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Research paper

Study and modelling of the handling of equipment: case of a self-propelled handling truck

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Abstract

This paper is the result of an industrial problem relating to the trauma suffered by forklift truck drivers when their trucks roll over sideways. The general objective of this paper was to model the forklift truck and the operator in order to test the different accident conditions. Specifically, a parameterised model of the forklift truck and driver was statically and dynamically modelled. This model can be used to represent most cantilever and counterbalanced forklift trucks with a nominal capacity of 2,000 to 3,000 kg, whether they are powered by petrol, propane or electricity. The forklift operator was represented by a 50th percentile Hybrid III dummy. A range of safety systems (lap belt, armrests, shoulder restraints, doors) and different rollover conditions were tested: low speed (static) and high speed (dynamic). This interface is used to enter the parameters required to create models of the truck and driver, and to define the accident conditions. The results of the static and dynamic simulations show that the models of the truck and driver are functional and relatively realistic, at least according to the limited data available in the literature and according to those involved in the field. The results show that the type of floor has little influence on the driver's injuries, but that the safety systems used have a very strong influence, for both static and dynamic rollover cases. At the current stage of modelling, doors and shoulder restraints in combination with a lap belt appear to be more effective in protecting the driver than armrests with or without a lap belt or no re-straint system at all.

Keywords: *Logistics; Handling; Self-Propelled Forklift Truck; Forklift Operator; Warehousing.*

1. Introduction

The economic development of the last decade has led to intense competition between industrial sectors. This competition has spread internationally, with foreign companies setting up operations around the world, sometimes in the same country, for economic and logistical reasons (proximity to markets/customers and/or proximity to raw materials).
As a result, with a large number of malfunctions, industrial companies have to produce, improve their production tools, maintain their equipment in operational condition and, lastly, satisfy the market in real time with finished products in their warehouses. Practical handling solutions are therefore essential in these factories and warehouses. To ensure that products reach the market quickly and on time, factories and warehouses need to have the right handling equipment to match their capacity and the size of the product being handled. A better understanding of the concept of handling is therefore essential.
Today, handling refers to any operation involving the transport or support of a load, the lifting, placing, pushing, pulling, carrying or moving of which requires the physical effort of one or more persons and which, because of its characteristics or the conditions in which it is carried out, may involve risks to the health and safety of workers.
Any part of the body can be affected by an injury during handling [1]. These injuries are generally part of a type of injury associated with the musculoskeletal system, which includes muscles, tendons, tendon sheaths, ligaments, bursae, joints, nerves, blood vessels and bones. Injuries and pain in the back, neck and upper and lower limbs affecting the musculoskeletal system are frequently classified as Musculoskeletal Disorders (MSDs) or Repetitive Strain Injuries (RSIs).
When it comes to handling loads, mechanical maintenance workshops have a wide range of lifting equipment. There are tools for every application, whether it's lifting a vehicle, plates or a component (engine, transmission and differential).
The use of lifting equipment requires the presence of intermediate parts to ensure the connection between the equipment and the load.
The choice of forklift trucks as the practical setting for this project is based on several aspects. Firstly, it is linked to the opportunity offered by a research programme focusing on motorised industrial vehicles (MIVs), with the aim of understanding the activity of forklift drivers and reducing the risks associated with rollovers and collisions. In addition, forklift trucks are considered to be one of the basic types of handling equipment in industrial and commercial companies and are used in different types of work contexts [2]. In addition, accidents involving forklifts and the variability of models and brands on the market are other aspects that have determined the choice of these vehicles. Accidents involving forklift trucks can be fatal or cause very serious injuries. Based on a review of the information provided by

manufacturers and distributors, as well as observations in the field, we also found that there is considerable variability between makes and models.
The problem of forklift trucks rolling over on their sides is frequently reported, and its effects on forklift operators are often unfortunate, even fatal [3]. According to the CSST, from 1974 to 1994, sideways rollover was responsible for 31% of serious or fatal accidents involving forklift trucks, i.e. approximately 4 deaths per year in Québec [4], [5]. The trucks most often involved are forklift trucks with cantilevered forks and counterweights, with a nominal capacity of 2000 to 3000 kg, whether they are powered by petrol, propane or electricity [4]. These vehicles operate both indoors and outdoors. Lateral rollovers occur when the forklift is empty (86% of cases) or when manoeuvring with the load at height [5]. Given the forklift's poor lateral stability, a sudden turn (even at almost zero speed), excessive speed when cornering (at 9 km/h or more, i.e. half its maximum speed), or driving over an obstacle on the ground are enough to cause the forklift to overturn [3].
Because of its intrinsic characteristics, improving the stability of the forklift truck is very complex. What's more, in the event of a sideways rollover, there are few means of protecting the driver, and the rollover time is often too short for the driver to have time to react. In an effort to increase safety, manufacturers have installed devices taken from the automotive industry (such as seat belts, wrap-around seats, armrests, etc.). However, they have never been adequately validated for forklift trucks, given that the stability and behaviour of a truck in a rollover situation differs significantly from that of a car involved in a collision. Their effectiveness is therefore still not clearly established, and depending on the tests carried out, the protocol used and the organisation carrying out the tests, the effects of safety devices differ and are sometimes even contradictory [6-10]. The studies already carried out show that there is no simple solution available. In addition, in response to the needs expressed by workplaces and the CSST, any solution will have to be integrated into manufacturers' designs if it is to have any chance of being adopted.
In order to better develop this paper, it will be structured in three main parts: literature review, materials and methods, and expected results and discussion.

2. Literature review

Many people see handling as a necessary evil in logistics jargon, labelling it as an activity with no added value. Yet its absence is very costly to the company, and this is where its importance lies. It is the exchange value [11]. While for a long-time companies focused on production resources, they are now concentrating much more on logistics functions [12].

2.1. Concept of transport

2.1.1. Literature review

Georges [12] defines logistics as the process of ensuring the efficient flow of goods and information from the point of origin to the point of consumption, via all storage and distribution points.
Logistics does not deal with the manufacture or transformation of products, which is a production activity. It is responsible for supplying products at the right time, in the right place, at the lowest cost and with the desired quality [11], [13-15].
The concept and field of application of logistics are changing with industrial development. It now takes into account the entire product life cycle with the introduction of reverse logistics [16].

2.1.2. The two logistics functions: warehousing and handling

Warehousing: This is the action of grouping together the goods or merchandise that make up the stock in a warehouse. Preferably, these are arranged in a specific order and in physical conditions that are conducive to their preservation and retrieval [15]. The terms warehousing and storage are sometimes considered synonymous in stock management. The difference is simply one of duration. Warehousing is intended to be temporary, whereas storage offers a solution for an indefinite period. The term storage warehouse is a pleonasm, because storage can also take place in a warehouse [15].
Handling: The action of automatically, mechanically or manually moving goods over a short distance, usually within a building such as a warehouse, using handling equipment. Handling is different from manipulation and transport.
Manipulation: This is limited to movements carried out within the area of a workstation, whereas transport corresponds to movements over long distances and generally outside the workplace [15].
All logistics chains have at least one or more warehouses [17].
The storage of goods is as old as history itself [18]. The purpose of warehouses is to store goods and protect them against loss, theft, damage, deterioration and bad weather. It helps to regulate supply and demand by keeping stocks of goods close to customers or consumers. Thanks to the warehouse, it is possible to meet deadlines, react more effectively to strong market reactivity and optimise logistics costs [14].

2.1.3. Roles of the warehouse

The main functions of the warehouse are:
- Receiving goods arriving from outside,
- storing them for a finite period of time,
- Picking goods for order preparation,
- Dispatch to customers.

