UNIVERSIDAD AUTONOMA DE NUEVO LEON

FACULTAD DE INGENIERIA MECANICA Y ELECTRICA

SUBDIRECCIÓN DE ESTUDIOS DE POSGRADO

“DESIGN METHODOLOGY FOR FLEXIBLE BRAKE HOSES OF COMMERCIAL VEHICLES USING A COSSERAT-SOLVER”

Por:
DANIEL MORENO CÁRDENAS

EN OPCIÓN AL GRADO DE:
MAESTRÍA EN CIENCIAS DE LA INGENIERÍA AUTOMOTRIZ

SAN NICOLÁS DE LOS GARZA, NUEVO LEÓN FEBRERO, 2026

UNIVERSIDAD AUTONOMA DE NUEVO LEON

FACULTAD DE INGENIERIA MECANICA Y ELECTRICA

SUBDIRECCIÓN DE ESTUDIOS DE POSGRADO

“DESIGN METHODOLOGY FOR FLEXIBLE BRAKE HOSES OF COMMERCIAL VEHICLES USING A COSSERAT-SOLVER”

Por:
DANIEL MORENO CÁRDENAS

EN OPCIÓN AL GRADO DE:
MAESTRÍA EN CIENCIAS DE LA INGENIERÍA AUTOMOTRIZ

SAN NICOLÁS DE LOS GARZA, NUEVO LEÓN FEBRERO, 2026

UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN
Facultad de Ingeniería Mecánica y Eléctrica
Posgrado

Los miembros del Comité de Evaluación de Tesis recomendamos que la Tesis "Design methodology for flexible brake hoses of commercial vehicles using a Cosserat-solver", realizada por el estudiante Daniel Moreno Cárdenas, con número de matrícula 1799917, sea aceptada para su defensa como requisito parcial para obtener el grado de Maestría en Ciencias de la Ingeniería Automotriz.

El Comité de Evaluación de Tesis

Dra. Tania Paloma Berber Solano
Director

Dr. Oscar Jesús Zapata Hernández
Co-director

Dr. Martin Castillo Morales
Revisor

Dra. Adriana Salas Zamarripa
Revisor

M.C. Enrique Ángel Garza Fernández
Revisor

Vo.Bo.

Dr. Simón Martínez Martínez
Subdirector de Estudios de Posgrado

Institución 190001
Programa 554502
Acta Núm. 4654

Ciudad Universitaria, a febrero del 2026.

Acknowledgments

I would like to express my sincere gratitude to SECIHTI for the financial support granted during my academic studies and the development of this research.

I am also thankful to Universidad Autónoma de Nuevo León, for the support and opportunities provided during my academic studies. In addition, thanks to Facultad de Ingeniería Mecánica y Eléctrica, especially to the Maestría en Ciencias de la Ingeniería Automotriz and the professors from this program for providing me with the knowledge and tools needed during the development of this research.

Furthermore, I would like to thank Dra. Tania Berber Solano for the guidance, supervision and for all the knowledge shared throughout the project.

I am equally grateful to International® for providing me the opportunity to conduct this research, especially to Ing. Ruben Lopez, M.C. David Davalos, and M.C. Enrique Garza for providing guidance and knowledge needed to successfully conclude this research. Moreover, thanks to the pneumatics and hydraulics team who offered key support and advisement during the development of the project.

Thanks to my parents for all the support and motivation given over the course of my life, and for their advice offered during my career and development.

Finally, I would like to acknowledge the support from my friends, family, and people who have provided advisement and motivation which greatly contributed to my career and the development of this research.

Dedication

To my parents and to my brother, whose invaluable support has inspired and encouraged me to overcome challenges and pursue continuous development, being a constant source of strength and guidance in my life. This achievement would not have been possible without their love and encouragement.

Daniel Moreno Cárdenas

Table of content

List of Figures

List of Tables

Acronyms and Abbreviations

ABS	Anti-lock Braking System
ADAMS	Automated Dynamic Analysis of Mechanical Systems
API	Application Programing Interface
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CSV	Comma Separated Values
DOT	Department of transportation
FLEX	Flexible Line Explorer
FMVSS	Federal Motor Vehicle Safety Standards
IROS	International Ride Optimized Suspension
MBD	Multy Body Dynamics
NX	Siemens Computed Aided Design software
OBJ	Object file format
PETG	Polyethylene Tetephtalate Glycol
PID	Proportional Integral Derivative
RMSE	Root mean square error
SAE	Society of Automotive Engineering
Mpa	Mega Pascals
kg	Kilograms
m	Meters
mm	Milimeters
N	Newtons
deg	Degrees
in	Inches

Resume

Pneumatic braking systems utilize different hoses to communicate air pressure throughout all their components to reduce the vehicle speed. To maintain communication between static components mounted on the vehicle's chassis and the moving components at the wheel ends, flexible hoses are needed. They should accommodate all possible changes in position from the suspension and steering systems while ensuring proper airflow. Improper routing may cause undesired conditions such as contact between the hose and surrounding components, collapse of the internal diameter due to a sharp bend radius or severe twisting forces, and excessive tension on connectors that could tear the hose ends. These conditions should be avoided because they could lead to performance losses in the braking system or even complete failure. Therefore, it is crucial to design a proper flexible hose configuration; this means selecting the connector type and orientations together with the hose length that ensures correct braking performance throughout the full range of motion.

At International®, multiple internal design practices are defined to gauge the effectiveness of designs and ensure that no undesired conditions are presented. For this, a simulation stage takes places after the design phases to validate the behavior of the proposed configurations of flexible hoses. However, the current design tools present limitations and require multiple time-consuming iterations. Additionally, they cannot reliably predict the real shape of the components. Consequently, designers are unable to evaluate the behavior of their configurations and must wait for the simulation process to be completed so they can receive feedback. This ends up in a lengthy process that delays the overall development of new commercial vehicles.

In this research, a methodology for designing flexible hoses is presented to successfully validate configurations and identify the presence of undesired conditions in early stages. It integrates the use of Flexible Line Explorer (FLEX), a tool developed to reliably design flexible hoses, allowing their proper evaluation and correction if needed. For achieving this, an overall understanding of the components involved was done. Later, validation reports were analyzed to identify the key differences between accepted and rejected configurations according to internal design practices.. Afterwards, the FLEX software was developed by using PyElastica, a python implementation of an open-source project for simulating assemblies of slender, one-dimensional structures using Cosserat Rod theory. Finally, the tool was integrated into a step-by-step methodology that guides the design of the flexible hose configurations while permitting the detection of undesired conditions.

The development of this project presented advantages like providing cost free specialized tools for designing flexible hoses. Together with the proposed methodology, the design process is improved and the possibility of detecting undesired conditions was given. Additionally, it creates the opportunities for diverse research lines in future projects that can improve current design process where flexible elements are utilized.

Chapter 1: Introduction

Braking systems are crucial for commercial vehicles to reduce speed and bring the vehicle to a complete stop. They use pneumatic pressure due to their capabilities to develop and transmit high mechanical forces over great distances using simple parts. Reliability is crucial to ensure the proper function of the system. Therefore, each single component is evaluated carefully during the design stages to predict and avoid any possible defect.

Flexible hoses connect the brake lines from the chassis to the wheel-end components, transmitting pressure while allowing steering and suspension movement. Because of this motion, the hoses should withstand torsion, bending, and pulling while having enough clearance between surrounding components that could potentially damage them. Nevertheless, in certain situations, these behaviors could reach a limit where the system leads to reduced performance or even compromise braking capabilities completely.

Because of the mechanical properties of flexible hose, basic tools in CAD software may not be sufficient for all possible positions of the component, requiring time-consuming validations with CAE software to validate their behavior. This underscores the need for an improvement on the design techniques of flexible hoses, ensuring safety and improving the overall design release time.

In this research, a design methodology will be proposed, by implementing a software to design flexible hoses in a more realistic way, considering mechanical properties and external factors such as gravity. This with the purpose of recognizing and avoiding critical conditions that could potentially impact braking performance.

1.1 Problem statement

The relative motion between a vehicle's chassis and tires, necessary for steering and dampening road imperfections, requires flexible hoses to connect pneumatic or hydraulic systems, ensuring reliability for the optimal control of the vehicle.

Because of this movement, the relative position between connectors varies, leading the hoses to extend, twist, fold and approach other components, conditions that the flexible hose can accommodate within a certain range. In critical conditions these behaviors may cause a reduction in flow, kinking of the hose, contact with other surrounding pieces or even disconnection, which may lead the system to failure or performance loss. The term “undesired conditions” will be used to denotate this severe behavior.

Proper assessment of these critical conditions is crucial to avoid major problems in brake systems, so every design is sent to a validation area to evaluate its behavior. Additional verification methods include physical tests done by lifting a unit to see the behavior of these components. The main limitation of this validation method is that real units may not be available to perform the tests. These validations can take from 2 to 6 months to complete. Once the design is approved, it is released for subsequent phases and the eventual production.

If, during validation or after assembly, any if the undesired conditions on the flexible hoses are detected, a redesign is needed, delaying the program release time. Current design strategies include using basic tools available in the CAD software. Nevertheless, these methods have limitations and require multiple time-consuming iterations and do not show feasible designs in specific conditions. Additionally, these tools do not always allow designers to easily recognize the presence of undesired conditions. In consequence, the design of flexible hose configurations relies on the previous experience of the designers, who might not have feedback on the hose conditions until the finalization of the simulation process, requiring time consuming reworks for correcting the configurations.

These restrictions highlight the necessity for a fast and reliable method to design flexible hoses while being able to evaluate the presence of undesired conditions in early design phases, ensuring safety and avoiding time-consuming reworks.

1.2 Justification

The flexible hoses utilized in commercial vehicles are essential for the safe and reliable operation of braking systems. These components are subjected to continuous deformation due to the relative motion between the chassis and axle components during steering and suspension travel, therefore, improper routing may lead the hoses to undesired behavior like kinking, twisting, or pulling, conditions that could potentially cause system failure or performance loss. Analyzing these conditions is crucial to ensure correct operation of the systems involved. Actual verification strategies ensure these safety requirements, finding defects before the design is released for production. However, recognizing these conditions in those advanced stages of the design process makes reworks time-consuming, impacting the program release timing.

Prioritizing reliability and safety of the system, and the time necessary for the program release, we can identify that a new methodology is necessary to allow designers to test the behavior of the flexible hoses and identify undesired conditions in early stages.

The purpose of this project is to establish a methodology for designing flexible brake hoses, with an emphasis on preventing undesired conditions like twisting, pulling and kinking. Implementing this strategy allows designers to perform the necessary improvements promptly, thereby reducing the incidence of time-consuming reworks, preventing delays in the scheduled program release time.

1.3 Relevant studies

This review aims to identify, analyze and compare the existing tools and approaches used in the virtual simulation of flexible components such as hoses, harnesses and wires. It provides a foundation for selecting the design tools and for defining the proposed methodology. These references will also serve as key elements for the discussion and interpretation of the results obtained throughout the development of this research.

The simulation of flexible components such as wire harnesses, cables and hoses has attracted significant research interest over the past two decades, utilizing different techniques. Some have developed software for this purpose. Chipperfield [1] presented a development of a C++ model to predict shapes of hydraulic hoses; it utilizes ADAMS software to calculate the predicted hose shape, and the C++ development works as a pre- and post-processing interface. The output of this integration is a file with the (x, y, z) positions of the hose points in their equilibrium position, as an approximation of the true path of the hose. This model was verified by comparing a real hose deformed in one plane with an output position file, achieving good results. Unfortunately, only bending applications were considered, arguing that torsional and axial models are not as important.

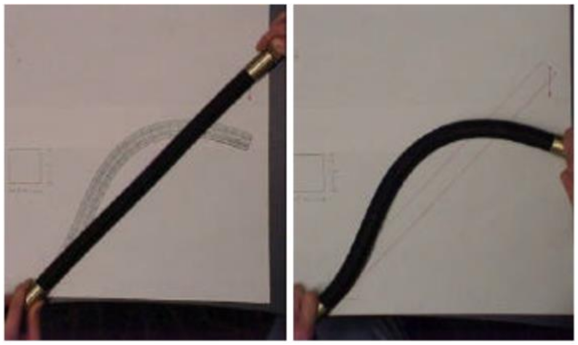


Figure 1.3.1 Real hose compared to hose model [1]

In another research work in this direction, Baaser [2] developed a C++ software, proposing a method to optimize the length of a brake hose. A numerical simulation at two different levels of observation was utilized. The first one for length optimization, utilizing the developed software to minimize the global bending energy as the sum of all given configurations as function of the hose length. On the other hand, the second numerical simulation was a finite element simulation, done to find the stress concentration at the bending state and make a lifetime prediction of the layered structure. The output of this was a 3D plot of the positions of points in the hose, that were compared with points obtained from a 3D scanned hose, showing good results. However, the effects of torsional energy were excluded from the analysis.

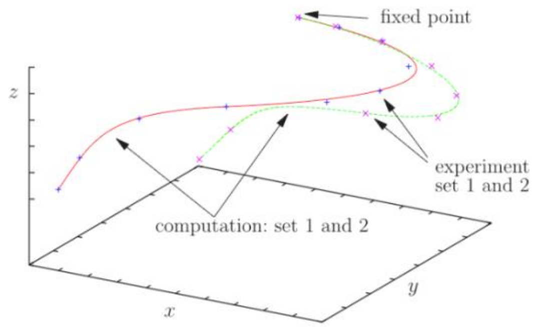


Figure 1.3.2 Experimental and computed shapes for two sets [2]**.**

Hermann et al. [3] presented a research work titled Search-based Real Time Prediction of Computer Aid Engineering Solutions with the objective of predicting the flexible hose position faster compared to conventional Computer Aid Engineering programs. In their approach, the hose is subdivided into smaller segments, each approximated by a known geometric configuration, which the authors refer to as *atomic shapes*. These fundamental shapes are stored in a database, and during prediction, the software identifies which atomic shapes best match the orientation and length between the hose connectors. By combining these predefined segments, the overall shape of the hose can be reconstructed The results of this research-based software are a plot of points that were compared with a set of points from a real hose, obtaining a deviation of approximately 10% along each axis. This validation was only made with a hose deformed in one plane and does not consider torsional efforts.

