension mechanism.

During a bus ride, numerous conditions force the door leaf out of its closed position. Examples of such conditions include a bumpy brick road, a (stationary) diesel engine and gust wind passing along the bus exterior. It is of great interest to examine the effects of inertia of the door leaves on the door suspension-and-drive mechanism as well as on attachment points to the bus frame. A dynamical model needs to be developed to simulate vibrations leading to fatigue and failure mechanisms. An understanding of how time-varying loads cause the weakest links of the door system to fail, the doors to open unexpectedly or the door leafs even to tear away from the bus is therefore vital.

A dynamic model for the door system can be build by considering the multi-body assembly of the door leafs, the door suspension systems, their interconnection and the attachment to the bus frame. The door leafs can be modeled as stiff (but not infinitely rigid) plates. Components of the door suspension system can be modeled as flexible bars. The interconnection of the door leafs, the door suspension system and the bus frame can be modeled as joints that act in part as springs and dampers. The attachment points are encircled in red in the left-most figure in Figure 2. The frame can be set in motion by allowing it to move in various directions. This motion can possibly be modeled by considering the analogy of a vibration plate. The eigenmodes of the system that are likely to cause resonant excitations can be examined. In a next step, the deformation and stress concentration of the weak parts of the mechanism can be studied.

**References**

1. `https://www.comsol.com/model/vibration-in-a-washing-machine-assembly-19957`

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