Other activities that can be considered as sub-functions are also carried out in the warehouse, such as inspection and quality control, quarantine, sorting, packaging, etc [19-25].
The products stored may be in the form of individual loads or in bulk. Isolated loads are the grouping together of several individual products in cartons, for example, to facilitate transport, handling, storage and delivery. When several individual loads are grouped together on a pallet, they form a palletised load. A palletised load is an assembly consisting of a pallet, or other related support, and the pallet it supports [15]. Bulk products are most often ores that are neither stowed nor packaged. They can be collected either in piles or in silos. The materials do not form the same heaps, so care must be taken with the angle at the top and the surface area at the base to avoid any danger of landslides, particularly during reclamation. Silos make it possible to avoid these disadvantages and increase the quantity stored.

When bulk products are packaged in bags, containers or other types of packaging, they naturally form isolated loads [13].

2.2. Handling systems

2.2.1. Handling framework and objectives

These are divided into two (2) main groups, i.e. typically in a factory and the objectives themselves.

- In a typical factory:
- 25% of heavy work is done in handling;
- 55% of the factory floor is reserved for handling;
- Also 87% of production time;
- Represents 15 to 70% of the total costs generated by the company.
- The objectives themselves:
- Reduce unit production costs;
- Maintain or improve product quality, reduce damage and protect materials;
- Maintain safety and improve working conditions;
- Promote productivity;
- Improve growth through usability;
- Control inventories.

2.2.2. Handling system equation

Any handling system can be equated in the form given by:
Materials + movements + methods = preferred system
This equation is obtained by answering the questions in the diagram in Figure 1.

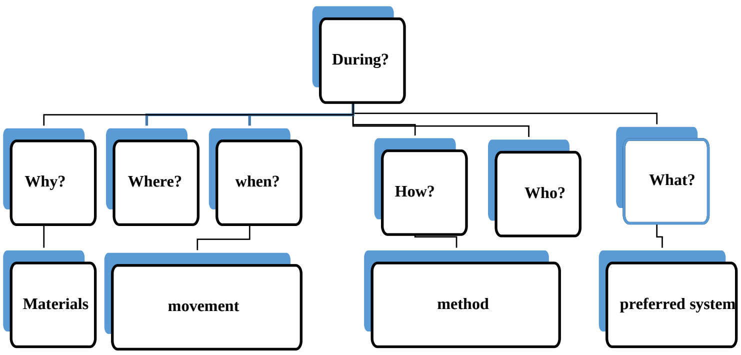

Fig. 1: Handling System Equation [15].

2.3 Selection of handling and storage equipment

2.3.1. Selection context

Handling and storage" (H&S) operations in factories and distribution systems such as warehouses can be carried out either manually or using equipment known as "handling and storage equipment" (HSE). Apple et al. [26] adhere to the philosophy that H&W operations should be manual unless conditions require H&W: "start with a solution based on manual processes and substitute with mechanisation/automation when the initial solution is no longer sufficient".
The Material Handling Institute [27] publishes on its website a taxonomy of EMEs created by Kay [28] and classified into five broad categories: transport equipment, positioning equipment, load unit formation equipment, storage equipment, and control and identification equipment. This taxonomy is inspired by different classifications of EMEs [29, 30] and a more detailed taxonomy of EMEs is proposed by Ward [31].

2.3.2. Problems encountered when selecting handling and storage equipment

There are three points to consider. We try to find out where the selection of EME takes place. What type of load unit is being targeted? What is the level of integration of the ME? Some answers to these questions are given in the following paragraphs, with examples of some representative articles.

2.3.3. Facilities

2.3.3.1. Manufacturing (Ma / FMS / FMC / CMS / IMS / KS - MRS)

Hadi-Vencheh & Mohamadghasemi [32] classify different conveyor/conveyor alternatives for a manufacturing facility. Other articles specify precisely the type of manufacturing system such as the flexible workshop which is translated into English as flexible manufacturing system (FMS), flexible manufacturing cells (FMC), and cellular manufacturing system (CMS). The CMS EMS selection problem of Lashkari et al. [33] is an extension of the work of Paulo et al. [34] dealing with the allocation of operations and the selection of EMEs in an FMS. The same problem of allocating operations and selecting EMEs in an FMS has been extended and modified by other researchers. Integrated manufacturing systems (IMS) are discussed by Kouvelis & Lee [35]. An IMS can be achieved without computers and automation in production and ME because Toyota's just-in-time (JIT) system results in production system integration via Kanban [35]. Yilmaz et al. [36] address the problem of line feeding systems such as kitting system (KS) and milk-run system (MRS).

2.3.3.2. Specific industries (EAI / IFA / IAu)

Certain specific industries are among the areas explored by the articles, namely the electronics assembly industry (EAI) [37]; the iron and steel industry (IFA) [38]; and the automotive industry (IAu) [39].

2.3.3.3. Warehouses (W)

EME types are similarly used in warehouses and distribution systems. Trevino et al. [40] address the problem of warehouse equipment and forklift selection and layout design for (E) warehouses. Poon et al. [41] address the selection and allocation of MSE in manufacturing and warehousing considering stochastic production demand. Tuzkaya et al. [42] note that EME selection in warehouses is particularly ignored.

2.3.3.4. General (G)

The problem addressed in an article is classified as general (G) when it considers a category or type of EME without specifying a particular type of installation. The article by Malmborg et al. [43] is in group G since it deals with the selection of industrial trucks without specifying a type of installation. According to Kay's [28] taxonomy, industrial trucks range from manual industrial trucks through forklifts to Automated Guided Vehicles (AGVs). They can be used for dock operations, unit load storage, order picking, in-process handling, and outdoor yard handling. Another example is Castleberry [44] who provides a decision analysis procedure for the selection of Automated Guided Vehicle Systems (AGVS).

2.3.4. Integration of handling and storage

2.3.4.1. Manual handling (MM)

Rossi et al. [45] integrate the ergonomic aspect into the EMT selection problem. They provide an evaluation between manual handling (MM) and that assisted by a Liftronic® EASY E80 INDEVA industrial manipulator.

2.3.4.2. Equipment (EME / EMEA)

Several works in the literature deal with the selection of a single EMT. For example, Chakraborty & Prasad [46] discuss the selection of industrial trucks. The models of Jiamruangjarus & Naenna [47] and Nguyen et al. [48] are designed for the selection of conveyors / transporters. Sometimes only automated EMTs (AEMTs) such as AGVs are considered [49].

2.3.4.3. System (SME / ST / SMEA)

EMS selection is referred to in most papers as the selection of a group of equipment consisting of different EMEs for different ME operations [50]. Raman et al. [51] determine the number of EMTs required to achieve efficient material flow in the EMS. Bauters et al. [52] provide a simulation model to evaluate different transportation systems (TS) in the automotive industry. Some papers only consider automated handling and storage systems (AHSS) such as self-guided vehicle systems (SVGA), automated storage systems (AS/RS) and "autonomous vehicle storage and retrieval system" (AVS/RS). This is the case of Rahman, Hussain, Kharlamov, Ali and Saif Ul (2007) who deal with SVGAs with robots and conveyors with robots. There is some work in the literature evaluating the performance of SMEAs [53, 54].