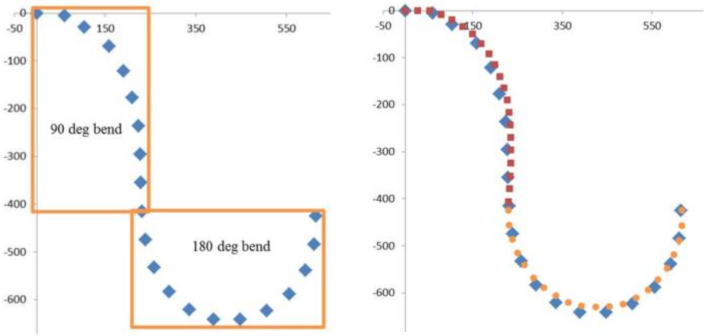


Figure 1.3.3 Real hose and calculated geometries [3]**.**

Raffaeli et al. [4], [5] present a knowledge-based approach for virtual prototyping of flexible parts in mechanical systems. The authors developed a knowledge-based system called FlexSim. It utilizes a Finite Element Method to simulate the behavior of the flexible hoses. This software can be integrated with CAD tools to visualize the hose in a virtual environment, providing important possibilities related to installation geometrical conditions. To validate the results of the virtual simulation, a test rig bench was designed to position the flexible hose in different positions; utilizing a 3D scanner, it was possible to compare the results. The author wrote that error increases with an increase in pipe length, but the results are normally good. This work does consider torsional effects and even allows simulating the weight of the hose and the fluid inside.

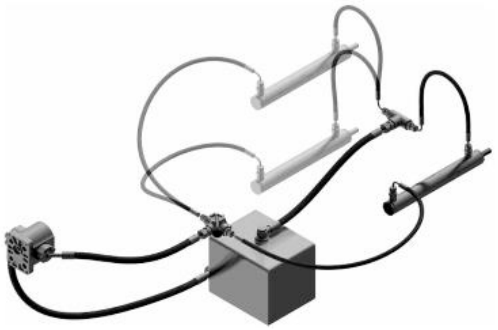


Figure 1.3.4 Modelled flexible pipes in alternative positions [5].

In recent years, Kim et al. [6] have proposed a graph-method routing algorithm to improve the routing design of different components of commercial vehicles. This work focuses on avoiding obstructions and adding support points to hold the component. For achieving this, a simplification of the CAD model into multiple cubes was made to improve the running time but with a less precise design layout. Then the routes were created in order of priority, considering end and beginning points and intermediary points. Nevertheless, the authors acknowledge that some effects were disregarded, like the number of bends, bending angles, or diameter of wires, tubes, and hoses.

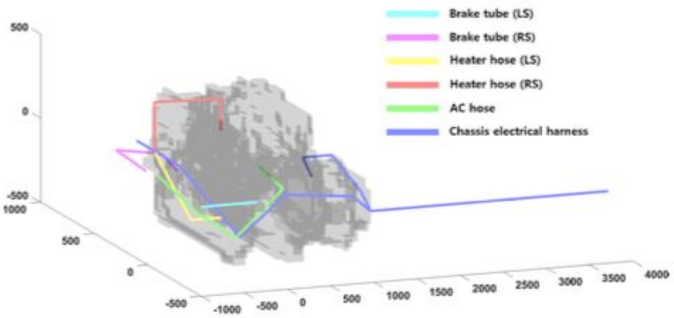


Figure 1.3.5 Design proposed by the routing algorithm [6].

In contrast to the previous research where software was developed to define the routing of flexible components, Tognolli et al. [7] utilized SimCenter 3D, a commercial software, to propose a validation methodology for virtual analysis of dynamic behavior for tubes and flexible hoses associated with suspension kinematics. The objective of this study was to optimize the analysis methodology proposed by other authors by evaluating 140 points on the range of motion instead of 977. To validate this methodology, a comparative analysis was made between a 3D scan of a McPherson-type front suspension and two virtual simulations: one with mathematical calculators and then one done with SimCenter 3D Flexible Pipe software, showing less difference with the second one. This work considers torsional behavior and rotation of the connectors.

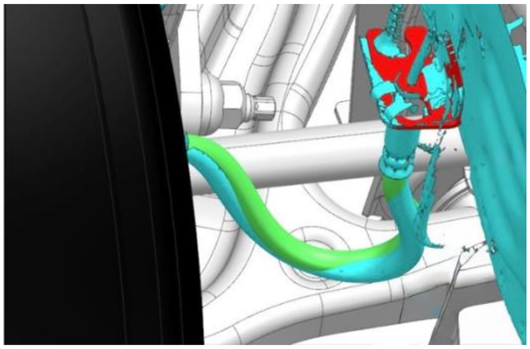


Figure 1.3.6 Real hose against generated with Flexible Pipe [7]**.**

1.4 Hypothesis

Based on the findings presented in the literature review, which demonstrate that developing and using proper design tools can predict the behavior of flexible hoses under real operating conditions, the following hypothesis is proposed:

Implementing a design methodology will make it possible to identify undesired conditions of flexible hoses like kinking, twisting, or pulling in early stages of the design process.

The previous findings support the expectation that, by detecting these issues before validation or assembly, a significant reduction in reworks is expected, leading to improvements in the overall delivery time of units.

1.5 Objectives

1.5.1 General objective

To develop a design methodology for flexible brake hoses of commercial vehicles, by means of the development of a Python application that utilizes Cosserat rod libraries. With the aim of improving the current design process, while preventing undesired conditions such as kinking, twisting and excessive tension or pulling of hoses.

1.5.2 Specific objectives

1. To conduct a literature review of key areas of study such as braking components, flexible hose characteristics, steering angles and suspension configuration, and their integration during vehicle assembly.

2. To perform a comparative analysis of flexible hose configurations, including those that were approved, rejected during validation, and those that failed during assembly or field operation, focusing on the associated system configuration and the specific failure modes or undesired conditions observed.

3. To build a theoretical framework by reviewing tools and methods used designing flexible components, emphasizing aspects such as accuracy, result visualization, and software integration.

4. To develop a design methodology for flexible brake hoses for preventing undesired conditions.

5. To evaluate and validate the performance of the proposed design methodology by comparing its results with those obtained through the current validation process and real 3D scanned hoses.

1.6 Thesis outline

This research is structured as follows:

The introduction focusses on developing and explaining the problem addressed by this project. It also contains related works on the subject, which served as the basis for defining the hypothesis. It concludes by mentioning the specific and general objectives proposed for testing the hypothesis.

The theoretical framework presents an overview of the systems and components related to the research. As mentioned before, commercial vehicles are the focus of the project; therefore, the information will be centered on them. It also includes a brief review of techniques for modelling flexible components, which helped to identify and select the Cosserat Theory for the development of the software.

The chapter on the methodology development includes multiple sections; the first one aims to merge the knowledge of the design and simulation departments by analyzing previous designs with and without undesired conditions to understand their differences. After this, a section will cover the development of the design software, starting with the theoretical basis to calculate the flexible hose position and requirements for its use; then, a summary of the reverse engineering performed to compare hoses generated by the software and real ones. Finally, it includes the detailed methodology for designing hose configurations.

The thesis concludes with the findings obtained from the development of the research, as well as suggestions for future research related to the subject.

Chapter 2: Theoretical framework

This section provides the theoretical background necessary to understand the components related to the braking hose, which is the focus of this study. The topics discussed in this theoretical framework are centered on commercial vehicles, as they constitute the primary scope of the project. It begins with an overview of the systems and elements involved in the research, and then concentrates on the flexible hose itself, including the applicable regulations and the failure conditions to be analyzed. Finally, a review of existing tools, simulation approaches, and methodologies for modeling flexible components is presented, laying the foundation for the selection and justification of the proposed methodology.

2.1 Braking systems

Braking systems are crucial parts of any vehicle, from recreational to commercial purposes. They are key components for the safety of drivers and people around them. There are two main ways in which the force is transmitted, hydraulic brake systems and pneumatic brake systems. Smaller scale passenger vehicles utilize some form of hydraulic braking system, that uses hydraulic fluid to operate the brakes. Meanwhile, air brakes use pressurized air to operate the braking system [8], [9] Hydraulic braking systems will not be discussed further, as this research is solely concentrated on pneumatic braking systems, which are prevalent in heavy-duty vehicles.

2.1.1 Pneumatic braking system

This system is used on large commercial vehicles because they can develop and transmit high mechanical forces over great distances using simple components. It uses compressed air stored in tanks to produce the force that is applied at each wheel [8]. A sample of a pneumatic braking system is shown in Figure 2.1.1.

The 5 main components of any air braking system are the following [10]:

1. Compressor: to build up and maintain air pressure
2. Reservoirs: to store the compressed air
3. Foot valve: to draw compressed air from reservoirs when it is needed for braking
4. Brake chambers: to transfer the force of compressed air to mechanical linkages
5. Brake shoes and drums or brake rotors and pads: to create the friction needed to stop the vehicle

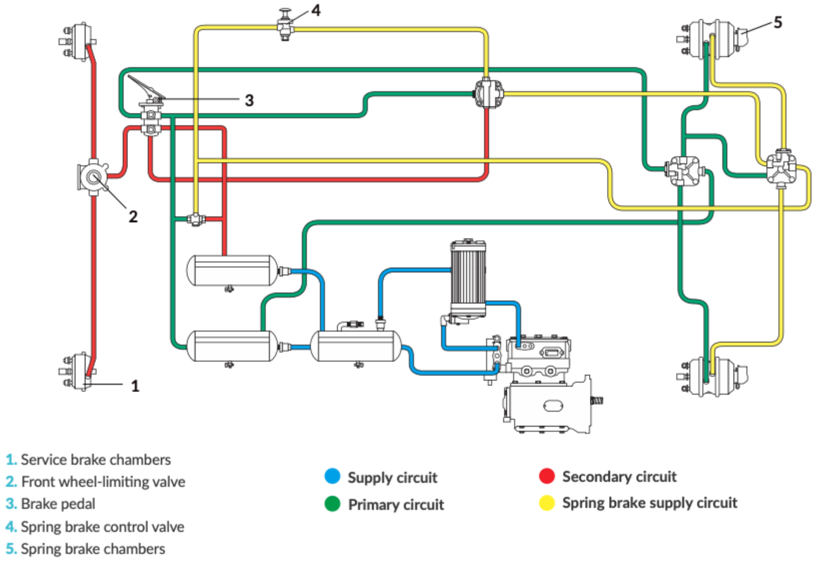
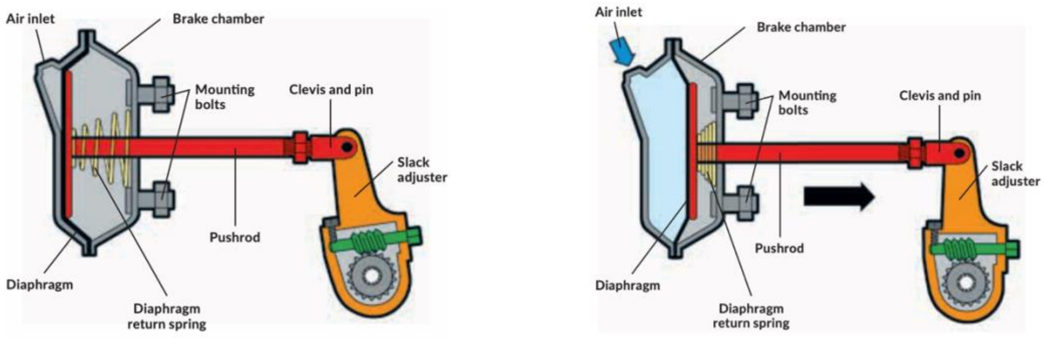


Figure 2.1.1 Pneumatic braking system [8].

The foot valve is linked to the brake pedal, when it is pressed, the air is allowed to flow from the reservoirs to the braking chambers building up pressure, that pushes the main rod linked to the braking mechanism, leading to the braking of the vehicle. When the braking pedal is released, air supply is closed and the relief valves are activated, allowing air to escape. This reduces the pressure in the braking chambers, retracting the rod and allowing the free movement of the tires [11]. For conducting the air pressure through valves and other components of the braking system, two types of conduits are typically used: rigid brake lines, and flexible hoses. The second ones are commonly referred to as brake hoses. Rigid brake lines, normally made from nylon, are used in places where there are no risks of damage from vibration, movement, or bending, since they are not elastic enough for withstanding deformations [11]. Brake hoses, which are the focus of this study, play a critical role in braking systems, since they are responsible for transferring the pneumatic pressure from the air tanks to the brake chambers, activating the brakes [12].

2.1.2 Brake chambers

Brake chambers are round metal containers located at each wheel, where compressed air is used to generate mechanical force to stop the vehicle. There are two kinds of pneumatic brake chambers: service and spring chambers. Service brake chambers are divided in the middle by a flexible diaphragm. They use air pressure to push a rod or a lever depending on the foundation brakes utilized (see section 2.1.3). When the air is released, a spring returns the components to their initial position. This force depends on the air pressure and the diameter of the diaphragm. Brake chambers frequently are smaller in the front axle than in the rear axles of the vehicle to reduce weight [13].



a) Brake not applied **b) Brake applied**

Figure 2.1.2 Service brake chambers [8]

The movement of the pushrod extending from the brake chamber is called pushrod stroke, and stroke length is the distance that the pushrod travels out of the chamber [8]. In case of using "S" cam brake, the slack adjusters allow changing the initial position from where the rotation starts; in consequence, the end position also changes.

2.1.3 Foundation brakes

The brake assembly components at the wheel of a vehicle are normally called foundation components because they are the base from where the rest of the system is built. They are the mechanical parts contained in or around the wheels that are operated by the air brake systems. Although these braking mechanisms (disc, wedge, and "S" cam) can also be actuated using hydraulic systems, in this research they are discussed only in the context of pneumatic actuation, since the focus of the study is on pneumatic brake systems. A vehicle can use several designs of foundation brake subsystems in the same vehicle. There are tree types of foundation brakes: “S” cam brakes, disk brakes and wedge brakes [8]. Wedge brakes will not be discussed because they are not used at International®.

2.1.3.1 “S” cam brakes

They are the most common type of brake used in commercial vehicles with pneumatic braking systems. As seen in Figure 2.1.3, the air chamber pushes the pushrod and makes the camshaft rotate. This causes the “S” shape at the end of the camshaft to push the brake shoes against the drum, creating friction and reducing the speed of the wheel [8].

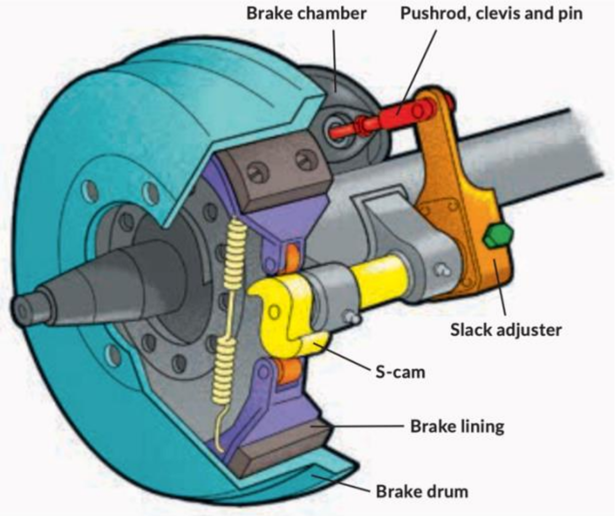


Figure 2.1.3 "S" cam brake [8].

The drum and brake shoes are located within the wheel together with other components to hold these parts in position. There are internal and external components, like the head of the “S” camshaft, the camshaft rollers that rotate with the camshaft while moving the brake shoes outward and inward, and the return spring to pull back the braking shoes to the released position [8].

2.1.3.2 Disc brakes

Disc brakes convert air pressure into braking force in a slightly different way. A cross-section view showing the brake operation can be seen in Figure 2.1.4. When the brake pedal is pressed, air enters the brake chamber creating pressure in the diaphragm. This pressure applies force to the pressure plate pushing the pressure plate forward. The pushrod acts against acts on the internal lever which pivots over an eccentric bearing moving the bridge, transferring motion to two threaded tubes and tappers, which move the inner brake pad. The force from the inner brake pad slides the caliper on two stationary guide pins, pulling the outer pad into the rotor, and applying the braking force over the disc [14].

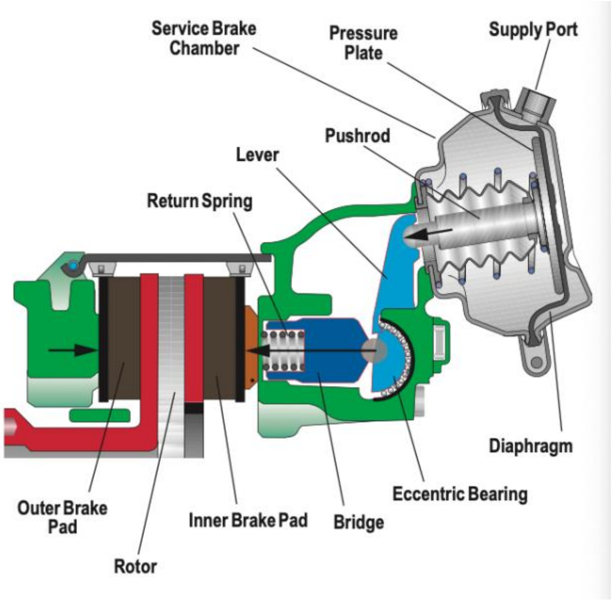


Figure 2.1.4 Pneumatic disc brake [14].

When the brake pedal is released, the pressure in the chamber is exhausted, allowing the return spring in the chamber and bridge to retorn the disc to a neutral, non-braked position [14]. In disc brakes, the position of the chamber may shift towards the disc to compensate for pad ware.

2.2 Suspension system

Suspension systems in commercial vehicles have a crucial role in performance and stability. They allow to handle bumps, dips, and anything encountered on the road. The high weight from the vehicle and its load, require suspensions that help soften the impact of harsh bumps on the road [15].

The key components of a commercial vehicle suspension system function together to enhance vehicle performance and durability under extreme conditions. The main components used are springs, shock absorbers, control arms, and axles. Springs like leaf springs offer the necessary load support and shock absorption. Shock absorbers have a crucial role in the control of rebound of the springs, helping with stability and comfort. In addition, control arms and axles ensure the correct alignment and movement of the wheel. The design of suspensions for commercial vehicles emphasizes durability, to withstand tough terrains and the demanding workloads while ensuring safety and efficient performance [16].

Suspension systems can have different configurations, in this section will be mentioned some of the categories of suspension systems utilized in front and rear axles.

2.2.1 Multileaf (flat leaf) springs

Multileaf springs use several layers of metal strips or "leaves" with constant width, stacked from the larger on top gradually decreasing in length towards the bottom, this reduces stress in single points and enhances the suspension durability [17]. They can be found as front or rear suspension, and with variations to accommodate different riding environments. For rear suspensions they can be found in single or even tandem configuration, these second ones are suspensions that share the same working mechanism in two paired axles. In Figure 2.2.1 Leaf spring with shock absorbers [18]. its shown a variation of this multileaf springs that uses shock absorbers to control rebound.

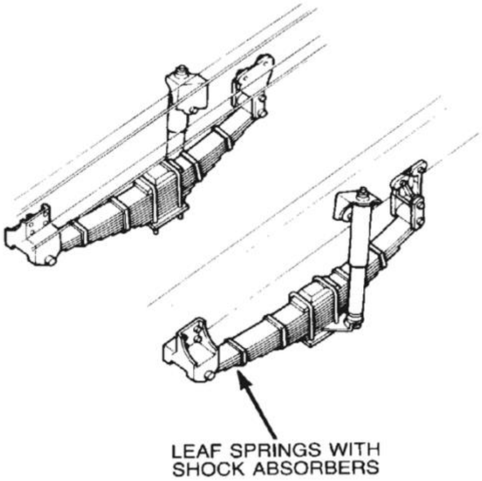


Figure 2.2.1 Leaf spring with shock absorbers [18]**.**

2.2.2 Air suspensions

Air suspensions use air bags to dampen motion; one example is the International Ride Optimized Suspensions (IROS).. These suspensions are known for their excellent ride quality and their lightweight design. They are designed for on-highway use, enhancing driver comfort while protecting cargo from the harsh and vibration caused by poor road surfaces. IROS suspensions have multiple benefits, like Height-control to maintain constant frame height at the rear axle, high lateral stiffness for improved handling, increased roll stiffness for improved control in turns and crosswinds, among many others [18]. Air suspensions are normally found in the rear of the vehicles, in single or tandem configuration.

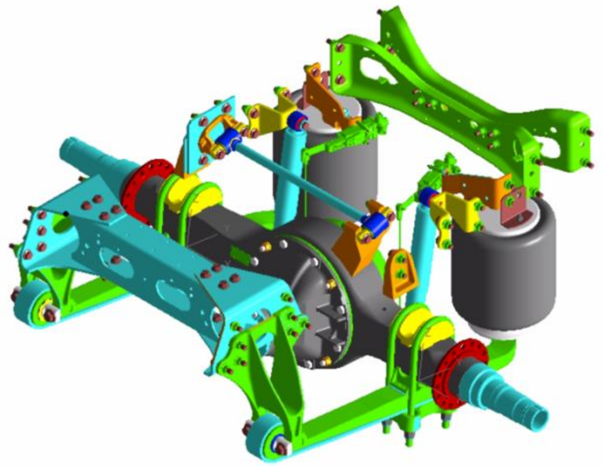


Figure 2.2.2 International Ride Optimied Suspension (IROS) [18]**.**

2.2.3 Solid mount suspensions:

Solid mount suspensions have no springs to absorb road shock. They are used in severe service applications where maximum roll stability is essential. Although a solid mount suspension is designed for maximum stability, it has a design named Walking Beam. It consists of a beam that connects the axles while allowing them to “walk” over bumps [18]. They are found in rear axles in tandem configuration.

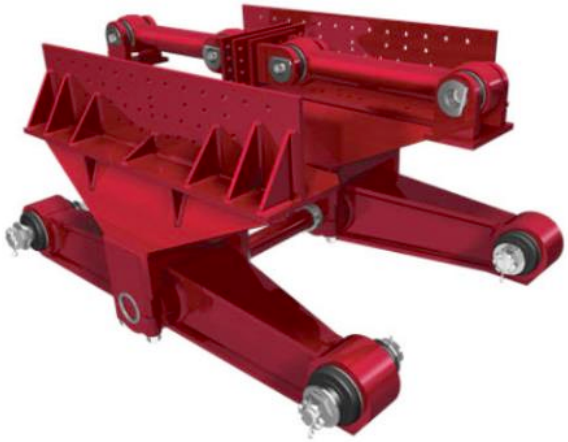


Figure 2.2.3 Solid mount suspension [18].

2.2.4 Suspension position

The suspension allows vertical movement within a range of motion. For describing the suspension position, the following terms are used:

1. **Normal ride height (Load):** Refers to the position while riding in even terrain without any bumps or holes in the pavement.
2. **Jounce:** Refers to the bounce or vertical movement of the vehicle suspension upwards when it contacts a bump in the road [19]. It can also be referred to as the highest point in the suspension movement
3. **Rebound:** Refers to the movement of the vehicle suspension in the opposite direction of jounce [19]. This means, the lower point in the suspension movement

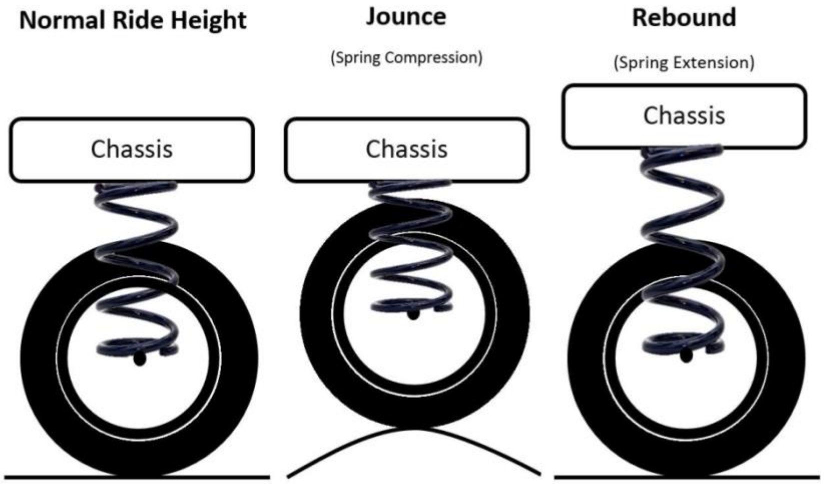


Figure 2.2.4 Suspension positions [20].

2.3 Steering system

Good steering and handling are one of the most critical characteristics of a commercial vehicle. Steering systems allow the driver to control the direction in which vehicle goes, by using a reasonable physical effort over the steering wheel [21].

This system is composed of different elements, for example:

- Axle
- Steering wheel
- Steering shaft
- Steering gear

This section will concentrate on the front axle, as it is the component most relevant to the scope of the research.

The front axle has two main functions: first, supporting the front of the truck, and providing good maneuverability through steering control. International® offers two types of front axles: non-driving and driving. Careful selection of the proper front axle is important for assuring the payloads, long service life, less maintenance, and lower operating costs [18].

One important characteristic is the turn angle capacity, that defines the degrees a tire can change the direction of the vehicle. This is relevant because, together with the suspension travel, causes the relative motion between the chassis and brake chambers, movement that will be studied throughout this research. During the design and simulation process, three positions are mentioned:

- **Left:** The position when the vehicle is steering completely towards lef.t
- **Straight:** The position when the vehicle is not steering.
- **Right:** The position when the vehicle is steering completely towards right.

2.3.1 Non-driving front axles

Front axles have several purposes. They are not only used to support the weight of the vehicle, buy also used to steer the vehicle. However, in the case or non-driving axles, they cannot perform power to spin the tires and move the truck. By matching the steering geometry with the specific wheelbase lengths, tire scrub and premature wear are reduced. As a result, tire life is improved [18].

Some of the main characteristics of the designs of font axles are:

- Sealed king pins and tie rod end for increased lubrication intervals and longer axle life
- Lube fittings for tie rod ends and king pins
- Anti-friction roller thrust bearing for low steering efforts.
- High turn angle capability

The designs of these axles may differ depending on the supplier. Even when they all aim to reduce the weight of the axle

There are different designs of front axles. Even when they all aim to reduce the weight of the axle, some suppliers may add different characteristics. For example: integrated air disc brake knuckle to eliminate parts and simplifying the assembly [22], or brake compatibility features for the possibility of using drum or disk foundation brakes [23]. Most of the non-driven front axles share the same turn angle of 50º.

Figure 2.3.1 Non-driving front axle [24]**.**

2.3.2 Driving front axles

Driving front axles are capable to transfer torque from the motor to each wheel. The ones offered by International® incorporate a hypoid gear system, where the pinion gear meshes with the ring gear below its center line, allowing a larger diameter pinion gear to be used. They have the following advantages [18]:

- Geater tooth contact area
- Better gear lubrication
- Quieter gear operation.

The steer angle in this driving front axle is up to 42 degrees [25].

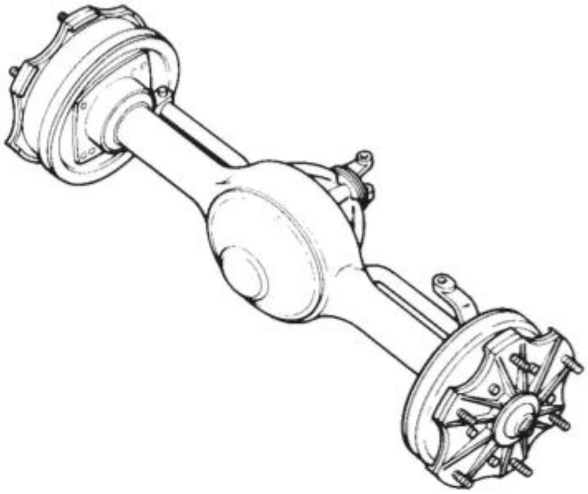


Figure 2.3.2 Driving front axle [18]**.**

2.3.3 Wheel-end components

Wheel-end is a crucial but often overlooked component. However, it is critical for a safe and reliable performance of the vehicle. A wheel end reefer to the components assembled at the end of an axle, where the wheels and tires are mounted [26]. This is critical for the research because it is the point with more movement in relation to the chassis, consequence of the suspension and steering motion. The wheel end includes the following components [26]:

- Wheel hub
- Bearings
- Brake chambers
- Foundation brakes
- Seals and fasteners

In Figure 2.3.3 we can see a non-driving front axle with the wheel-end assembly at both ends. In this case, we have a pneumatic disc brake system. As seen in previous sections, this axle is mounted to the chassis through the suspension system, this means that those wheel-end components will have movement caused by both suspension and steering motion.