2.4. Self-propelled industrial trucks

2.4.1. Background to the selection of self-propelled forklift trucks

Handling and moving material is a common part of production operations, and forklift trucks are ubiquitous handling equipment in the companies we serve. Unfortunately, they are also involved in many accidents, often with serious consequences. Even if a forklift is no bigger than a small car, it weighs at least five times as much, and often carries loads as heavy as a car. The operator, known as the forklift truck driver, does not have the same visibility as behind the panoramic windows of a car, and his manoeuvres are far more complex. Finally, the tipping of a forklift truck, even at low speed, often knocks the operator off his feet and crushes him mercilessly. Yet driving a mobile car is much more regulated (manufacturing, safety, training, licences, highway code, etc.) than driving a forklift truck.
It is therefore easy to understand why, in 2007, the legislator introduced four new sections dealing specifically with lift trucks into the Regulation respecting occupational health and safety (RROHS), in section xxiii Handling and transport of material [55-58]:

- Minimum age for forklift operators (s. 256.2) in force since January 6, 2007;
- Driver training (s. 256.3) in force since 6 January 2007;
- Operator restraint system (a. 256.1) in force since 4 January 2008;
- Lifting a worker (s. 261) in force since 4 January 2008.

These regulatory changes have breathed new life into forklift truck safety, with a particular focus on compulsory training for forklift truck operators.
This data sheet covers the following subjects, all relating to the handling and transportation of materials:

- Definition and types of forklift trucks for lifting a person;
- Driver training and restraint systems;
- Pedestrians and signalling, pallet racking, loading bays.

2.4.2. Definition of a forklift truck

An existential question if ever there was one! But what is a forklift truck? Intuitively, we could say that a forklift truck is not a transport vehicle like a car. Rather, it is a handling machine used to lift and stack loads, transport them over short distances and lower and unload them.
Article 1 "Definitions" of the RROHS does not provide any definition of lift trucks. Further on, Article 256, "Forklift trucks", while not defining them, does require them to comply with the Safety Standard for Low Lift and High Lift Trucks B56.1-19931,2. There are several

types of forklift truck: cantilevered forklift trucks (the "classic" counterbalanced forklift) and high-lift trucks with a liftable driver's platform (the famous "order-picker"), of course, but also ride-on trucks, low-lift trucks, powered pedestrian trucks (or electric pallet trucks), and so on.

These models vary according to:

- whether the truck has a low or high lift (load lifting height);
- the operator's posture: seated, mounted (standing), walk-behind;
- whether or not the driving position can be raised;
- the type of grip (side, front, retractable).

Each model may have specific features that require training for the forklift operator.

2.4.3. Drawing up specifications

In order to purchase a forklift truck that meets the selected selection criteria, the user must draw up a set of specifications to submit to the supplier. The specifications are the document that informs the supplier of the customer's precise requirements and reassures him that he has supplied the customer with equipment that meets these expectations in accordance with the regulations. Its content is defined in fascicle ED1450 safety specifications for the consultation of the invitation to tender when purchasing handling equipment. The specifications must include the following points, among others:

- A reminder of the applicable regulations;
- Reference to standards;
- Specifications relating to technical standards, such as
- Nature of loads to be transported (weight and centre of gravity);
- Lifting height;
- Door clearance height;
- Width of aisles;
- Ground conditions;
- Indoor traffic;
- Outdoor traffic: night-time on public roads;
- Electrical or thermal energy.
- Terms and conditions of delivery and supplier intervention;
- Documentation to be supplied: maintenance and operating instructions;
- Staff training requirements (forklift drivers).

2.5. Solutions proposed to prevent accidents and/or improve operations

Various solutions have been proposed to improve comfort and reduce the risks associated with forklift truck driving positions. These solutions mainly concern: a) accidents, b) visibility, c) vibrations and d) controls.

2.5.1. Accidents

Several elements have been identified to help reduce slips and falls:

covering the cab floor with non-slip material, lowering the cab access area as much as possible [2]. As for rollovers and collisions, three elements are proposed: wearing a seatbelt fastened from the shoulders upwards [59], using a restraint system added to the driver's seat and a speed limiter to help control speed when travelling and avoid rollovers [60]. Currently, all manufacturers cover the floor of their trucks with anti-slip material. Manufacturers such as Toyota, Hyster and Caterpillar mention in their catalogues the presence of a low step for access to the cab.

In terms of rollover protection, all trucks are doubly equipped with

Equipped with a restraint system plus a safety belt. Although the speed limiter is still an optional extra, manufacturers are becoming increasingly aware of the importance of this device, to such an extent that Toyota's new Tonero series includes it in its catalogue as one of the elements to be considered when purchasing a truck.

2.5.2. Visibility

Three solutions were proposed: changing the structure of the mast (shape and dimensions), adding mirrors and using a pivoting cab. The mast has become thinner and the protection system for the lifting system simpler. In the early 90s, most forklift truck manufacturers introduced the "high visibility mast". For example, Toyota introduced a mast that improved forward visibility area to 59%, compared with 50% for most others. To accommodate rearward driving, several manufacturers have installed mirrors on both sides and in the centre [60] to allow drivers to look without turning their trunk or neck. However, mirrors pose a problem: they allow one-sided vision and are ineffective in blind spots. What's more, the risk of collisions increases if the mirrors are very far from the truck [2]; forklift drivers do not use them to reverse [61].

More recently, Linde has introduced a pivoting cab to its new Panorama series. The design allows the driver to swivel the seat 45 degrees to the right if the forward field of vision is obstructed by a bulky load. A joystick control is located on the seat. A set of pedals is also placed on the right-hand side so that it can be activated when the seat is 45 degrees from the dashboard [2]. This rotation makes it possible to look backwards without adopting an awkward posture.

2.5.3. Vibration and noise

Various solutions have been explored to reduce vibrations. Verchoore et al. [62] studied tyre characteristics and driving comfort using various types of tyres and seats. The solution of a seat with an anti-vibration system appears to be more effective than simply replacing the tyres. The integration of an anti-vibration system under the seat has been very popular and is strongly recommended [2]. According to

Angel Alberto [2], raising the engine to a 35-degree angle significantly reduced vibrations, rather than isolating the cab from the engine with noise-absorbing materials or separating the cab from the rest of the chassis with a hydraulic suspension system.

2.5.4. Controls

Two aspects are fundamental: location [63] and the forces to be applied. One of the solutions being explored is the installation of a swivel seat for driving in reverse, with controls located directly on the seat, to enable the driver to operate the controls with his arms resting on the armrest and to reduce awkward postures. Researchers such as [64] recommend that all controls (levers and pedals) as well as the steering wheel should be adjustable. These should be located close together to save movement [2, 64], and allow better handling. This proximity would also reduce static forces [2]. Experts also recommend the use of a hydraulic mechanism capable of transmitting the forces applied to the controls to the truck's various systems.
Overall, all the modifications made to trucks by manufacturers over the years and the solutions provided by researchers have been aimed at improving driver-truck interaction.

3. Materials and methods

In this section, we present the material we used to prepare this work and the methodology we employed to achieve it. This paper is the result of an industrial problem involving injuries sustained by forklift truck drivers during sideways rollovers. The general objective of this study is to model forklift trucks and forklift drivers in order to predict their rollover. This modelling will enable manufacturers of forklift trucks and accessories to test different safety systems to be fitted to their vehicles under different accident conditions (low/high speed, more or less rigid floor, steering wheel held by 1 or 2 hands, etc.).

3.1. Materials

The equipment consists of a laptop computer (ProBook 450) and the self-propelled trolley shown in Figure 2.

- Performance :

Travel speeds are in the region of 15 to 20 km/h for electric forklifts and 20 to 25 km/h for internal combustion forklifts.
Lifting speeds are generally between 0.25m/s and 0.40 m/s.
The capacity of these truck's ranges from less than 1,000 kg to 50,000 kg.

Fig. 2: Self-Propelled Forklift and Its Operating Performance.