Figure 2.3.3 Non-driving front axle with wheel end assembly [22].

2.4 Flexible hoses

In vehicles, safety is a crucial factor to consider, and one vital component for ensuring safety is the braking hose. These hoses ensure the correct function of braking systems and they are one of the most government-regulated components on a vehicle [27], [28].

A brake hose is a flexible section in the braking system that connects the rigid brake lines to the brake chambers at each wheel-end. They are responsible of carrying brake fluid or air which helps to transfer the braking force to stop the vehicle [29]. These hoses may have the following features [30]:

1. Flexibility: They need to be capable of accommodating the movement of articulation of various vehicle components and environmental conditions.
2. Durability: To ensure the air brake can withstand high pressure, they have many layers inducing a robust inner tube, reinforce material, and an outer cover.

2.4.1 Regulations

All aftermarket hose, fittings and complete hoses must conform to FMVSS 106 (from the U.S. Department of Transportation) and SAE J1401, that are tests to analyze their performance. These tests are demanding and often exceed what a vehicle will see in a real environment [28].

In brief, the U.S. Department of Transportation (DOT) states that the hose must be flexible in a wide range of temperatures while having a predictable expansion ratio, ensuring the same pedal feel and ABS response during winter and summer. In addition, it specifies that the hose must be able to twist and bend at certain angles without collapsing, kinking or bursting [28], [31].

FMVSS 106 and SAE J1401 do not specify the construction materials, but they do outline a test procedure that the complete hose must pass:

1. **Labeling:** Each hydraulic hose, except for the original hoses, must have at least two clearly identifiable stripes placed on opposite sides of the hose, parallel to its longitudinal axis. These lines are called "torque stripes", and their purpose is to prevent twisting during assembly and installation.
2. **Tensile strength:** The hose must withstand a pull of 325 pounds without separation from its fittings in a slow pull test, and it must withstand a pull of 370 pounds in a fast test.
3. **Cold resistance:** A brake hose chilled below -49º F for 70 hours shall not show cracks when bent around a cylinder.
4. **Chemical resistance:** The hose should pass a burst test after being in a temperature of 248º F for 70 hours while filled with SAE "Compatibility Fluid".
5. **Ozone resistance:** A brake hose assembly exposed to ozone for 70 hours at 104º F shall not show any crack.
6. **Fitting corrosion resistance:** After 24 hours of exposure to salt spray, a hydraulic brake hose end fitting must show no base metal corrosion on the surface.

2.4.2 Internal design practices

At International ®, there are internal design practices that evaluate the performance and acceptance of designs. They aim to prevent 3 main conditions: kinking caused by a small curvature radius, excessive pullout forces acting on the connectors, and contact between the hose and other static or dynamic components. The results of each indicator are categorized into three performance levels: unacceptable, marginal and preferred.

2.4.3 Undesired conditions

Flexible brake hoses must allow the suspension to travel its full possible range without compromising braking performance. For this reason, flexible hose manufacturers propose installation and routing design guidance to ensure the optimal operation of the component. Disregarding these recommendations may result in improper setup, leading the system to performance loss or failure [32], [33]. As mentioned before, this research will evaluate the 3 critical conditions that may be presented in flexible hoses, which are, kinking, pulling and interference. Excessive twist is identified as a critical condition; however, it will not be considered in this study. This decision is based on prior project conducted at International ®, which demonstrated that the routine motion of the wheel-end and chassis does not produce a significant degree of twist warranting attention. These critical states will be referred to as undesired conditions.

Twisting

Attention must be given to the optimum routing and installation to minimize problems like excessive torsion, that can failure or reduce the tube and fitting life. This undesired condition is presented when the relative motion of the components cause a torsional mechanical strain [33], [34]. As mentioned in section 2.4.1, each hydraulic braking hose shall be labeled, these marks are normally called "torque stripes" [28], and as seen in Figure 2.4.1, they help to identify twisted hoses.

a) Hose with twisting condition. b) Hose with correct routing (no twisting).

Figure 2.4.1 Twisting condition [33].

Kinking

The bending radius is measured at the centerline of the bent section of the hose. Minimum bending radius are specified by suppliers because going beyond this radius may kink the hose. This condition refers to a sharp bending where the outside diameter collapse, therefore, narrowing the inner section of the hose [33], [34]. Kinked braking hoses can cause flow restrictions, resulting in poor braking or failure of the system [32], [35].

a) Hose with kinking condition. b) Hose with correct bend radius.

Figure 2.4.2 kinking condition [33].

Pulling

Pulling is caused by a tensile mechanical load in the hose. To avoid excessive tension, the hose length must be determined so that the assembly has enough slack to allow the components to move without creating tension in the hose [33]. The FMVSS 106 [31] have requirements for these pulling forces, that were mentioned in section 2.4.1.

a) Hose under excessive tension. b) Hose with appropriate slack allowance.

Figure 2.4.3 Pulling condition [33].

Clearance

Flexible hoses should not be exposed to direct surface contact that may lead to abrasive wear or even perforations on the hose. For this reason, attention should be taken regarding the clearance distance between the hose and other moving or static elements [33].

a) Hose contacting objects. b) Hose with appropriate clearance.

Figure 2.4.4 Clearance condition [33] .

2.4.4 Fittings

Fittings, also known as connectors, are essential in pneumatic systems. They accommodate different conditions and requirements in pneumatic systems [36]. There are straight connectors, and elbow connectors at 45 degrees or 90 degrees. The type and orientation of the connector can be changed to obtain a different routing configuration with different results. How ever, it is preferred to have straight connectors, because 45 and 90 degree connectors may reduce the air flow [37].

2.4.5 Modeling techniques

The modeling of flexible components has attracted significant research interest due to their multiple uses, such as cables and hydraulic or pneumatic lines. While many commercial CAD software have provided design and simulation tools regarding these flexible components, researchers have developed custom software utilizing a variety of approaches. In this section a review of methodologies is presented in Table 2.4.1 Physical models of flexible linear objects [38]..

Elastic models	Advantages	Disadvantages
Mass-spring model	Widely used Easy to implement Computationally efficient Les memory occupation	Simplified theoretical model Limited accuracy
Multi-body model	Intuitive Good real-time performance Less memory occupation	Simplified theoretical model Limited accuracy
Elastic rod model	Good theoretical basis More realistic and accurate	Relatively large amount of calculation More memory occupation Lowe calculation speed
Dynamic spline model	Good theoretical basis Continuous model Higher authenticity	A relatively large amount of calculation More memory occupation Lowe calculation speed
Finite element model	Hight accuracy Real results	A large amount of computation Not suitable for real-time simulation

Table 2.4.1 Physical models of flexible linear objects [38]**.**

2.4.5.1 Cosserat rod theory

The Cosserat rod theory is derived from continuum mechanic models and regards cable-like deformable linear objects as elastic rods. It is an improvement of another common theory that does not consider axial extensional and sectional shear deformations of rods [38]. This theory was selected for the development of the software because it provides a powerful and versatile framework to model flexible elements [39], and because of the PyElastica library available for python.

PyElastica is the python implementation of Elastica: an open-source project for simulating assemblies of slender, one-dimensional structures using Cosserat Rod theory [40], [41], [42]. It considers mechanical properties like Young's modulus, Poisson's ratio, density, hose radius and gravitational forces to define the position of a centerline that represents the flexible hose.

In brief, Cosserat rods are described by their centerline $\boldsymbol{r}(s,t)$ and local reference frame $\boldsymbol{Q}(s,t) = \{d_1, d_2, d_3\}$, with consist of 3 orthonormal vectors, being d_1 andd_2 perpendicular vectors in the same plane as the cross-sectional area, and d_3 the tangent vector normal to this plane. The dynamics of the rod are then described by equations for conservation of linear and angular momentum throughout the rod [39].

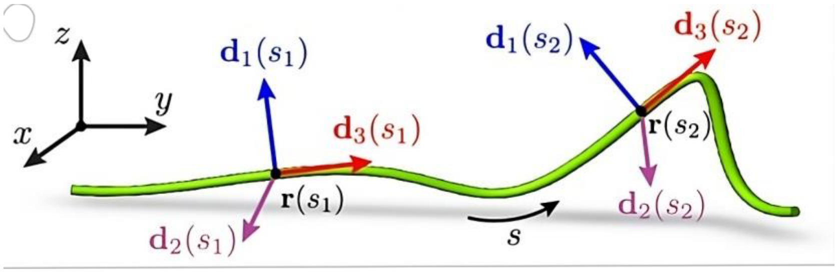
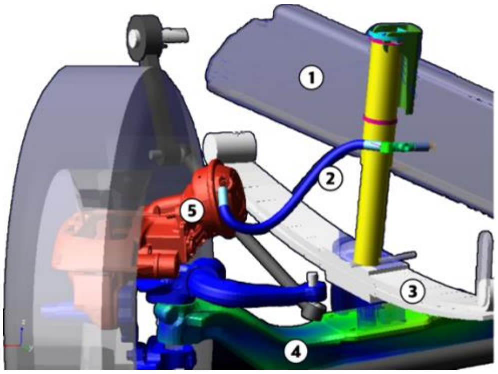


Figure 2.4.5 Cosserat Theory representation [43].

2.5 Integration of systems and components

As motioned before, wheel ends, which house critical components from the braking system, are subject to movement caused by the suspension and steering system. Air pressure needs to be transmitted from the rigid lines to the braking chambers located at the wheel ends. This requires the use of flexible hoses for accommodating changes in position of the components.



1- Chassis
2- Flexible hose (brake hose)
3- Leaf spring suspension
4- Front axle
5- Brake chamber

Figure 2.5.1 Integration of systems and components. Front axle.

In Figure 2.5.1 is shown a front axle of a commercial vehicle, where the flexible hose (2) is connected from the chassis (1) to the brake chamber (5). It's also shown a leaf spring suspension (3), and the front axle (4) steering towards the right side of the vehicle. On the rear axles, only suspension displacement changes the position of the braking chamber since no steering is involved.

Chapter 3: Methodology development

The following methodology aims to provide designers with a guide for developing new flexible hose configurations with the possibility of recognizing undesired conditions such as contact with components, kinking and pulling. For achieving this, multiple steps where needed, starting with the analysis of current conditions and previous designs, the development of a specialized tool for designing flexible hoses, and the definition of the methodology that results from the previous activities and the knowledge of the designers and their best practices.

In this chapter, 4 sections are presented to describe in detail the development of methodology. They are ordered in the following way:

1. **Analysis of previous validation reports:** For obtaining information of previous simulations that did not meet the internal design practices and the activities done to correct them.
2. **Development of the design software**: Describes the workflow needed for the usage of the software.
3. **Definition of the design methodology:** Establishes the best practices and step by step process for designing flexible hose configurations.

The need for a hose design could come from different reasons and have multiple objectives. Therefore, the proposed methodology covers the activities done in the CAD software to define the connector types and orientations together with the hose length. It does not consider previous steps or acquisition of the required information for the design process. Further information in relation to the boundaries of the methodology is provided in section 3.3

3.1 Analysis of previous validation reports

In the typical industrial workflow, designers propose a routing configuration that is sent to the simulation team to validate the bending radius, pullout forces, and clearance between other components. These reports include the analysis of the proposed routing, and 2 or more configurations suggested by the simulation team in case the first one is not accepted, or other configurations accommodate better. To perform the simulation, a Multi Body Dynamic (MBD) software is utilized. The hose is routed according to the length and position of the fittings proposed by designers, and then the simulation is performed based on the displacements of the steering and suspension system. The simulation team proposes configurations making iterative changes based on their experience, performing a simulation with each iteration.

After analyzing the reports, it is shown that there are conditions that can be changed for the design to have a tendency of passing the three internal design practices. Due to the limited number of configurations evaluated, no definitive conclusions can be drawn about the relationship between connector orientation, hose length, and approval probability. Nonetheless, the data do indicate a trend suggesting that these changes may positively influence the likelihood of approval.

3.2 Development of the design software

There are different commercial solutions for drawing and simulating flexible hoses offered as integrated CAD modules or as standalone applications that require an export-import workflow. While these options offer advanced tools and capabilities, they tend to have costly licenses and most of their features won't be needed during the design process.

This thesis requires a tool that allows designers to draw a flexible hose from a start position to an end position with a specific hose length, while monitoring the minimum bend radius and pull-out force. To meet these requirements, a dedicated tool named Flexible Line Explorer (FLEX) was developed using Python. It offers a license-free solution with cross-platform capabilities that can be further developed according to future needs.

3.2.1 Flexible Line Explorer

This software aims to support the proposed design methodology with a specialized tool that allows designers to correctly predict hose shapes. Additionally, the software facilitates the evaluation of the configurations regarding the internal design practices mentioned in section 2.4.2.

The program uses PyElastica, the python implementation of Elastica: an open-source project for simulating assemblies of slender, one-dimensional structures using Cosserat Rod theory [40], [41], [42]. It considers mechanical properties like Young's modulus, Poisson's ratio, density, hose radius and gravitational forces to define the position of a centerline that represents the flexible hose. This geometry starts in the frame side connector, that will be referred to as a to origin connector, and ends at the chamber side connector, referred to as to target connector.

For each connector, the following points are needed for the simulation:

- **Connector point:** It is located at the outlet of the connector. From there the hose will start or end, depending on if it is the start (frame side connector) or the target (chamber side connector).
- **Direction point:** In the previous point, only the position from where the hose will start or end was selected. This second point will define the correct orientation, so the hose is orientated correctly.
- **Normal point:** This point is used to lock the rotation of the hose in its tangent axle. It is crucial for maintaining the effects that the torsional forces have on the overall shape of the hose.

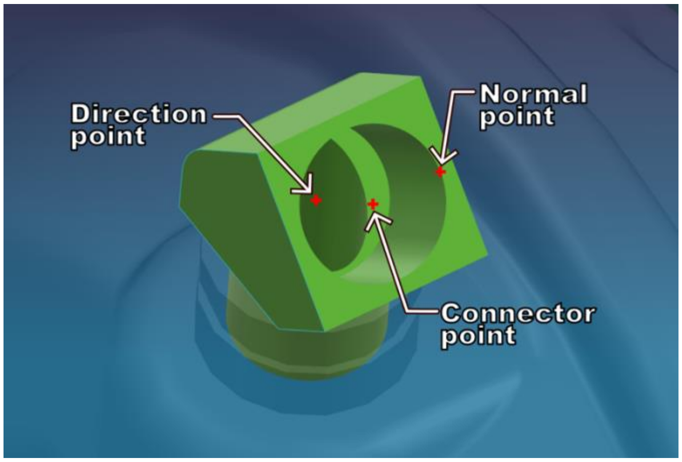
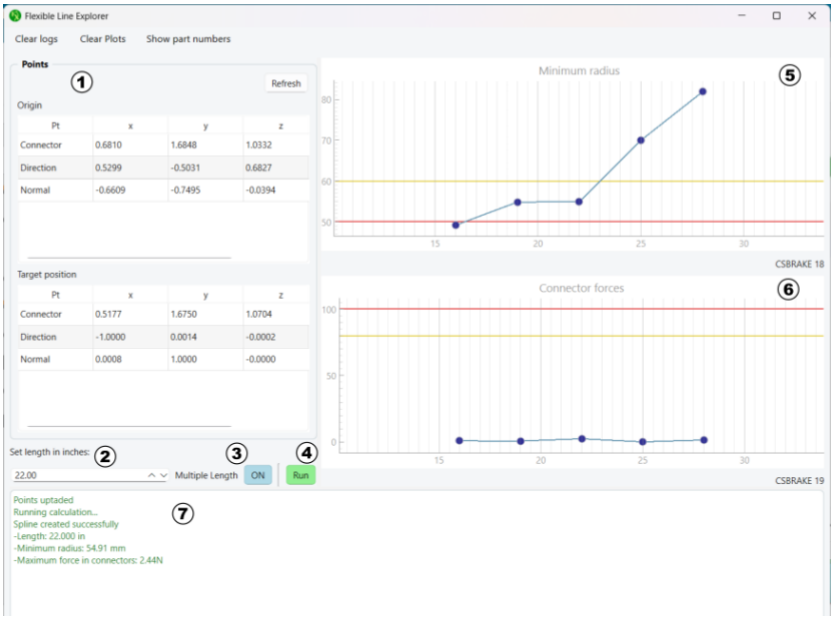


Figure 3.2.1 Connector points.

In the user interface of FLEX (Figure 3.2.2) is possible to see different sections: at the top left, the previous points for both connectors; the length input to specify the hose length, a multiple length button that delivers data from 2 smaller hoses and 2 larger hoses than the selected length; and a "RUN" button that starts the calculations. At the top right, 2 plots are visible, the first one shows the minimum bend radius of the hose, and the second one shows the maximum connector forces. Finally, at the bottom is found a text box where the results are displayed.



Origin

Pt	x	y	z
Connector	0.6810	1.6848	1.0332
Direction	0.5299	-0.5031	0.6827
Normal	-0.6609	-0.7495	-0.0394

Target position

Pt	x	y	z
Connector	0.5177	1.6750	1.0704
Direction	-1.0000	0.0014	-0.0002
Normal	0.0008	1.0000	-0.0000

Set length in inches: 22.00

```
Points uptaded
Running calculation...
Spline created successfully
-Length: 22.000 in
-Minimum radius: 54.91 mm
-Maximum force in connectors: 2.44N
```

1- Points section
2- Length input
3- Multiple length button
4- Run button
5- Minimum radius plot
6- Maximum force plot
7.- Text box

Figure 3.2.2 Flexible Line Explorer user interface

The software works by creating a straight rod represented by 60 elements starting from the origin connector point. The starting point of the spline is fixed in position and rotations. The end of this centerline is controlled by a PID force that pushes it to the target position and orientation. In Figure 3.2.3 is shown a visualization of the calculations done by the software. In blue is represented the elements that represent the hose, including their normals represented with a black arrow. In the last element, where the force is applied, is visible its normal, direction and an additional orthogonal vector. This process takes around 30 seconds to complete, and around 2:30 minutes in case the multiple length generation is selected, because it generates 5 rods.

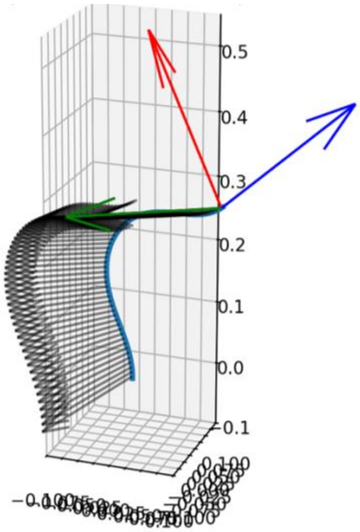


Figure 3.2.3 Visualization of software's calculations

Most CAD software offers an Application Programming Interface (API) that allows users to run code for automating tasks or obtaining data. Siemens NX has a tool called NX Open API, that includes an embedded Python interpreter to execute NX Open Python scripts. For using the Flexible Line Explorer, two complementary Python scripts will run in the CAD application programing interface, resulting in the following workflow:

1. **Point selector:** This first step runs in the CAD software API**.** There is one script for selecting points from the start connector and one for selecting the points from the target position. During this research, this script will be referred to as the origin or target selection tool.
   The point's coordinates are stored in a CSV file that will serve as input for the Flexible Line Explorer.

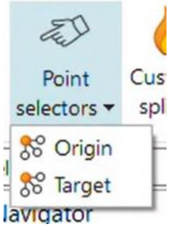


Figure 3.2.4 Origin and target selection tool buttons.

2. **Flexible Line Explorer (FLEX):** This is the main application. Since the Python interpreter embedded the CAD software's API has limitations. FLEX runs as an independent Python program. The application takes as inputs the coordinates stored in the CSV file from the previous step and allows the users to define the hose length to start the calculation.

The output of FLEX, besides the information plotted, is a CSV file with a set of coordinates corresponding to the hose position. This will be used as input in the following step

Figure 3.2.5 Button for opening FLEX.

3. **Spline creation**: This last script reads the coordinates stored in the previous CSV file and creates a spline that goes through those points. This spline can then be utilized as usual, for creating tubes, sweeps, and measures from it. In future sections of the research, this script will be referred to as custom spline creation tool.

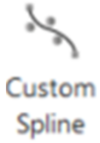


Figure 3.2.6 Spline creator tool button.

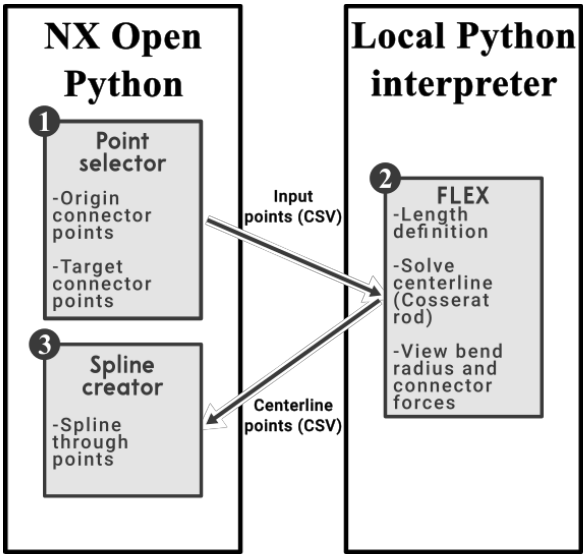


Figure 3.2.7 Workflow for using Flexible Line Explorer.

3.2.2 Software validation

To validate the geometries generated by FLEX, a comparative was done against real hoses. In this section it will be discussed how geometries were obtained and compared. In the subsequent section, the results will be analyzed to evaluate the performance of the Flexible Line Explorer

3.2.2.1 Evaluation with real hoses

A 3D scanner was utilized for obtaining the geometry of real hoses and making the comparation. 4 stages were necessary for the scanning process:

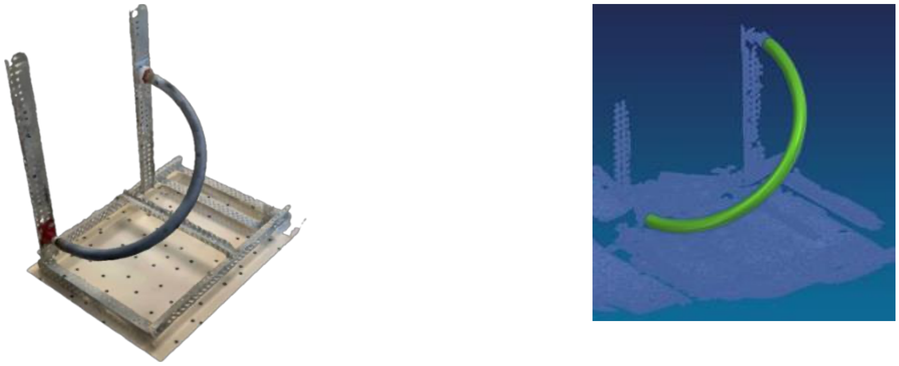
1. **Creation of the scanning rig:** To accommodate the hose connectors in specific positions, a scanning rig was built using aluminum profiles from a VEX robotic kit [44]. This building material was selected due to its capabilities for easy modification and robustness. Additionally, for holding the hose ends, a custom fixture was created for each side and 3D printed with a PETG filament. They can be easily mounted in the aluminum frame to change the hose position.
   3 different configurations were defined to be analyzed, they are shown on the left column of the Figure 3.2.8.
2. **3D scanning:** Each one of the different configurations was scanned using an EinScan Pro 2X Plus [45]. The point cloud was converted to a mesh and then it was exported as OBJ file.
3. **Spline creation:** The mesh was imported into Siemens NX to obtain the centerline of the hose. It was possible by developing the following steps:
   - **Defining points on the surface:** To be able to work with the mesh, the Fit Curve tool was used, it allows to draw a curve from points on a surface. Around 20 to 25 evenly spaced curves were created along the mesh. Each curve was built by defining 3 transversal points as straight as possible.
   - **Convergency of points:** A 3-point arc was created for each Fit Curve from the previous step. This results in a transversal arc that can give us a point at the center of the hose in that section.
   - **Center points:** With the point tool where created points at the centers of the arcs from the previous step.
   - **Spline creation:** Using the studio spline, a Through Points Spline was created by selecting the points from the previous step. The length of the spline was measured with the measure tool inside NX, and it was later inputted into FLEX for recreating the hose.
   - **Tube creation:** Once the spline was obtained, the hose can be created by using the Tube tool, defining an outer diameter of 22.222 mm and setting a Single Segment output. The results for each configuration can be seen in Figure 3.2.8.
4. **Definition of FLEX input points:** Once the centerlines were obtained, it was necessary to define the connector, direction and normal point for each side of the hose. For achieving this, the following steps were needed at each spline end:
   - **Connector point:** A point was created at the end of the spline. It will indicate the location where the hose starts or ends, depending on the spline side.
   - **Direction point:** The direction point was created by defining a new point in the same location as the previous point and selecting the offset along vector option. The spline must be selected as the offset vector. The offset distance used was 1 millimeter, however, the vector between the connector point and the direction point will be normalized, therefore this offset distance can be different, and the results will not be affected.

- **Normal point right:** For defining the normal point orthogonal to the direction vector, it was first created an arch with radius of 5 mm with origin at the connector point. The drawing plane for this arch was created normal to a line created between the connector and direction point. Once having the arch, a point was created at the right side of the connector point.

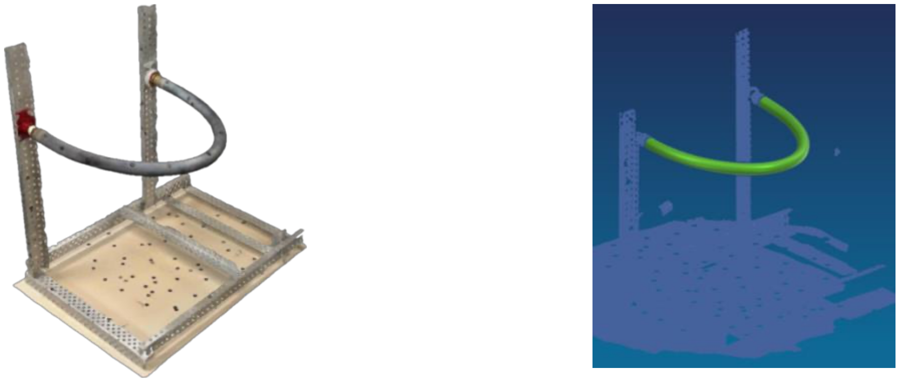
After defining the points on each side of the spline, they were inputted into FLEX, and the hose was recreated using the length obtained in step 3 and drawn in the CAD software by using the corresponding script.

5. Data extraction: For both the scanned and the FLEX geometry, 50 evenly separated points were created along the spline. The coordinates of each point set were extracted into a CSV file by using a Python script.

a) Configuration #1: Real model and 3D scanned geometry



b) Configuration #2: Real model and 3D scanned geometry



c) Configuration #3: Real model and 3D scanned geometry

Figure 3.2.8 Geometries obtained from 3D scanned hoses.

In Figure 3.2.9 is shown a comparison of the generated geometry of the configuration number 1 and the corresponding hose created in FLEX

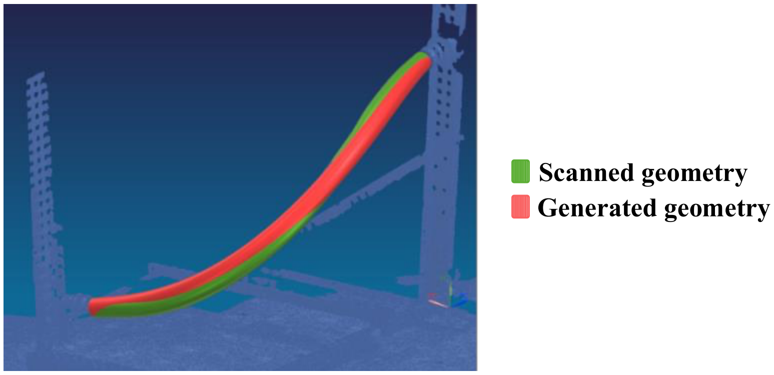


Figure 3.2.9 Comparation between scanned and generated geometries for configuration #1

3.2.3 Results analysis

The results obtained from the evaluation stage are discussed in the following section. The analysis focusses on the performance of the software in detecting the undesired conditions studied in this research, specifically:

1. **Clearance between surrounding components:** The software should correctly predict the hose shape to allow correct measurements to evaluate the clearance between surrounding components.
2. **Minimum radius**: The radius obtained by the software should correspond to the radius measured in Siemens NX by using the measure tool.
3. **Pullout forces:** The pullout forces on connectors should correspond to the forces measured through current validation tools that use MBD tools.