3.2. Methodology

Generally speaking, the steps in the methodology are: (1) to assess the needs of the manufacturers, (2) to create the kinematic models of the forklift truck and the operator, taking into account the needs expressed by the manufacturers, (3) to simulate lateral rollover conditions, (4) to develop the interface for the data capture software and (5) to simulate several safety system situations and compare the results with the data taken from the existing literature. The following paragraphs summarise the main stages of this research project and give the latest results.

3.2.1. Assessment of the needs of forklift truck and accessory manufacturers

The first part of the research project consisted of targeting and contacting manufacturers of forklift trucks and accessories in order to find out their needs with regard to the problem of driver safety. A number of manufacturers and distributors of forklift trucks and accessories as well as stakeholders involved in forklift truck safety research and standardisation were met. Needs and expectations were determined by discussing with them their current means of improving vehicle safety, and in particular solving the problem of forklift trucks tipping over sideways. These meetings also enabled us to assess their willingness and ability, both in material and human terms, to get involved in our project.

3.2.2. Model development

The broad outlines of the development of the models of the forklift truck, the driver and the safety systems are set out in the paragraphs below.

3.2.2.1. Choice of software

The first step in developing the models was to evaluate and select the rigid body modelling software. Of the ten or so software packages listed, two were considered in particular: MADYMO and ADAMS. The latter had been used for the project's feasibility study [65] but posed problems in terms of modelling the forklift operator. The selection criteria were based on both mechanical and biomechanical modelling capabilities, the possibility of parameterising the models, and the platform used to ensure that it was compatible with that of the manufacturers.

3.2.2.2. Mechanical modelling of the forklift truck

The category of forklift trucks targeted by the study includes those with cantilevered forks and counterweights, with a nominal capacity of 2000 to 3000 kg, powered by petrol, propane or electricity, as these are the forklift trucks most susceptible to lateral overturning [3]. The geometry of the truck was simplified in order to retain only those elements that were necessary and sufficient to define the computer model. In addition, this model was parameterised to represent any type of truck in the chosen category by entering only the characteristic parameters (such as track width, wheelbase, front tyre diameter, counterweight mass, chassis inertias, etc.). To do this, it was necessary to define the dimensions and characteristic properties of a forklift truck to model the different types of forklift trucks involved in the project, and then program the forklift model files.
Other data such as masses, inertia and centres of gravity were calculated or estimated from solid geometric models of these parts produced using CATIA CAD software. Eventually, these data could be measured directly on the truck under study.

3.2.2.3. Biomechanical modelling of the forklift operator

Modelling of the driver was developed using the database of dummies available in the modelling software version 5.4. The 50th percentile Hybrid III anthropomorphic dummy (in weight and size) was selected as it is the most appropriate for our simulations of a forklift truck lateral rollover. In fact, it represents an "average" forklift driver. All the biomechanical properties of the dummy (joint stiffness and damping, masses and inertias of the 37 different body segments, etc.) were taken directly from the software database. The biomechanical properties of the dummy therefore represent the real Hybrid III dummy of the 50th percentile in weight and size.

3.2.2.4 Modelling safety systems

Several safety systems were modelled, including a seat with lateral hip support (or armrests), a seat with lateral shoulder support, a lap belt (pelvic belt) and doors. These are the devices most commonly used today and referenced in the literature, although there are many other types, such as helmets and airbags, which can be modelled later if required. In all cases, the contacts between the driver and these safety systems have been defined by providing the properties of contact stiffness, damping and friction.

3.2.3. Development of simulations

Two types of lateral rollover simulations were developed, similar to those carried out during the feasibility study [3] and those used by Johnson [9]: "static" low-speed simulations and "dynamic" higher-speed simulations. Analysis of the results and calculation of the trauma severity criteria for each of the simulations made it possible to quantify the effect on the driver of the protection systems and other parameters tested.
The progress reports and technical details of the methodology are followed for the static and dynamic simulations of the forklift and driver rollover. Only the broad outlines of these models are given in the paragraphs below.

3.2.3.1. Static simulations

The "static" simulations correspond to an "unstable" rollover situation at very low speed. They are approximated by placing a forklift at a standstill on a tilting table which tilts at a constant angular velocity of 30°/second or 0.523 rad/s. Friction parameters between the forklift and the floor were introduced to allow the forklift to glide over the floor after impact. The impact properties on the ground (stiffness, damping and friction) were adjusted according to the type of ground and the contact properties of the segments of the driver or trolley concerned.

3.2.3.2. Dynamic simulations

These simulations correspond to a situation where the forklift truck is unstable due to the centripetal forces generated when cornering at higher speeds.
Dynamic modelling is carried out by subjecting the model of the forklift truck and driver to a variable A_c normal and A_t tangential acceleration field that takes into account the change in direction of the velocity vector as well as the variation in velocity over time.
This acceleration field is equivalent to the acceleration that the forklift truck would undergo when taking a given bend at a certain initial speed, with the driver being able to brake more or less strongly.

3.2.3.3. Trauma severity criteria

Craniocerebral trauma is predominant in the lateral rollover of a forklift truck. Initially, the Head Injury Criterion (HIC) (Duquette & Benoit, 1997; Johnson, 1999) and the resulting maximum accelerations of the head and torso were considered, as they are the most widely used in the literature for lateral rollover. The HIC criterion is calculated from the resultant acceleration at the centre of gravity of the head as a function of time according to the area under this curve over a given period of time, generally 36 ms [3-5]. The animation of the simulation was evaluated to ensure that the driver was not crushed by the protective structure, which happens regularly in rollovers without seatbelts.

3.2.4. Development of the CARISSIMO software

The primary objective of the CARISSIMO software is to provide a user-friendly interface to the simulation software, enabling manufacturers of forklift trucks and accessories to use the models and simulations for the integrated design of safety components. This interface was developed using Microsoft's ACCESS software.
CARISSIMO's design criteria were to:

- Specify the characteristic parameters associated with the definition of the forklift model (wheelbase, diameter of the front wheels, mass of the forks, inertia of the counterweight, lateral spacing of the forks, etc.);
- Position the driver (back angle, position of hands-on steering wheel, steering wheel grip force);
- Specify the parameters of the model(s) of safety system(s) to be fitted to the forklift truck (armrests, lap belt, etc.);
- Choose the conditions for lateral tipping (static: speed at which the plate rises; dynamic: rolling speed, braking speed; type of floor, etc.);
- Manage the database (save, modify, copy, duplicate, etc.);
- Export information to create models and run simulations in the dynamic simulation software.

In this way, the manufacturer only has to enter the required parameters via the CARISSIMO interactive interface to easily create the forklift model and its operator in the desired conditions. The manufacturer will therefore need no knowledge of the modelling software to achieve his goals.

3.3. Model evaluation

3.3.1. Exploitation of the forklift truck and driver models

Several series of simulations were carried out to exploit the forklift truck and driver models developed.
The very first study [68] consisted of identifying the forklift parameters that had the greatest influence on the forklift's sensitivity to lateral rollover during a static simulation. A statistical experimental design was used to study the effects of 15 characteristic parameters on the forklift's lateral rollover, i.e. on the critical angle of inclination of the plate that causes the vehicle to roll over. These 15 parameters are the overall width, the front and rear track width, the mass and inertia Ixx of the chassis, the z-position of the CG of the counterweight, the inertia Ixx of the counterweight, the mass and inertia Ixx of the rear axle, the z-position of the CG of the motor, the mass and inertia Ixx of the motor, the mass of the mast, the limit angle of rotation of the rear axle pivot and the z-height of the rear axle pivot.
The aim of the second study [69] was to identify the seat parameters with the greatest influence on the trauma suffered by the driver when the truck overturns sideways. An experimental design made it possible to study the effects of 3 parameters on the HIC and the resulting speed of the head on impact with the ground. These 3 parameters are the rigidity of the polyurethane foam, the coefficient of friction of the contact between the driver and the seat and the protuberances of the backrest.
The third series consisted of testing other parameters in the "static" case, i.e. with a forklift at a standstill on a lifting plate tilting at the given angular speed. The following influence tests were carried out:

- Angular speed of 30 to 60°/second;
- Forklift tyre stiffnesses from 600 to 6666 kN/m (1500 kN/m by default);
- Floor stiffnesses from 25 to 200 MN/m (100 MN/m by default);
- Safety systems: lap belt, lap belt + armrests, lap belt + side shoulder restraints, lap belt + doors, armrests, side shoulder restraints, doors, no safety systems (default lap belt);
- Maximum steering wheel holding force from 190 to 820 N (default 460 N);
- Tyre geometry;
- Torsional stiffness of the steering wheel;
- Steering wheel hold modelling.