3.2.3.1 Clearance between surrounding components

For analyzing the geometries obtained from the 3D scans and those created with FLEX, 50 equidistant points were created along the splines. For each point from the constructed splines, a comparison was made with the corresponding point from the 3D scanned splines. This allowed to determine the Euclidian distance between paired points and subsequently calculate the root mean square error (RMSE) and the maximum distance.

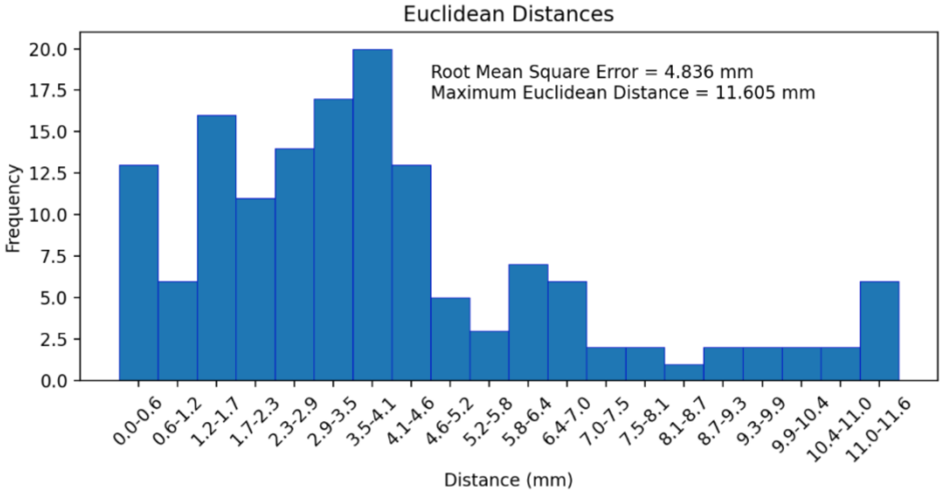


Figure 3.2.10 Histogram of Euclidean distances.

From this data it is possible to observe that the software is able to successfully predict the real shape of the hose. Even though there is a difference between certain points, the results are similar to those obtained through the current MBD tool in a previous study.

3.2.3.2 Minimum radius

The minimum bend radius obtained by the Flexible Line Explorer can be easily verified by using the measure tool available in Siemens NX. For this, a front suspension layout was used to create 3 hoses of different length in 4 positions: right jounce, right rebound, left jounce and left rebound. This resulted in 12 different hoses that were measured in Siemens NX. The results are shown in Table 3.2.1.

The data obtained are consistent and provide accurate approximations, indicating that the Flexible Line Explorer successfully predicts the spline's radius. An additional consideration could be to validate the bend radius near the rejection threshold.

Position	Length in	FLEX radius mm	NX radius mm	Difference mm	Absolute error
Right jounce	17.6	95.38	94.34	1.04	1.10%
	20.6	86.91	84.86	1.05	1.22%
	22.6	84.73	83.5	1.23	1.47%
Right rebound	17.6	75.81	74.83	0.98	1.31%
	20.6	72.45	71.29	1.16	1.63%
	22.6	73.24	71.9	1.34	1.86%
Left jounce	17.6	62.68	62.19	0.49	0.79%
	20.6	78.47	77.72	0.75	0.97%
	22.6	88.72	88.1	0.62	0.70%
Left rebound	17.6	67.85	67.28	0.57	0.85%
	20.6	71.83	71.09	0.74	1.04%
	22.6	75.87	74.85	1.02	1.36%
			Average	0.92	1.19%

Table 3.2.1 Minimum bend radius comparation

3.2.3.3 Pullout forces

To evaluate FLEX results regarding connector forces, 4 splines from a front articulation study with their corresponding connector forces were provided by the simulation team. Unfortunately, the results calculated by the Flexible Line Explorer were different as the ones provided with multi body dynamic methods. They can be seen in Table 3.2.2. At the current state of this research, the reason for this difference is unknown. However, possible sources for this discrepancy are recognized:

1. **Mechanical properties:** The mechanical properties used by the simulation team were calculated empirically based on results obtained from a previous project. The values used for the Flexible Line Explorer were obtained from research conducted on a similar hose [46]. Poisson’s ratio was changed to allow a small amount of deformation in the simulation:
    - Young heather: 17 MPa
    - Density: 1347.9 kg/m^3
    - Poisson’s ratio: 0.49
2. **Force obtention:** As mentioned in section 3.2, the software creates a straight rod and locks the start end in position, then a PID force is applied in the free end until it is at the target position. The final PID force is not currently obtained, and only the force at the start connector is possible to obtain. However, hoses have been generated in the opposite direction to evaluate improvements, but significant changes are not seen.
3. **Oscillations in steady state:** During the application of the PID force to the free end of the hose, the full length of the hose experiments changes in position that

remains even when the force is no longer applied. This movement pushes and pulls the connectors and may influence results depending on the state of the oscillation at the end of the simulation.

However, force validation against real hoses and experimental measurements is recommended to compare the performance of the software against the behavior of real components.

		FLEX N	**MBD** N
Left	**Jounce**	2.57	21
	Rebound	3.93	24
Right	**Jounce**	10.26	2
	Rebound	13.59	5

Table 3.2.2 Comparative of obtained connector forces.

3.3 Definition of the methodology

The proposed methodology aims to merge the best practices and advice learned from prior experience, aiming to facilitate the creation of future flexible hose configurations. Moreover, it serves as a guide for designers who approach the subject for the first time. The methodology, together with the usage of the Flexible Line Explorer, will streamline the design of flexible hose configurations, while reducing the need for reworks and reducing the probability of defects during the assembly process.

The need to design or validate flexible hose configuration can be originated by different causes. It can be made during the regular development of a new unit, requested to solve an issue found during the assembly process, or because of other reasons that will not be included during the development of this research. Therefore, this methodology will only cover the design done in the CAD software regarding the selection of the type and position of connectors and hose length.

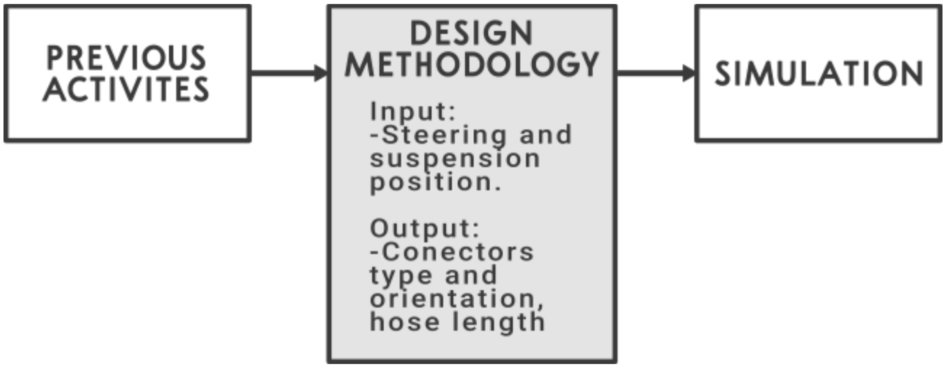


Figure 3.3.1 Boundaries of the design methodology.

Main requirements:

For defining the flexible hose configuration, it is necessary to know the surrounding components that could interfere with the hose to make sure that they are visible in the CAD software. Additionally, it is important to have the layout prepared with the suspension and wheel-end components in the following positions:

Front axle	Rear axles
Jounce, Left	Jounce
Jounce, Right	Load
Load, Straight	Rebound
Rebound, Left	
Rebound, Right	

Table 3.3.1 Points required for the design process.

These points are going to be evaluated in the design methodology while considering the recommendations of the following section.

3.3.1 Recommendations

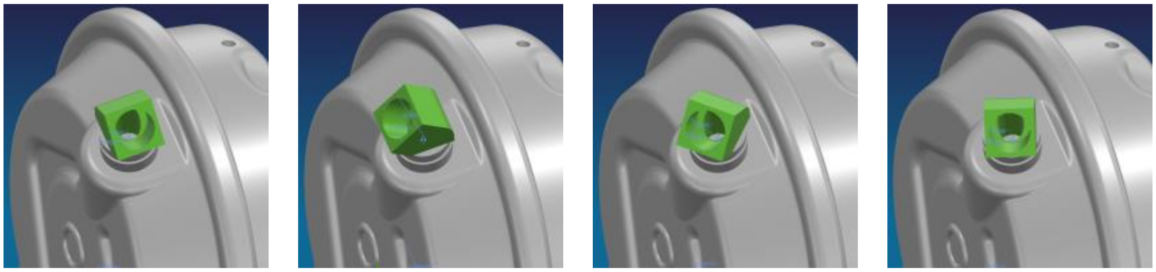
The following recommendations are derived the analysis of previous configurations discussed in section 3.1, information from section 2.4 in the theoretical framework, and personal communication with designers. They aim to summarize the knowledge gained from experience and make it accessible so that it can serve as guidance for future designs created. As seen in Table 3.3.2, the criteria for each recommendation can be categorized as: Ideal, Acceptable, and Tolerable. While "ideal" refers to the preferred condition to have in a design, "tolerable" is still feasible if required.

Connector angle

As mentioned in section 2.4.4, the angle of the connector has an effect in air flow. Therefore, is preferred to have straight connectors. 45-degree elbows are the second preferred connector to use; however, 90-degree elbows can be used if necessary.

Connector orientation

In the assembly process, the connectors are installed manually. Therefore, the position should be easy to evaluate. The ideal orientation is the one that es defined by 90 degrees increments, for example 0° or 90° (Figure 3.3.2 a, b) from the defined initial orientation. 45 degrees increments (Figure 3.3.2 c) are also acceptable. Increments smaller than 45º (Figure 3.3.2 d) are harder to validate in the assembly process, thus they should be avoided unless necessary.



a) Connector at 0º b) Connector at 90º c) Connector at 45º d) Connector at 20º

Figure 3.3.2 Connector orientation.

Quantity of hose lengths

Having only one part number for all the hoses in the configurations designed can help to avoid controls and possible mistakes during assembly. For this reason, the ideal condition is to only have one same hose length for all the hoses in the same axle. Having more than 2 lengths could lead to assembly problems but it is still possible if required.

Configuration symmetry

For similar purposes than the previous recommendation, the configuration between left and right side of each axle should be symmetrical. Changes to one side of the axle are tolerable if the layout requires them.

These recommendations are summarized in Table 3.3.2

Criteria	Preferred	Acceptable	Tolerable
Connector angle	0 deg connectors	45 deg elbows	90 deg elbows
Connector orientation	90 deg increments	45 deg increments	< 45 deg increments
Quantity of hose lengths	1 same length	2 different lengths	> 2 different lengths
Configuration symmetry	Symmetric configuration between left and right side	--	Asymmetric configuration between left and light side

Table 3.3.2 Recommendations for designing flexible hoses.

Proposed design methodology

The following methodology was developed based on the recommendations from design engineers with experience in flexible hoses and the analysis done in section 3.1. It also merges the use of the Flexible Line Explorer to facilitate the definition of the configuration while being able to evaluate its behavior according to the internal design practices discussed in section 2.4.2. The purpose of this methodology is to guide the development of future hose designs through a step-by-step process that, together with the recommendations and the Flexible Line Explorer allows designers to identify undesired conditions.

The methodology, as seen in Figure 3.3.3, comprises four stages that include activities on the CAD software and the usage of the Flexible Line Explorer. The purpose of each stage is:

1. **Preparation of connectors and input points:** To define the connectors type and orientations, and to obtain the three points (connector, direction and normal) for the origin and target positions according to the requirements mentioned at the beginning of section 3.3. These points are the ones that will be evaluated during the complete methodology.
2. **Minimum length evaluation:** To obtain the minimum hose length required for the current configuration. It is done at the beginning to ensure that the length will be long enough for all the points.
3. **Closest point evaluation:** To validate the configuration when the distance between the origin point and the target point is the smallest. This is one of the

points where undesired conditions are commonly found, therefore it is evaluated right after defining the hose length to make changes promptly if needed.

4. **Evaluation of remaining points:** To validate the behavior of the configuration in the rest of the point. It ensures that the hose length and connector types and orientations are correct for the rest of the positions defined in the first stage.

These stages were separated by their objectives, but during the development of the process, it may be necessary to return to specific activities from previous stages.

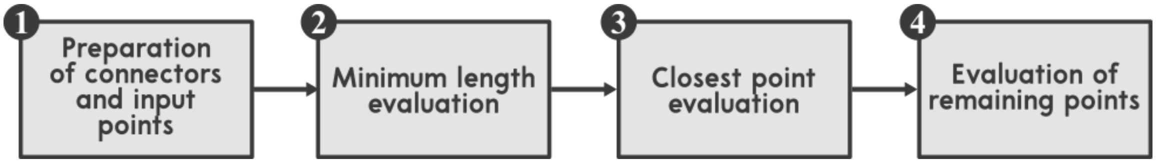


Figure 3.3.3 Stages of the design methodology.

Preparation of connectors and input points

This stage starts in the CAD software and requires the connectors to be already in the positions mentioned in Table 3.3.1. The process for this stage aims to create the connector, direction and normal point for the connectors at each position. Later, the distance between the origin and target connectors will be measured to find the closest and furthest position. The process is detailed below:

1. **Connector type and orientation:** Based in the analysis done in section 3.1and first and second recommendation of section Table 3.3.1 Points required for the design process., select the connector angle and orientation so that the outlet directions lean towards each other, taking as reference the load position (load straight position if working on a front axle). The connector type and orientation should be replicated in every position.
2. **Point creation:** For each connector, create the connector, direction and normal point as described in Figure 3.2.1.
3. **Distance measurement:** Using the measure tool, measure the distance between the origin connector and each of the target connectors. The outcome of this step is the identification of the furthest and closest point
4. **Origin points selection:** Select the connector, direction and normal points from the origin connector using the origin selection tool that sends the points coordinates to FLEX.

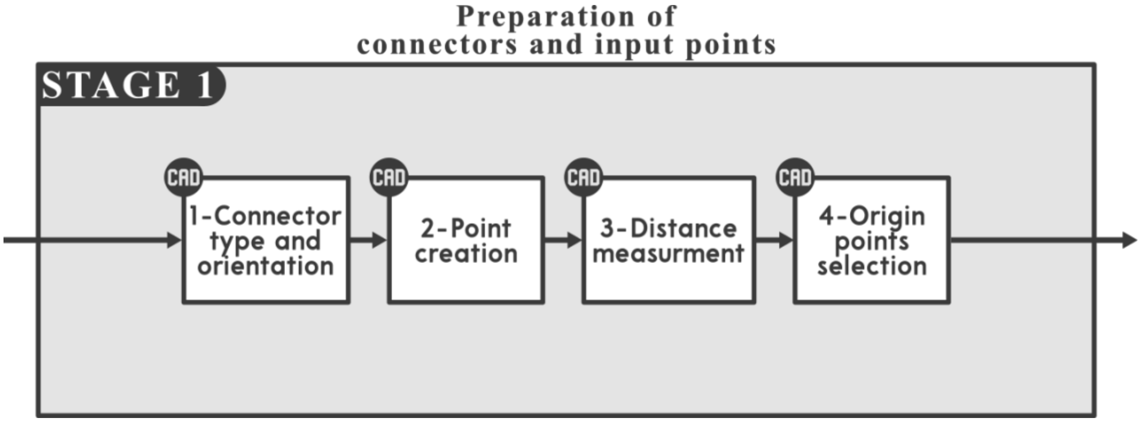


Figure 3.3.4 Stage 1 of the design methodology.

Minimum length evaluation

In this stage, the minimum length needed for the configuration will be determined. The target will be the furthest connector identified in step 3 of the previous section.

1. **Target points selection:** Using the target selection tool, select the connector, direction and normal point for the furthest connector and refresh the points in FLEX.
2. **Length identification**: In the Flexible Line Explorer, run the simulation with the multiple length option on. The first time, it is recommended to set the length 4 inches longer than the linear distance between connectors. However, later this length might be changed.
3. **Radius and forces evaluation:** The minimum radius and the maximum connector forces generated in the previous step are now shown on the plots. If the results of 3 or more hoses land in the accepted region, go to next step. Else, change the hose length and go back to step 2. These accepted lengths will be used later during the development of the process.
4. **Hose generation:** Select one of the accepted hose lengths accepted from the previous step and create the hose in FLEX without selecting the multiple length. When the calculation finishes, go to the CAD software and draw the hose spline using the custom spline tool.
5. **Clearance evaluation:** Using the measure tool, measure the distance between the closest surrounding components. If it is accepted according to the internal standard for clearance, go to the next stage. Else, select another accepted length and go back to step 4. If after changing the hose length no significant improvement is shown, go to step 6
6. **Modify connector type and orientation:** If the unaccepted clearance distance is located close to one of the connectors, it is likely that changes in length will not have significant improvement. Therefore, this connector should be changed or oriented so that the outlet direction leans away from the component. Once these changes are done, go back to step 2.

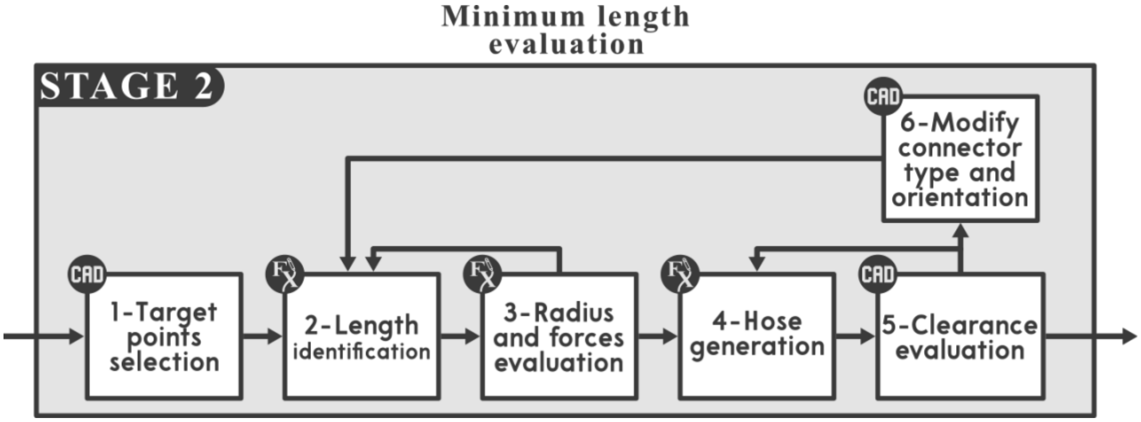


Figure 3.3.5 Stage 2 of the design methodology.

Closest point evaluation

After defining the minimum hose length, it is important to validate that the configuration works in the closest point. In this stage the target connector used is the closest connector identified in step 3 of the first stage.

1. **Target points selection:** Using the target selection tool, select the connector, direction and normal point for the closest connector and refresh the points in FLEX.
2. **Hose calculation:** In the Flexible Line Explorer, use the current length selected to generate the hose. In this step it is not necessary to select the multiple lengths button.
3. **Radius and force evaluation:** The minimum radius and the maximum connector forces generated in the previous step are now shown on the plots. If the hose does not meet the internal design practices of minimum mend radius or maximum connector forces, another length from the identified in the second stage of the methodology should be selected and the process should go back to step 4 of the second stage.
4. **Hose generation:** When the calculation finishes, go to the CAD software and draw the hose spline using the custom spline tool.
5. **Clearance evaluation:** Using the measure tool, measure the distance between the closest surrounding components. If it is accepted according to the internal standard for clearance, go to the next stage. Else, select another accepted length and go back to step 4 from the second stage. If after changing the hose length no significant improvement is shown, go to step 6
6. **Modify connector type and orientation:** If the unaccepted clearance distance is located close to one of the connectors, it is likely that changes in length will not have significant improvement. Therefore, this connector should be changed or oriented so that the outlet direction leans away from the component. Once these changes are done, go back to step 2 from the second stage

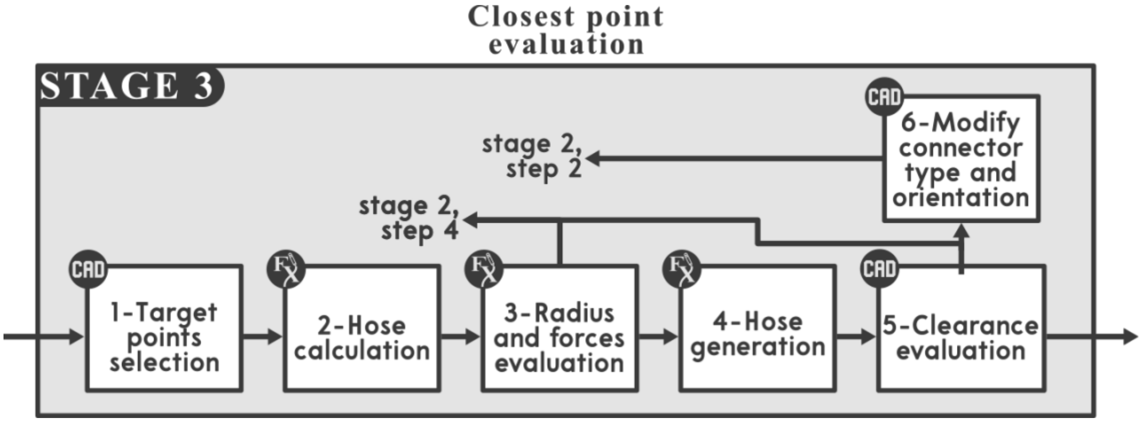


Figure 3.3.6 Stage 3 of the design methodology.

Evaluation of remaining points

This final stage is meant to be repeated with the rest of the points mentioned in Table 3.3.1. Therefore, the target used will change depending on the position evaluated.

1. **Target position definition:** Using the target selection tool, select the connector, direction and normal point for the closest connector and refresh the points in FLEX.
2. **Hose calculation:** In the Flexible Line Explorer, use the current length selected to generate the hose. In this step it is not necessary to select the multiple lengths button.
3. **Radius and force evaluation:** The minimum radius and the maximum connector forces generated in the previous step are now shown on the plots. If the hose does not meet the internal design practices of minimum mend radius or maximum connector forces, another length from the identified in the second stage of the methodology should be selected and the process should go back to step 4 of the second stage.
4. **Hose generation:** When the calculation finishes, go to the CAD software and draw the hose spline using the custom spline tool.
5. **Clearance evaluation:** Using the measure tool, measure the distance between the closest surrounding components. If it is accepted according to the internal standard for clearance, Repeat this stage with the next point until necessary. Else, select another accepted length and go back to step 4 of the second stage. If, after changing the hose length, no significant improvement is shown, go to step 6
6. **Modify connector type and orientation:** If the unaccepted clearance distance is located close to one of the connectors, it is likely that changes in length will not have significant improvement. Therefore, this connector should be changed or oriented so that the outlet direction leans away from the component. Once these changes are done, go back to step 2 from the second stage

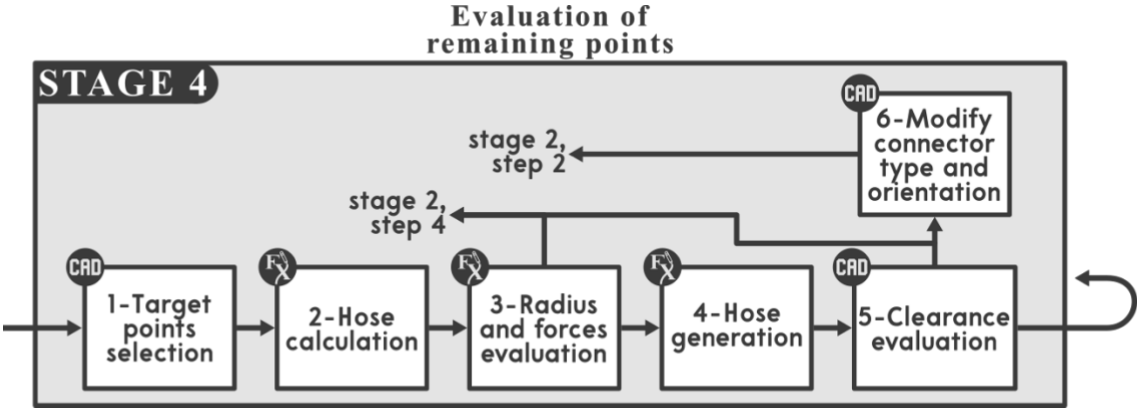


Figure 3.3.7 Stage 4 of the design methodology.

The final connector type and orientation, together with the hose length, is the information that should be sent to the simulation team to continue with their analysis. The main advantage that this design methodology proposes, is the possibility to recognize when the configurations do not meet the internal design practices so the corresponding changes can be made promptly.

Chapter 4: Conclusions and future works

The project achieved an improvement in the design process of flexible hoses on braking systems by allowing designers to identify undesired conditions such as contact with surrounding components, kinking and pulling. In this chapter is included the conclusion for each stage of the research including the key findings, recommendations and achievements obtained. Ending with a proposal of future related research that can be useful for attending real automotive engineering needs.

4.1 General conclusion

The foundation of this project was the analysis conducted on the current design process. For this, it was necessary to conduct a literature review of the components involved and related to the investigated issue. Additionally, it was crucial to understand the relationship between components for the purpose of performing a comparative analysis between approved and rejected configurations. These activities permitted the integration of knowledge obtained through previous experiences and highlighted the need for a dedicated design tool for flexible hoses. A general understanding of the possible approaches that could be used to develop the tool was also performed and helped to define the usage of the Cosserat Theory. Finally, proper measurements were taken to evaluate its behavior against real hoses and hoses created with MBD tools.

The development of this project allowed to define a design methodology that considers best practices and a series of steps that help to improve reliability and streamline the design workflow. Additionally, the developed software permitted to identify undesired conditions such as possible contact with surrounding components, kinking, and excessive tension of the hose at the design stage.

Regarding the project outcomes, firstly, the proposed methodology includes recommendations that may be considered while designing flexible hose configurations. They were obtained through the comparative analysis of previous configurations, comments from the design team, and insights from the validation team. The purpose of these guidelines is to lead future designs by incorporating the experience and lessons learned from previous configurations. Secondly, a step-by-step design methodology is proposed to reduce the iterations needed during the definition of hose configurations. The usage of the developed software is included within the steps of the methodology.

The benefit of the development performed during the project is that it can be further developed to meet additional requirements. This provides the ability to communicate the software with different CAD tools with programing interfaces. Additionally, the interface could also be improved to facilitate its use.

The proposed methodology is limited to the activities regarding the CAD drawing stage. Further expansions of the project could also consider previous steps and afterward steps to standardize the registration, flow and obtention of the information involved. Additionally, the proposed software serves as a first approach to the development of specialized tools for improving current engineering processes. It opens the possibility to explore further procedures that could potentially be improved in similar ways

4.2 Specific conclusions

The following conclusions were obtained from each step needed to accomplish the main objective of the research and prove the hypothesis.

4.2.1 Literature review

The conducted review successfully permitted to acquire the necessary knowledge of each of the components involved in the project. It started with the general understanding of braking, suspension and steering system. Later the section centered on flexible braking hoses, including regulation, design practices and the undesired conditions studied.

This was accomplished by reviewing technical manuals, papers and additional mechanical web pages. Frome these sources was only selected the information related to the research for example: types of braking systems, foundation brakes, type of suspension system and steering angle.

A key part of this section is the integration of systems and components, since it integrates the previous findings and makes it possible to understand the relation among them.

4.2.2 Analysis of approved and rejected hose configurations

The analysis carried out allowed the identification of different characteristics between approved and rejected hose configurations evaluated by the simulation team. It was also possible to obtain recommendations from the design and simulation team that helped to define the proposed methodology.

This outcome was obtained thanks to the comparative performed between configurations that did not meet the internal requirements, and their corrections proposed by the design team. Additionally, the insights from designers were crucial to understanding the possible causes of the problems presented and the changes made.

From the results obtained, it is possible to conclude that there are things that increase the likelihood of having an approved flexible hose configuration. Unfortunately, due to the iterative simulation process and the limited quantity of configurations available to analyze, it is not possible to measure a relationship or to define specific characteristics in this regard, therefore these empirical observations can only indicate a tendency.

In addition, the development of this analysis emphasized the need for a dedicated design tool to be able to evaluate the configurations according to the internal design practices defined.

4.2.3 Theoretical framework for flexible hose modeling

This stage permitted to identify the benefits and limitations of different techniques for drawing flexible hoses. It was crucial for analyzing the possibilities between commercial software and mathematical models that could serve the purpose. Additionally, it allowed us to select the Cosserat Theory to develop the software.

For achieving this purpose, a key resource was utilized as guide [38]. Then each technique was further investigated to identify projects with similar purposes as this research. During the realization of this activity, PyElastica [41], [42] was found and selected for the development of the design tool.