When the influence of a parameter is not tested, this parameter is equal to its default value defined previously.
The fourth series consisted of testing several parameters in the "dynamic" case, i.e. with a forklift truck travelling at a given speed before taking a bend.
The following influence tests were carried out:

- Driving speed of 10 to 20 km/h (default 20 km/h);
- Safety systems: lap belt + armrests, lap belt and lateral shoulder restraints by default, no safety system (lap belt + lateral shoulder restraints);
- Influence of steering wheel position.
- Turning radius of 4 or 5 m (default 4 m);
- Braking speed.

When the influence of a parameter is not tested, this parameter is equal to its default value defined above. The other parameters are set at 100MN/m for the ground (asphalt), 1500 kN/m for the tyres (superelastic), 2-handed steering (12 degrees of freedom) with medium grip force, and 0.28g braking performed 0.6 seconds after entering the bend.

3.3.2. Preliminary assessment

An initial assessment of the modelling was carried out by comparing the main results of the simulations with some published data [9, 70]. The parameters considered are the HIC, the maximum acceleration of the operator's head and the rollover time.

3.3.3. Preliminary tests for experimental validation

A series of simulations was carried out in order to obtain the experimental characterisations required for the subsequent validation of the forklift truck and dummy models. Tests of the influence of the stiffnesses of the doors, seat and seatbelt, and of the damping and friction of the forklift/ground contact were carried out to determine whether the parameters needed to be characterised experimentally.

4. Results and discussion

The final results of the various stages presented in the methodology are presented below in the same order.

4.1. Model development

4.1.1. Choice of software

The trolley modelling feasibility study had also been used by Johnson for Hyster trolley rollover simulations [9]. However, given the problems of modelling the human body encountered with ADAMS [66, 67], the modelling of a forklift truck, its driver and the simulation of a lateral rollover were carried out. MADYMO was found to be more relevant, better adapted and more efficient than ADAMS.

4.1.2. Forklift development

The forklift model created in the feasibility study with ADAMS [67] is shown in Figure 3a while the forklift model created with MADYMO is shown in Figure 3b. This forklift, a Toyota 42-5FG20, whose current model is fully functional in MADYMO, comprises 11 bodies (excluding safety systems), namely (1) the engine, (2) the chassis, steering wheel and pedal system, (3) the counterweight, (4) the safety structure, (5) the fork, grid and mast system, (6) the front wheels, (7) the rear wheels, (8) the external fuel tank, (9) the seat, (10) the front axle and (11) the rear axle with oscillating movement limited to ± 5°.

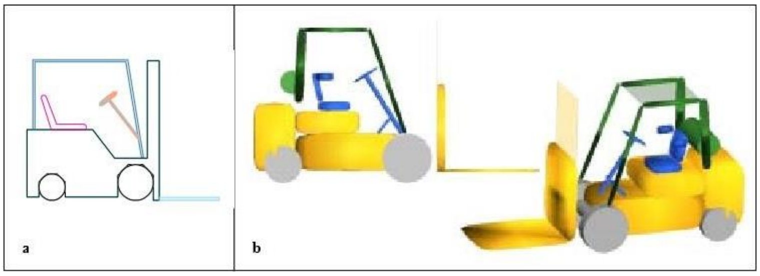

Fig. 3: Model of the Forklift Made with ADAMS (A), Compared with the One Made with MADYMO (B).

The parts of the forklift truck are considered to be rigid. The contacts between these parts and the external elements (driver, floor, lifting plate) are rigid, with the exception of the steering wheel, the seat (made of polyurethane foam) and the tyres (pneumatic or solid), which are flexible. Sufficiently detailed geometry ensures that the impact of the forklift on the ground and contact with the operator during sideways tipping are correctly managed.
The truck model is parameterised for its dimensions and mechanical properties. For example, it is possible to specify its wheelbase, front and rear track width, counterweight mass and inertia, etc. In all, the truck has 156 parameters, including 11 for the engine, 23 for the chassis, steering wheel and pedals system, 12 for the counterweight, 19 for the safety structure, 17 for the forks, grid and mast system, 18 for the front and rear wheels, 24 for the external fuel tank, 12 for the seat, and 20 for the axles.

4.1.3. Development of the forklift operator

The forklift operator model chosen was a 50th percentile HYBRID III dummy representing an "average" forklift operator. The preliminary modelling of the forklift operator on Adams comprised 12 segments (Figure 4). The characteristics of the preliminary study are reported in [67].

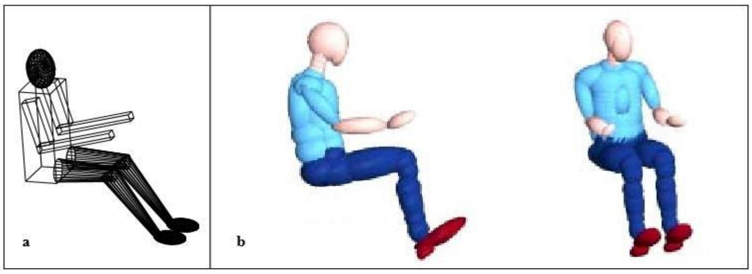

Fig. 4: Modelling the Forklift Operator on ADAMS (A) and MADYMO (B).

Most of the android's segments have contact properties supplied with MADYMO to manage the android's contacts with its environment. However, some segments (abdomen, neck, head, shoulders, arms, hands and thighs) have no associated contact properties. We therefore had to make assumptions about the missing contact stiffnesses, and we therefore used the stiffnesses of other segments that "resemble" the segment in question, or stiffnesses from the literature: the contact stiffnesses of the thighs, arms and hands were assumed to be equivalent to those of the lower legs; the contact stiffnesses of the shoulders and abdomen were assumed to be equivalent to those of the hips and lower torso; the contact stiffness of the head was based on data from an SAE report on lorry rollovers [71].
The biomechanical properties of the operator's segments and joints are defined to give him a realistic dynamic behaviour during the lateral tipping of the truck and all the contacts are defined with his environment (stiffness, damping and friction).
Most of the android's segments have contact properties provided to manage the android's contacts with its environment. However, some segments (abdomen, neck, head, shoulders, arms, hands and thighs) have no associated contact properties. We therefore had to make assumptions about the missing contact stiffnesses, and we therefore used the stiffnesses of other segments that "resemble" the segment in question, or stiffnesses from the literature: the contact stiffnesses of the thighs, arms and hands were assumed to be equivalent to those of

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The biomechanical properties of the operator's segments and joints are thus defined to give him a realistic dynamic behaviour during the lateral tipping of the truck and all the contacts are defined with his environment (stiffnesses, damping and friction).

4.1.4. Development of safety systems

The lateral supports are represented by ellipsoids, with the actual dimensions of the armrests and shoulder supports. Their contact properties, which are fairly rigid, are identical. Solid doors are modelled using two ellipsoids that extend down to the chassis. The geometry is very simplified, but should give a good idea of the influence of the doors. The contact properties are given by defining the same force-depression function as the armrests and shoulder supports, as a first approximation. A study of the influence of the stiffness of the door has been carried out, but the trauma suffered by the driver hardly changes even if the door is ten times stiffer.

4.2. Development of simulations

4.2.1. Static simulations

A static simulation was carried out using the most "standard" rollover conditions at low speed, 30°/s. The vehicle was fitted with super-elastic tyres and rolled over on an asphalt surface, with the driver held by a lap belt who held the steering wheel with 2 hands and a medium grip force. The results are given in Table 1.
The lateral supports are represented by ellipsoids, with the actual dimensions of the armrests and shoulder supports. Their contact properties, which are fairly rigid, are identical. Solid doors are modelled using two ellipsoids that extend down to the chassis. The geometry is very simplified, but should give a good idea of the influence of the doors. The contact properties are given by defining the same force-depression function as the armrests and shoulder supports, as a first approximation. A study of the influence of the stiffness of the door has been carried out, but the trauma suffered by the driver hardly changes even if the door is ten times stiffer.

Table 1: Static Results with Belt

Abdominal safety belt	
HIC criterion	4078
Max. resultant head acceleration (m/s^2)	4415
Max. resultant acceleration of the upper torso (m/s^2)	835
Max. resultant acceleration of the lower torso (m/s^2)	241
Max. resulting head speed (m/s)	4.16
Max. resulting upper torso speed (m/s)	3.49
Max. resulting lower torso speed (m/s)	2.92

The HIC is very high, above the 1000 risk threshold for the appearance of brain damage.

4.2.2. Dynamic simulations

A dynamic simulation was carried out using the conditions most representative of a high-speed rollover, i.e. a truck travelling at 20 km/h and then braking at 0.28g 0.6 seconds after entering a 4-metre bend. The vehicle is fitted with super-elastic tyres and rolls over on an asphalt surface with the driver held by a lap belt and lateral hip restraints who holds the steering wheel with 2 hands and a medium grip force. The numerical results are given in Table 2.

Table 2: Results of Cornering from 4 to 20 Km/H and Braking of 0.28g

Lap belt and armrests	
HIC criterion	2801
Max. resultant head acceleration (m/s^2)	4041
Max. resultant acceleration of the upper torso (m/s^2)	640
Max. resultant acceleration of the lower torso (m/s^2)	478
Max. resulting head speed (m/s)	5.69
Max. resulting upper torso speed (m/s)	5.29
Max. resulting lower torso speed (m/s)	4.81

The HIC is still high and above the risk threshold for the appearance of brain damage of 1000.

4.3. Development of the CARISSIMO software

CARISSIMO was created in Microsoft Access. A demonstration version is currently functional. The CARISSIMO main menu allows you to:
1) enter or modify data relating to the trucks
2) provide data on accident conditions (9 parameters),
3) position the driver and (4 parameters),
4) select safety systems (165 parameters minimum), and
5) manage the database.

4.4. Evaluation of the models

4.4.1. Use of the models

4.4.1.1. Static simulations

In the following paragraphs, only the simulations testing the influence of the intrinsic parameters of the truck and its seat, the floor, the safety systems and the steering wheel position will be described, as these were the ones that gave the most significant results.
Based on a statistical analysis of the results of the experimental design carried out by Statistica, it was determined that the significant factors (at more than 5%) were the overall width (A), the position (B) in z of the CG of the counterweight, and the width (C) of the rear and front tracks. The significant effect of these parameters A, B and C was to be expected as these factors directly affect the stability base of the truck, but in practice it is often impossible to change these values due to restrictions on aisle width and manoeuvrability of the forklift, as not all trucks have the same overall width, z-position of the counterweight CG and width of the front and rear lanes. The z-position of the CG of the counterweight also has a major influence (around 50% of the influence of A) on the stability of the truck, since the centre of gravity of the counterweight is high in relation to the chassis.
For the influence of the seat, based on a statistical analysis of the results of the experimental design with Statistica (Johnson, 1988), it was possible to determine that no factor was significant at 5% with the modalities used.
The test for the influence of soil gives the results given in Table 3. The conditions are:

- Static simulations at 30°/s,
- vehicle fitted with superelastic tyres,
- driver held by a lap belt and armrests,
- steering wheel held by 2 hands (6 degrees of freedom per hand) with medium grip force,
- 65 psi foam seat.

Table 3: Results of the Influence of Soil Stiffness

	STATIC		
	a)	b)	c)
HIC criteria	3561	3368	3499
Max. resultant head acceleration (m/s^2)	4226	4146	4112
Max. resultant acceleration of the upper torso (m/s^2)	864	851	826
Max. resultant acceleration of the lower torso (m/s^2)	252	324	314
Max. resulting head speed (m/s)	4.15	4.16	4.15
Max. resulting upper torso speed (m/s)	3.50	3.49	3.49
Max. resulting lower torso speed (m/s)	2.93	2.92	2.92

(a) K_{soil} = 25 MN/m (compacted gravel); (b) K_{soil} = 100 MN/m (asphalt); (c) K_{soil} = 200 MN/m (asphalt).

The results for the HIC criterion and the acceleration of the head and torso are very high in all cases, and the HIC is always greater than 1000. This means that all the parameters evaluated remain virtually unchanged. The range of stiffness of the floor studied, on which the trucks usually travel, does not therefore seem to influence the severity of the operator's injuries during a sideways rollover.
The test of the influence of the safety systems gives the results given in Table 4. The conditions are:

- Static simulation at 30°/s,
- vehicle fitted with superelastic tyres,
- asphalt floor,
- steering wheel held by 2 hands (6 degrees of freedom per hand) with medium grip force,
- 65 psi foam seat.

Table 4: Results of the Influence of Static Safety Systems

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
HIC criteria	*	4078	2854	4702	81	3368	**	82
Max. resultant head acceleration (m/s^2)	84	4415	3802	4696	536	4146	151	553
Max. resultant acceleration of the upper torso (m/s^2)	219	835	715	809	192	851	383	271
Max. resultant acceleration of the lower torso (m/s^2)	485	241	142	173	211	324	205	162
Max. resulting head speed (m/s)	3.59	4.16	3.75	4.37	4.27	4.16	4.39	4.11
Max. resulting upper torso speed (m/s)	3.55	3.49	3.78	3.85	3.75	3.49	3.58	3.49
Max. resulting lower torso speed (m/s)	3.79	2.92	3.57	3.38	3.19	2.92	2.89	2.92

With legends: (a) no safety system; (b) belt; (c) armrests; (d) shoulder restraint; (e) doors; (f) belt + armrests; (g) belt + shoulder restraint; (h) belt + doors.
* driver ejected from the truck and crushed by the FOPS
** driver not touching the ground with his head.
All the parameters measured (HIC, accelerations, speeds) presented in Table 4 are sensitive to changes in safety systems. In particular, in the case of static rollover, the shoulder support system with belt and side doors, whether or not combined with a lap belt, are the most promising protection systems. The case without a safety system, the case with lateral hip support (armrests) with or without a belt and the case with the belt alone appear to be the most dangerous for the driver. In the case without a belt, the driver is very often ejected from his seat and crushed in the neck by the safety structure when the truck hits the ground. This part of the modelling is at least similar to what happens in industrial accidents. These results are indicative only, as the models of the truck, driver and safety systems will first have to be validated experimentally before the effectiveness of the driver protection systems can be asserted. In addition, it should be emphasised that static rollover is only one particular condition for the lateral rollover of a forklift truck.
The following two figures illustrate the position of the driver at the same moment of the rollover (t = 1.55 s) in two cases. Figure 5 shows the driver who is ejected from the vehicle because there is no safety system and his neck will be trapped under the safety structure (FOPS). Figure 6 shows the driver using a shoulder support system and a lap belt. In this case, the driver is better restrained and still has the strength to hold on to the steering wheel.