Overall, these findings demonstrate that it is possible to implement the Cosserat Theory to predict hose shapes under different connector positions and orientations. It is important to note that the reason for selecting this approach was due to the available Python library. Even though the current possibilities of the software developed are limited, it is possible to discover and implement features from PyElastica.

4.2.4 Development of the design methodology

This section successfully provided a step-by-step methodology that guides designers in the definition of flexible hose configurations while evaluating the internal design practices for the clearance between objects, minimum bend radius, and pulling forces. It allows designers to have an easier design process, as well as to promptly correct the configurations if needed. This will significantly reduce the need for reworks in later stages of vehicle development.

The proposed methodology relies on the experience and recommendations from the design and simulation team. A fundamental activity, besides the previous analysis of rejected and approved configurations done, was to understand how designs were made by different team members, to recognize the advantages and disadvantages of each approach. Later, this information was segregated and merged into a step-by-step process where the usage of the software developed is included.

In summary, this section shows the importance of documenting and sharing personal knowledge and experience with the aim of defining guidelines and suggestions that could be further improved and used to guide subsequent executions of the activities.

4.2.5 Performance evaluation

The evaluation conducted demonstrates that the outcome from the design software that utilizes the Cosserat Theory is comparable to the results obtained through current MBD tools. This successfully shows that hose behavior can be predicted correctly and can allow designers to identify undesired conditions.

These observations were obtained by comparing hoses calculated with the developed software against real hoses and hoses provided by the simulation team utilizing MBD tools. For the analysis 50 equidistant points were defined along the centerline of each hose. Then their coordinates were imported into a Python script that compared each corresponding point and obtained the distance between them. With this data, it was calculated the mean square root distance.

It can be concluded that the usage of the developed tool is beneficial during the design process due to its capabilities to imitate real hose shapes. Additionally, the integration of the software with the step-by-step methodology will help designers identify undesired conditions during the design process, decreasing the time needed for defining these configurations and reducing the necessity for reworks in later stages.

4.3 Future studies

The limitations and challenges faced during the development of this project suggest different research lines to continue this work..

Research lines to continue this project:

1. **Expansion of the methodology:** The current methodology only involves the process done during the CAD modeling. This achieves a reliable prediction of the behavior of flexible hoses but the information and requirements needed before arriving at this stage still does not follow any standard procedure. Therefore, is suggested the development of a methodology with the aim of standardizing the obtention and transference of the data needed for designing these flexible hose configurations such as suspension travel and steering angle. This will also help when a simulation is requested, since all the related information will be easily retrievable.

2. **Compatibility with additional CAD software and user interface improvements:** The current developments extracts data from Siemens NX and then it is obtained by the design tool. If the CAD software is changed in the future, its corresponding scripts should be generated to obtain the coordinates of the points needed. In addition, the proposed research line could also include the analysis of the current user interface to make improvements and add features to facilitate its use and the interpretation of results.

3. **Performance improvements:** The current state of the software developed has limitations that could be improved in the near future. This may include the proper measurement of the flexible hose mechanical properties and the analysis of the differences obtained by changing them. Also, the oscillations in steady state could be reduced by experimenting with dampening and other stability techniques to improve the outcome of the software.

4. **Adaptation to other flexible lines:** The mathematical model utilized during the research could potentially be utilized to describe the behavior of other flexible lines such as fuel lines, colling hoses and cables. Complete research should be performed in order to understand the requirements for each component and the mechanical properties have to be obtained or estimated to be imputed in the software.

Chapter 5: References

[1] K. A. Chipperfield and J. M. Vance, “Modeling of Hydraulic Hose Paths,” Proceedings of the ASME Design Engineering Technical Conference, vol. 2, pp. 1099–1103, Jun. 2008, doi: 10.1115/DETC2002/DAC-34152.

[2] H. Baaser, “Global optimization of length and macro–micro transition of fabric-reinforced elastomers with application to a brake hose,” Comput. Mater. Sci., vol. 39, no. 1, pp. 113–116, Mar. 2007, doi: 10.1016/J.COMMATSCI.2006.02.023.

[3] T. Hermann, L. Patil, L. Srinivas, and K. Murthy, “A SEARCH-BASED APPROACH FOR PREDICTION OF FLEXIBLE HOSE SHAPES,” 2012. [Online]. Available: http://www.asme.org/about-asme/terms-of-use

[4] R. Raffaeli, M. Mandolini, and M. Germani, “Automation of flexible components virtual prototyping: methodology, tools and validation | Journal of Design Research,” Journal of Design Research, vol. 8, no. 3, pp. 272–297, Apr. 2010, Accessed: May 06, 2025. [Online]. Available: https://www.inderscienceonline.com/doi/epdf/10.1504/JDR.2010.03261

[5] R. Raffaeli and M. Germani, “Knowledge-based approach to flexible part design,” Journal of Engineering Design, vol. 21, no. 1, pp. 7–29, Feb. 2010, doi: 10.1080/09544820802086996.

[6] S. Kim, T. Choi, S. Kim, T. Kwon, T. H. Lee, and K. Lee, “Sequential graph-based routing algorithm for electrical harnesses, tubes, and hoses in a commercial vehicle,” J. Intell. Manuf., vol. 32, no. 4, pp. 917–933, Apr. 2021, doi: 10.1007/S10845-020-01596-9/TABLES/3.

[7] A. Tognolli, F. Utiyke, Y. Paiva, J. Costa, and R. Grespan, “Methodology for virtual analysis of dynamic behavior for tubes and flexible hoses associated with suspension kinematics,” SAE Technical Papers, Jan. 2024, doi: 10.4271/2023-36-0009.

[8] “Air Brake Manual.” Accessed: Jun. 01, 2025. [Online]. Available: https://www.mpi.mb.ca/wp-content/uploads/2022/10/AirBrakeManualNEW.pdf

[9] “Hitting the Brakes: Hydraulic vs Air - Valley Driving School.” Accessed: Jun. 02, 2025. [Online]. Available: https://www.valleydrivingschool.com/blog/main/brakes-hydraulic-vs-air

[10] “Air Braking Systems and pneumatic systems for heavy duty vehicles.” Accessed: Jun. 03, 2025. [Online]. Available: https://cmatic.com/blog/air-braking-systems-and-pneumatic-systems-for-heavy-duty-vehicles/

[11] A. Cisneros Topete, “Metodología para la caracterización y optimización del sistema de frenado diseñado para vehículos pesados.,” Master’s thesis, Universidad Autónoma de Nuevo León, San Nicolas de los Garza, 2018. Accessed: Jun. 07, 2025. [Online]. Available: http://eprints.uanl.mx/id/eprint/16282

[12] “The Basics Of Air Brake Hose: A Comprehensive Guide.” Accessed: Jun. 23, 2025. [Online]. Available: https://kingdaflex.com/what-is-air-brake-hose/

[13] J. I. Castillo Ortiz, “Desarrollo e implementación de banco de pruebas para la caracterización de componentes del sistema de frenos para vehículos pesados de clase VIII,” Master’s thesis, Universidad Autónoma de Nuevo León, San Nicolas de los Garza, 2020. Accessed: Jun. 09, 2025. [Online]. Available: http://eprints.uanl.mx/id/eprint/25710

[14] “Bendix ® Air disc brake manual,” May 2005.

[15] "Air Ride vs. Leaf Spring Commercial Suspension Systems." Accessed: Jun. 11, 2025. [Online]. Available: https://www.cushcorp.com/commercial-vehicle-suspension-systems-air-ride-vs-leaf-spring

[16] WW Editorial Staff, "Understanding Heavy-Duty Suspension Systems and Their Benefits - Wheels & Wisdom." Accessed: Jun. 11, 2025. [Online]. Available: https://wheelsandwisdom.com/heavy-duty-suspension-systems/?utm_source=chatgpt.com

[17] "Multileaf vs. Parabolic Leaf Springs: Understanding the Differences and Their Impact on Vehicle Performance | www.owensprings.co.uk." Accessed: Jun. 11, 2025. [Online]. Available: https://www.owensprings.co.uk/multileaf-vs-parabolic-leaf-springs-understanding-the-differences-and-their-impact-on-vehicle-performance/

[18] International ® Component Book. International Motors, LLC, 2025.

[19] R. P. Tata and R. Tata, "Automotive Suspension Systems Credit: 2 PDH," 2012.

[20] "Figure 5 from The Design of an Innovative Automotive Suspension for Formula SAE Racing Applications | Semantic Scholar." Accessed: Nov. 25, 2025. [Online]. Available: https://www.semanticscholar.org/paper/The-Design-of-an-Innovative-Automotive-Suspension-Darius/f79b6f404afe90353b7a453288646762cb39eef7/figure/7

[21] BASTOW D, "Steering Mechanisms," Proceedings of the Institution of Mechanical Engineers: Automobile Division, vol. 184, no. 6, pp. 137–156, 1969, doi: 10.1243/PIME_AUTO_1969_184_016_02.

[22] "Spicer ® D-Series Steer Axles." Accessed: Jun. 16, 2025. [Online]. Available: www.dana.com/cv

[23] "Hendrickson - STEERTEKTM NXT / Fabricated Front Steer Axle." Accessed: Jun. 16, 2025. [Online]. Available: https://www.hendrickson-intl.com/products/steertek/steertek-nxt

[24] "E-Series Steer Axles." Accessed: Jun. 16, 2025. [Online]. Available: https://www.dana.com/product/commercial-vehicle/e-series-steer-axles/

[25] "Meritor specialty products," 2023.

[26] "Understanding Wheel Ends: Essential Components for Vehicle Performance and Safety." Accessed: Jun. 18, 2025. [Online]. Available: https://mycarheaven.com/2024/07/understanding-wheel-ends-essential-components-for-vehicle-performance-and-safety/

[27] "Asegurar la seguridad y la fiabilidad: el papel de las mangueras de freno de aire en el transporte moderno." Accessed: Jun. 19, 2025. [Online]. Available: https://www.marketresearchintellect.com/es/blog/ensuring-safety-and-reliability-the-role-of-air-brake-hoses-in-modern-transportation/

[28] A. Markel, "Brake Hose Regulations: What You Need to Know." Accessed: Jun. 19, 2025. [Online]. Available: https://www.brakeandfrontend.com/brake-hose-regulations-what-you-need-to-know/

[29] "Symptoms of a Bad Brake Hose - AutoZone." Accessed: Jun. 19, 2025. [Online]. Available: https://www.autozone.com/diy/brakes/symptoms-of-a-bad-brake-hose

[30] "What is an air brake hose - Orientflex -Hose Manufacturer." Accessed: Jun. 19, 2025. [Online]. Available: https://www.orientflexhose.com/what-is-an-air-brake-hose/

[31] National Highway Traffic Safety Administration, Standard No. 106; Brake hoses. Code of Federal Regulations, 2025. Accessed: Jun. 19, 2025. [Online]. Available: https://www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-571/subpart-B/section-571.106

[32] “Dexter Installation instructions. Brake line kits.” Accessed: Jun. 20, 2025. [Online]. Available: https://www.dextergroup.com/user_area/content_media/raw/2021.05_059-B17-00_BrakeLineInstructions.pdf

[33] “Hydraulic Hoses, Fittings and Equipment Technical Handbook,” 2019.

[34] “Masterflex: Glossary | Expert knowledge (spiral) hoses | Masterflex.” Accessed: Jun. 21, 2025. [Online]. Available: https://www.masterflex.de/en/competencies/glossary/

[35] “Especificaciones de las mangueras de freno: una descripción general completa.” Accessed: Jun. 21, 2025. [Online]. Available: https://cntopa.com/brake-hose-specifications-a-comprehensive-overview.html

[36] “A Complete Guide to Pneumatic Fittings by Festo.” Accessed: Jul. 24, 2025. [Online]. Available: https://uk.rs-online.com/web/content/discovery/ideas-and-advice/pneumatic-fittings-guide

[37] P. Beater, “Pneumatic Drives System Design, Modelling and Control.” Accessed: Jul. 24, 2025. [Online]. Available: https://fliphtml5.com/fr/fwsuv/yedl/basic/251-300?utm_source=chatgpt.com

[38] N. Lv, J. Liu, H. Xia, J. Ma, and X. Yang, “A review of techniques for modeling flexible cables,” Computer-Aided Design, vol. 122, p. 102826, May 2020, doi: 10.1016/J.CAD.2020.102826.

[39] “Cosserat Rods | Elastica.” Accessed: Nov. 05, 2025. [Online]. Available: https://www.cosseratrods.org/

[40] “GitHub - GazzolaLab/PyElastica: Python implementation of Elastica, an open-source software for the simulation of assemblies of slender, one-dimensional structures using Cosserat Rod theory.” Accessed: Oct. 23, 2025. [Online]. Available: https://github.com/GazzolaLab/PyElastica

[41] X. Zhang, F. K. Chan, T. Parthasarathy, and M. Gazzola, “Modeling and simulation of complex dynamic musculoskeletal architectures,” Nat. Commun., vol. 10, no. 1, pp. 1–12, Dec. 2019, doi: 10.1038/S41467-019-12759-5.

[42] M. Gazzola, L. H. Dudte, A. G. McCormick, and L. Mahadevan, “Forward and inverse problems in the mechanics of soft filaments,” R. Soc. Open Sci., vol. 5, no. 6, Jun. 2018, doi: 10.1098/RSOS.171628.

[43] A. Lazarus, J. T. Miller, and P. M. Reis, “Continuation of equilibria and stability of slender elastic rods using an asymptotic numerical method,” J. Mech. Phys. Solids, vol. 61, no. 8, pp. 1712–1736, Aug. 2013, doi: 10.1016/J.JMPS.2013.04.002.

[44] “Inicio - VEX EDR - VEX Robotics México.” Accessed: Dec. 07, 2025. [Online]. Available: https://www.vexrobotics.com.mx/vexedr/

[45] “EinScan Pro 2X Plus - Shining3D Latest Handheld Scanner | EinScan.” Accessed: Dec. 07, 2025. [Online]. Available: https://www.einscan.com/handheld-3d-scanner/2x-plus/einscan-pro-2x-plus-specs/

[46] P. A. Mayer, A. Petronilho, A. Tognolli, F. S. Batista, and J. V. Da Silva, “Brake Flexible Dynamic Analysis Attached to McPherson Suspension, Optimizing the Input Parameters in IPS Cable Simulation,” SAE Technical Papers, vol. Part F127082, no. October, Oct. 2016, doi: 10.4271/2016-36-0157.