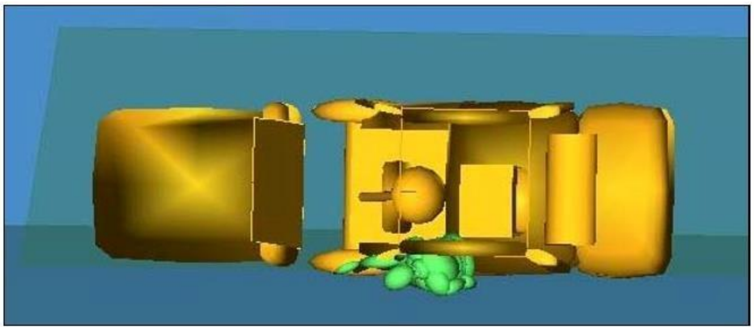

Fig. 5: Lateral Rollover Without A Safety System (Just Before the Truck Hits the Ground).

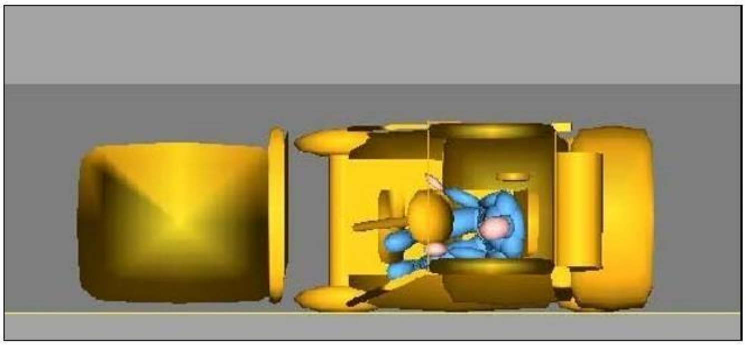

Fig. 6: Lateral Rollover with Shoulder Support System (Just Before the Truck Hits the Ground).

The test of the influence of steering wheel hold gives the results shown in Table 5. The conditions are:

- Static simulation at 30°/s,
- vehicle fitted with superelastic tyres,
- asphalt floor,
- lap belt,
- steering wheel with 1 degree of freedom per hand,
- 65 psi foam seat.

Table 5: Results of the Influence of the Static Steering Wheel Position

	Low 1 hand Left	Average 1 hand Left	Strong 1 hand Left	Low 1 hand Right	Average 1 hand Right	Strong 1 hand Right	Low 2 hands	Average 2 hands	Strong 2 hands
HIC criterion	2749	3005	2930	2231	2282	2263	1955	3157	3128
Max. res. head acceleration (m/s^2)	3546	3885	3913	3189	3314	3303	3003	3967	4000
Max. acceleration res. lower torso (m/s^2)	176	137	136	211	183	185	209	214	209

The acceleration of the lower torso remained virtually unchanged, whereas the acceleration and HIC of the head were more sensitive to changes in the grip on the steering wheel. It would appear from this study that a medium to strong grip with both hands on the steering wheel is more dangerous (higher HIC) than any other case. The best case would be to hold the steering wheel lightly with both hands, if the modelling of hand contact with the steering wheel is validated experimentally with the forklift truck and forklift operator. In all these cases, the HIC criterion predicts major and even fatal injuries (HIC = 1000: risk threshold for the appearance of brain damage). However, it cannot be concluded that the effect will be the same with other combinations of safety systems.

4.4.1.2. Dynamic simulations

In the following paragraphs, only the simulations testing the influence of the turning radius and safety systems will be presented, as these are the most significant results.

The test of the influence of the turning radius gives the results given in Table 6 and Figure 7. The conditions are as follows:

- vehicle fitted with superelastic tyres,
- asphalt surface,
- braking of 0.28 to 0.47g,
- steering wheel held with 2 hands (6 degrees of freedom per hand) with a medium grip force,
- 65 psi foam seat,
- seat belt and armrests.

Table 6: Results of 4 and 5 M Bends at 20 Km/H and Braking of 0.28g

	Braking 0.28g		Braking 0.28g	
	Curve R = 4	Curve R = 5	Curve R = 4	Curve R = 5
Max. resulting head speed (m/s)	5.69	1.96	5.46	1.96
Max. resulting upper torso speed (m/s)	5.29	1.08	4.87	1.08
Max. resulting lower torso speed (m/s)	4.81	0.74	4.43	0.71

Max. resultant head acceleration (m/s^2)	4041	20.4	4345	22.0
Max. resultant acceleration of the upper torso (m/s^2)	640	17.9	661	17.9
Max. resultant acceleration of the lower torso (m/s^2)	478	13.4	329	13.4
HIC criterion	2801	*	2657	*

* Driver not touching the ground with his head, HIC not significant.

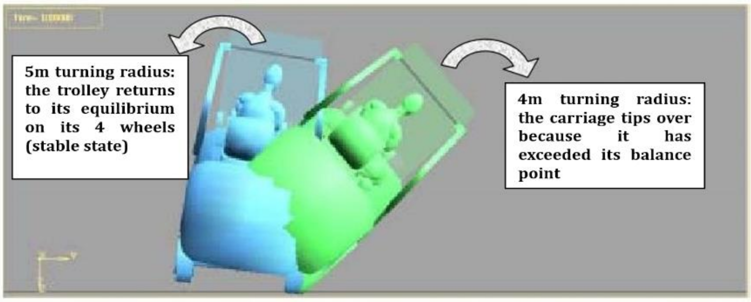

Fig. 7: Comparison of A 4 and 5 Metre Bend.

We can see that the results are quite different, since in a 4-metre bend the forklift tilts, whereas it tilts slightly but returns to its equilibrium position in the case of the 5-metre bend (Figure 7). Furthermore, in the case of the 4-metre bend, the driver's head touches the ground and the HIC is higher than the limit of 1000.

The test of the influence of the safety systems gives the results given in Table 7. The conditions are:

- Dynamic simulations at 20 km/h with deceleration of 0.28g within a radius of 4m,
- vehicle fitted with superelastic tyres,
- asphalt surface,
- 2-handed steering wheel grip (6 degrees of freedom per hand) with medium grip force,
- 65 lb/in2 foam seat.

Table 7: Results of the Influence of Dynamic Safety Systems at 20 Km/H

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
HIC criterion	*	1549	7733	2997	1672	2801	* *	844
Max. resultant acceleration of the head (m/s^2)	2815	3499	5420	3736	2963	4041	190	1777
Max. resultant acceleration of the upper torso (m/s^2)	458	597	1384	1335	576	640	433	457
Max. resultant acceleration of the lower torso (m/s^2)	611	896	323	579	221	478	384	177
Max. resulting head speed (m/s)	6.63	5.59	6.37	6.45	6.30	5.69	6.22	5.59
Max. resulting upper torso speed (m/s)	6.83	5.21	5.82	5.89	6.03	5.29	5.55	5.21
Max. resulting lower torso speed (m/s)	6.91	4.79	5.43	5.50	5.68	4.81	4.84	4.79

With the following captions:
(a) no safety system; (b) belt; (c) armrests; (d) shoulder restraint; (e) doors; (f) belt + armrests; (g) belt + shoulder restraint; (h) belt + doors.
* driver ejected from the truck and crushed by the FOPS
** driver not touching the ground with his head

The restraint system used by the forklift operator has a major impact on the injuries sustained. The worst case is when the forklift has no safety system at all, because the driver is run over by the forklift. The other systems perform poorly, with an HIC ranging from 1672 to 7733, except for the belt with a shoulder or door restraint system. But only the shoulder restraint system with a belt seems to have a very beneficial effect on any injuries to the driver, because the driver's head does not hit the ground. However, the speed of the head is higher than normal. These results are indicative only, as models of the truck, driver and safety systems will first have to be validated experimentally before it will be possible to draw more definite conclusions about the effectiveness of driver protection systems.

4.4.2. Preliminary assessment

Table 8 compares some of the results of our simulations with those published.

Table 8: Comparison of the Results of Our Simulations with Those Published

		abdominal belt and shoulder support	belt and armrests	without safety system
HRC	static literature	68 to 897 [9]; 1815 to 8654 [7]; 52 to 773 [72]; 1461 to 3292 [73]	12 to 865 [9]	4 to 64 [7]; 283 to 1787 [73]; 8 to 216 [74]
	dynamic literature	242-682 [9]	34-652 [9]	152 to 1813 [74]
	static simulations	21 to 32	2987 to 8092	3 to 39
	dynamic simulations	21 to 24	1936 to 3327	804 to 1217
Acceleration acceleration head	static literature	246 to 744 g [7]; 33 to 271 g [72]; 412 to 608 g [73]	-	5 to 79 g [7]; 214 g [72]; 131 to 452 g [73]; 14 to 130 g [74]
	dynamic literature	-	-	79 to 342 g [74]
	static simulations	151 to 183 g	382 to 585 g	84 to 691 g
	dynamic simulations	157 to 190 g	1 to 482 g	2815 to 2541 g

Static rollover time (CG over wheels) - literature - simulations	1.3 s [9] (exp) 1.4 s [9] (simu) 1.0 to 1.5 s [73] (exp) Approx. 0.8 second
Dynamic rollover time since wheels lifted off ground - literature - simulations	1.05 secondes [73] 0.95 seconde
Dynamic rollover time (CG over wheels) - literature - simulations	0.4 seconds [9] 0.4 seconds

These few comparisons show that the model's rollover times are very close to the values obtained from the literature and the animations seem fairly realistic.
The resulting maximum accelerations of the head are also fairly close to the literature in most cases. However, the HIC is very different except in the case without a safety system.
These differences are firstly attributable to the conditions of the computer or experimental tests (type of truck, type of driver modelling, static and dynamic test methods, etc.), which are only very sparsely described in the literature. Many of these parameters can have a significant influence on the results. In fact, as the study by Riendeau [68] and the comments given in paragraph 3.3.1 show, forklift truck properties such as track width or the centre of gravity of the counterweight have a major influence on the behaviour of the forklift and therefore on driver injuries. A difference in the dimensions of the forklift alone can therefore lead to major differences in the simulation results. This is why, even from one article in the literature to another, the results vary enormously. This highlights the importance of experiments to validate the modelling.
The only means available to us to check the fidelity of the rollover representation is therefore, firstly, to make a visual assessment of the dynamic behaviour of our model of the forklift truck and the operator during the lateral rollover (which seems to be good). Secondly, to evaluate the numerical results by comparing the different simulation cases. Finally, to propose an experimental test method to validate the computer model, which will be the focus of this paper.

4.4.3. Preliminary simulations for experimental validation

These simulations showed that none of the parameters tested (door stiffnesses between k and 100*k, seat and seat belt stiffness, damping and friction of the trolley/floor contact) within the modalities likely to be encountered appear to have a sufficient influence to require experimental characterisation before the tests with the trolley and the dummy.

4.4. Experimental validation

Experimental validation, which is essential before using the CARISSIMO software to design the forklift truck or the protective devices, will have to be carried out in another paper. This will involve experimental evaluations using forklift trucks and anthropomorphic dummies to ensure the quality of our simulations of lateral rollovers. A pre-study based on the preliminary design of test rigs for simulating the lateral rollover of a forklift truck [75] has already highlighted two possible solutions at reasonable cost for validating static and dynamic simulations. In the static case, a lifting plate mounted by jacks is used, and in the dynamic case, a rail describing a bend that the forklift must follow. A research protocol, describing in detail the test rigs to be used and the equipment required, will be proposed at the end of this paper. Changes may therefore be made to the techniques and number of tests.
All the numerical results of the simulations in this research project are given for information only, as they are obviously conditional on the experimental validation of the models of the forklift truck, the driver and the safety systems, which will take place in a later phase of the project.
The results of the static and dynamic simulations show that the models of the forklift truck and driver are functional and relatively realistic, at least according to the few data available in the literature and according to those involved in the field. The results show that the type of floor has little influence on the driver's injuries, but that the safety systems used have a very strong influence, for both static and dynamic rollover cases. In the current state of modelling, doors and shoulder restraints used in conjunction with a lap belt appear to be more effective in protecting the driver than armrests with or without a lap belt or without any restraint system.

5. Conclusion and outlook

The forklift and forklift operator modelling for side rollover simulation developed in this paper is very advanced, currently capturing most of the information required for the simulations is functional for the main tasks and will be completed as the forklift and forklift operator models are improved. All the numerical results of the simulations in this paper are given for information only, as they are obviously conditional on the experimental validation of the models of the truck, driver and safety systems, which will take place in a later phase of the paper.
Simulations of the static lateral rollover of the forklift truck and driver to test the influence of the main parameters or to evaluate the influence of safety systems and steering wheel restraint show the good functionality of our models. These simulations show that, in general, the maximum speed of the driver's head or body are rarely critical, but that the acceleration of the head and the HIC criterion very often reach or exceed critical values for the driver. These last two results are therefore the most important for assessing the influence of safety systems on the driver. These simulations suggest that only shoulder restraint combined with a lap belt with a fairly loose two-handed grip on the steering wheel is the most promising situation from a safety point of view.
Simulations of the dynamic lateral tipping of the forklift truck and driver carried out to test two bend radii, several safety systems and the steering wheel restraint show that the modelling works well and is consistent. The forklift tilts in a 4m bend and regains its balance in a

5m bend. As in the static case, the use of a lap belt and shoulder support by holding the steering wheel with both hands appears to be the best solution, compared with the case with a lap belt and armrests or the case without a safety system.
The effectiveness of using doors seems much more uncertain, since they are effective in static cases, but not at all when conditions are more like a dynamic rollover.
An initial comparison of our results with the literature was made. Some of the results are different, but great care must be taken when making this comparison with the literature, since not all the published results are reliable, and the models and test conditions are often different and poorly defined. On the other hand, the rollover times and the animation of lateral rollovers are fairly similar and certainly the easiest to check, but give little or no information on the behaviour of the driver and his injuries during a rollover.
The next stage of the paper is now to experimentally validate the behaviour of the forklift truck and its interface with the driver. To do this, an initial series of (computer) influence tests has already been carried out to assess which parameters of the model need to be better defined. None of them seems to have sufficient influence to characterise these parameters, within the limits of the test conditions. However, these influence tests need to be carried out in greater depth to ensure that several model parameters are correctly taken into account, such as holding the steering wheel with one or two hands, to a greater or lesser extent. Manufacturers can repeat these tests themselves if they wish. The experimental tests will then consist of validating the model during a static and dynamic lateral rollover. The experimental data will also be used to adjust the modelling in MADYMO if necessary, so that we end up with a reliable model that is representative of reality and can be used to improve driver safety. Eventually, other, more sophisticated safety systems could be tested, such as a finite element-defined seatbelt or airbags.

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